CHAPTER 248

USE OF THREE-DIMENSIONAL HYDRODYNAMICS MODEL FOR TIDAL INLETS STUDIES

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ABSTRACT

This study utilizes a multi-dimensional hydrodynamics model originally developed by Sheng (1989) and later modified by Sheng *et.al* (1992) to first quantify the flow field in Little Sarasota Bay in Florida, USA with a closed (present condition) and an opened (proposed condition) Midnight Pass, and then to produce a closure curve of the Midnight Pass. This study demonstrates that robust multi-dimensional hydrodynamics models can be used to provide more quantitative analysis of tidal inlet stability.

INTRODUCTION

Tidal inlets connect various bays and lagoons to coastal oceans. As such, tidal inlets can have significant effects on circulation and transport in the bays/lagoons as well as longshore sediment transport in the coastal oceans. For example, tidal inlets can affect the location of nodal zones and flushing of materials into and out of the bays/lagoons (e.g. Sheng *et.al.*, 1992). Tidal inlets can also affect longshore sediment transport by causing erosion on the downstream side of the inlet while causing deposition on the upstream side of the inlet (Dean and Dalrymple, 1994).

Tidal inlets, however are not very stable and often require dredging to keep them open. Since the closing and opening of tidal inlets can significantly affect the circulation and transport within bays/lagoons, it is essential to be able to predict the stability of tidal inlets. Escoffier (1940) performed a simple analysis to study the stability of a tidal inlet. van de Kreeke (1985) analyzed the stability of multiple inlet

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system. Basically, for a single inlet system, one needs to calculate a "closure curve" that relates the cross-sectional area of an inlet with the maximum current in the inlet for given tidal conditions, inlet length and inlet shape. The next step is to compute an equilibrium velocity or bottom stress at which the sediment transport capacity of the inlet currents is just sufficient to remove the sediment deposited in the inlet. Van de Kreeke (1992) pointed out that to determine the exact closure curve for a real inlet, it requires a full-fledged multi-dimensional model for the hydrodynamics of the inlet and the bay.

This study is an extension of a project funded by the Sarasota Bay National Estuary Program. The primary objective of the project was to quantify the circulation and transport in the Sarasota Bay system, located in the southwest coast of Florida, USA (Figure 1). The Sarasota Bay project consists of a field study and a modeling study. For the field study, the University of Florida collected continuous data of surface elevation, current, salinity, water temperature, turbidity, and wind at five stations during two months in 1991, and two months in 1992. For the modeling study, the three-dimensional circulation model CH3D, originally developed by Sheng (1989), was applied, improved, calibrated and verified.

The estuarine system shown in Figure 1 is actually formed by two interconnected sub-systems: the Tampa Bay system, which is a classical coastal plain estuary, with a manmade navigation channel, and the Sarasota Bay system, which is a multiple-inlet shallow coastal lagoon. In the southern part, the Little Sarasota Bay has an average depth of less than 2 meters and a manmade IntraCoastal Waterway (ICW) which bisects the length of the bay. In Little Sarasota Bay, a tidal inlet, Midnight Pass, has been closed since 1983, and much has been discussed about the feasibility and potential environmental implications of its proposed opening.

Based on the field data collected in 1990 and 1991, the CH3D model has been applied and verified for the Sarasota Bay and Tampa Bay system. There is generally a good agreement between model results and field data, with the errors on thc order of 5-10% for surface elevation and 10-20% for currents (Sheng and Peene, 1992; Sheng *et al.*, 1992; Sheng *et al.*, 1994a). The effect of the Midnight Pass on the circulation and tidal flushing inside the Little Sarasota Bay was studied by Sheng *et al.* (1992).

This study utilizes the CH3D model to first quantify the flow field in Little Sarasota Bay with a closed (present condition) and an opened (proposed condition) Midnight Pass, and then to produce a closure curve of the Midnight Pass in its proposed opened conditions.

METHODOLOGY

To study the stability of a tidal inlet, one can use the simple analysis of

Escoffier (1940), O'Brien and Dean (1972) or, in the case of multiple inlets, the analysis of van de Kreeke (1985). All these methods are based on the Keulegan repletion coefficient, which is strictly applicable to the case of uniform water level over the entire bay, an inlet flow depending exclusively on the head difference between the bay and the ocean, and a friction term represented by the Manning's coefficient (Figure 2). According to Escoffier (1940), the following limitations should be considered in applying this analysis:

> "The available values for Manning's n are based on observations made in uniform prismatic channels and their reliability in nonuniform channels such as those usually found in inlets is uncertain;
> Little is known about the loss of head that takes place due to the contraction and expansion of the currents passing through the inlet; and
> The formula is for steady state flow and ignores the temporal acceleration."

In addition, the simple analysis ignores the nonlinear effects associated with complex geometries inside the bay.

To improve estimates of the simple analysis, an approach which does not contain any of the above assumptions should be used. For this study, the CH3D model was used to quantify the detailed flow pattern in the vicinity of the Midnight Pass. To determine the closure curve of the Midnight Pass, the bottom shear stress within the opened Midnight Pass was simulated using both the 3-D version and the 2-D vertically integrated version of CH3D.

CH3D is a three-dimensional hydrodynamic model which can use non-orthogonal boundary-fitted grid as well as orthogonal or Cartesian grids. This feature allows the model to better represent the small scale processes in bays/lagoons with complex geometries. The vertical turbulent eddy coefficients are computed from a simplified second-order closure model, and the horizontal turbulent eddy coefficients are assumed to be constant, which vary with grid size and horizontal current.

In order to make the stability analysis more quantitative, it is necessary to characterize the capacity of an inlet to transport sediments in terms of the bottom shear stress. In the three-dimensional model CH3D (Sheng, 1989), the bottom shear stress is obtained from the near bottom velocity within a logarithmic boundary layer, according to:

$$(\tau_x, \tau_y) = \left[\frac{\kappa}{\log(z_1/z_0)} \right]^2 \cdot \sqrt{u^2+v^2}\Big|_{z_1} \cdot (u,v)\Big|_{z_1} \tag{1}$$

where, (τ_x,τ_y) are components of bottom shear stress, κ is the von Karman constant, z_1 is the reference height, z_0 is the bottom roughness height, and (u,v) are the horizontal velocity components at z_1 within the bottom boundary layer. The only empirical coefficient, z_0 appears in the logarithmic denominator, thus making it less sensitive.

In the 2-D vertically-integrated model, the bottom shear stress is obtained from the vertically-averaged velocity components (U,V), according to:

$$(\tau_x, \tau_y) = \frac{g}{H C_c^2} \sqrt{U^2+V^2}\ (U,V) \tag{2}$$

where g is gravitational acceleration, H is total water depth, and C_c is the Chezy coefficient.

In the simple analysis, the repletion coefficient relates the inlet cross-sectional area to tidal forcing and bottom friction, according to (Keulegan, 1967):

$$K = \frac{T}{2\pi a_0} \frac{A_c}{A_B} \frac{\sqrt{2 g a_0}}{\sqrt{K_{en} + K_{ex} + \frac{fl}{4R}}} \tag{3}$$

where T is the tidal period, a_0 is the tidal amplitude, A_c is the inlet cross-sectional area, A_B is the bay surface area, K_{en} is the friction loss at the entrance, K_{ex} is the friction loss at the exit, f is the Darcy-Weisbach friction coefficient, l is the inlet length, and R is the hydraulic radius of the inlet.

RESULTS FOR AN IDEALIZED INLET-BAY SYSTEM

Before performing the analysis of inlet stability in Midnight Pass, the 2-D results of CH3D were compared with the simple method for the case where the simplified assumptions were valid. A Cartesian grid with 40 by 30 cells was used, with a uniform grid spacing of 250 m. The tidal forcing along the boundary was represented by a sinusoidal wave with an amplitude of 46 cm and a period of 12 hours. The depth in the offshore region and inside the bay was assumed to be a constant 2 m. The inlet cross-sectional area was varied by keeping the width constant and varying the depth from 50 cm to 2 m.

Figure 3 shows the ebb flow in the idealized bay in a five day simulation for the case of an inlet with 1.5 m depth. Repeating this simulation for different inlet configurations, it was possible to construct two closure curves for the hypothetical inlet, one for each inlet width, and then to compare these results versus the curves obtained from the simple analysis (Figure 4). The closure curves present the maximum ebb velocity (in cm/s) as a function of the inlet cross-sectional area (in m^2), for a given tidal forcing and Manning's coefficient. These curves clearly demonstrate the concept of critical cross-sectional area at which the velocity attains its maximum. The dots represent the 2-D model results and the solid lines represent the results of simple analysis. In the second plot, a different closure curve was obtained due to a different width of the inlet, which affects the hydraulic radius. Different values of hydraulic radius corresponding to rectangular, trapezoidal and parabolic cross-sections were used, but the simple analysis does not seem to be sensitive to different shapes in cross-section.

Results of the 2-D model and the simple analysis shows some discrepancies, particularly in terms of the critical cross-sectional area. The discrepancies can be attributed to the high sensitivity of the simple analysis to the Manning's coefficient. In this case, even the 2-D model requires significant calibration. Although the 3-D version of CH3D also contains some model coefficients, these coefficients are less empirical, and the bottom friction formulation shown by Equation (1) is much more robust than the Chezy-Manning formulation shown by Equation (2).

APPLICATION TO MIDNIGHT PASS, FLORIDA

The CH3D model was sufficiently calibrated and validated with data from Tampa Bay and Sarasota Bay (Sheng and Peene, 1992, Sheng *et al.*, 1992). For this study, the 2-D and 3-D versions of CH3D were used to compute the detailed flow within the Midnight Pass under various hydrodynamic forcing conditions, and various configurations of the Midnight Pass. The closure curve obtained from the 3-D model runs and the simple analysis is shown in Figure 5, wherein the dots represent the CH3D results while the solid lines were obtained from the simple analysis using different Manning's coefficients. The simple analysis is highly sensitive to the Manning's coefficient, thus producing a wide range of values of maximum velocity.

CH3D was used to simulate three scenarios: the first scenario (solid circle) represents the bay prior to the dredging of the IntraCoastal Waterway (ICW); the second one (square) represents the bay with the ICW and a shallow inlet (1.5 m deep); the third one (triangle) represents the bay with the ICW and a deeper inlet (3 m deep); and the fourth one (circle) represents the bay with the ICW and a much wider inlet. Results shown in Figure 5 indicate that the ICW made the Midnight Pass less stable. Figures 6,7 and 8 show the residual flow fields obtained from the 30 day simulations corresponding to each of the three scenarios.

Figure 9 shows the stability curve expressed in terms of the bottom shear stress, the cross-sectional area of the Pass, and the equilibrium bottom shear stress of Bruun (1978). This shows that the inlet is only marginally stable even for the case without the ICW.

DISCUSSION

Due to its importance to human activities, tidal inlets have been a subject of coastal engineering studies for many years. Studies have showed that physical processes in tidal inlets are quite complex and much scientific study is needed to improve the empirical engineering analysis. This study demonstrates that multidimensional numerical hydrodynamics model can be used as a comprehensive tool to provide more accurate analysis and guidance to further understanding of the physical processes involved.

Our modeling study showed that the IntraCoastal Waterway (ICW) probably made the Midnight Pass more unstable, although the Pass was only marginally stable for a long time prior to its closure. This is consistent with the earlier suggestions by Davis *et al.* (1987) and Dean (1992), which did not provide a quantitative analysis.

To determine if the Pass should be opened, a more comprehensive and quantitative study is needed. The CH3D model can be used to simulate the circulation and inlet stability under a variety of hydrodynamic conditions and inlet configurations. Additional parameters such as water quality dynamics and sediment can be considered by using a coupled hydrodynamics-sediment-water quality model being developed (e.g., Sheng *et al.* 1994b).

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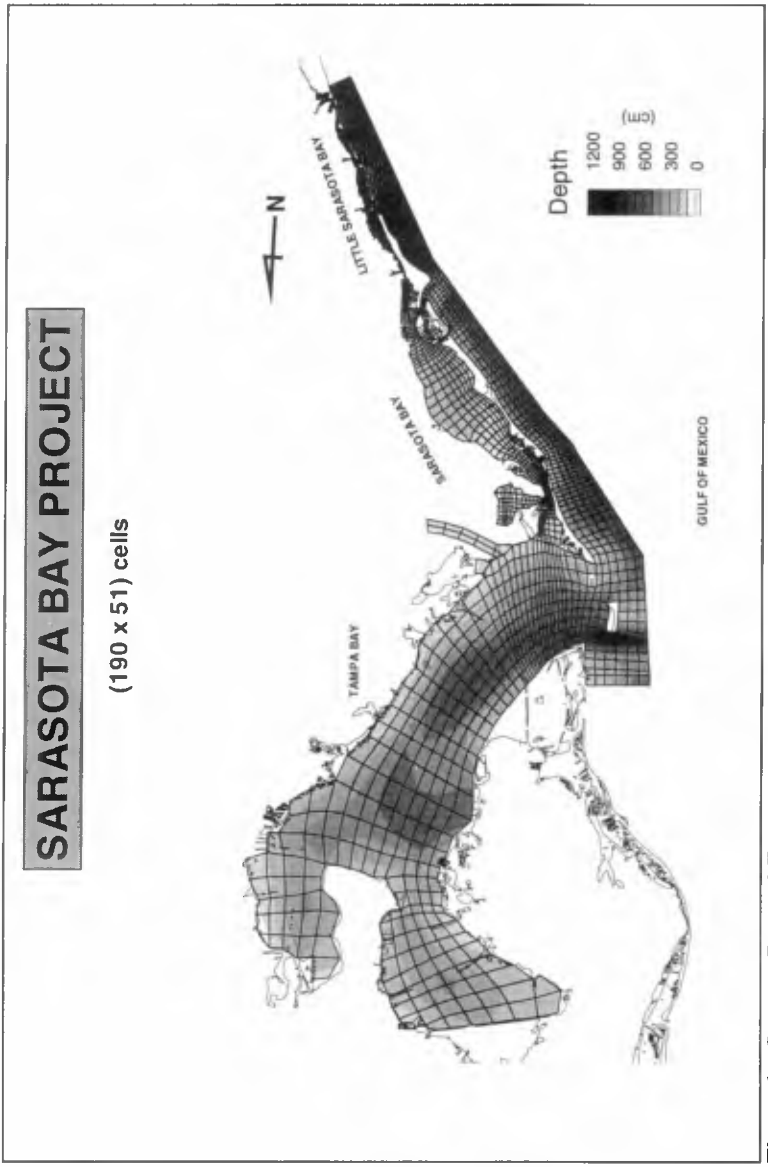

Figure 1 - Sarasota Bay and Tampa Bay Systems

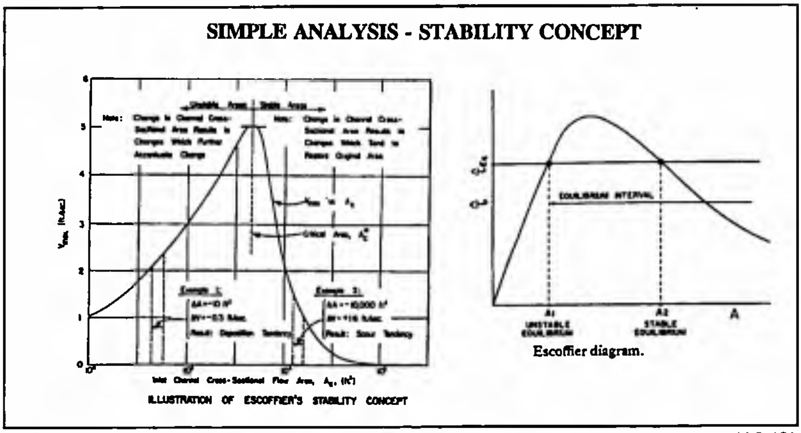

Figure 2 - Closure curves based on the analysis of (a)O'Brien and Dean (1972) and (b)van de Kreeke (1985).

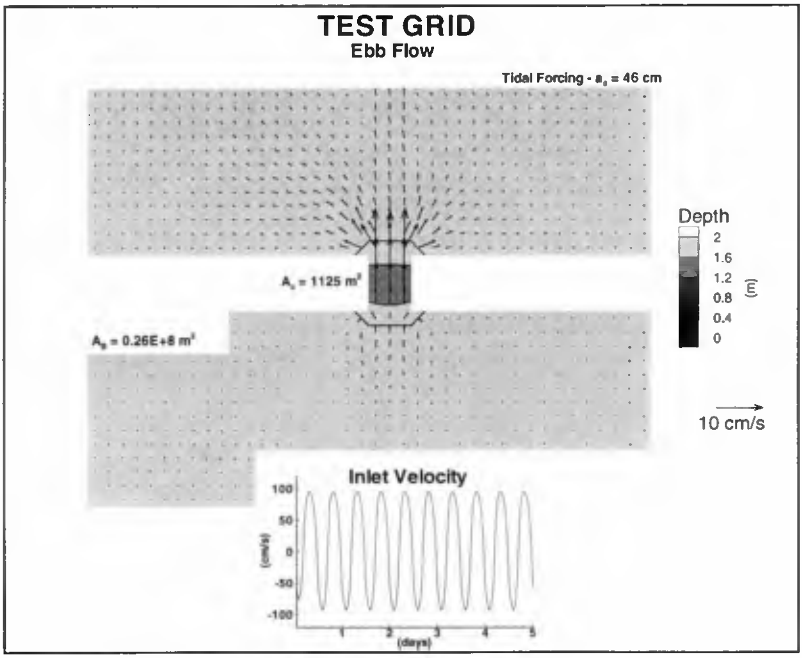

Figure 3 - Vertically-averaged ebb flow in idealized basin with 40x30 points, a grid spacing of 250m, and a depth of 2m.

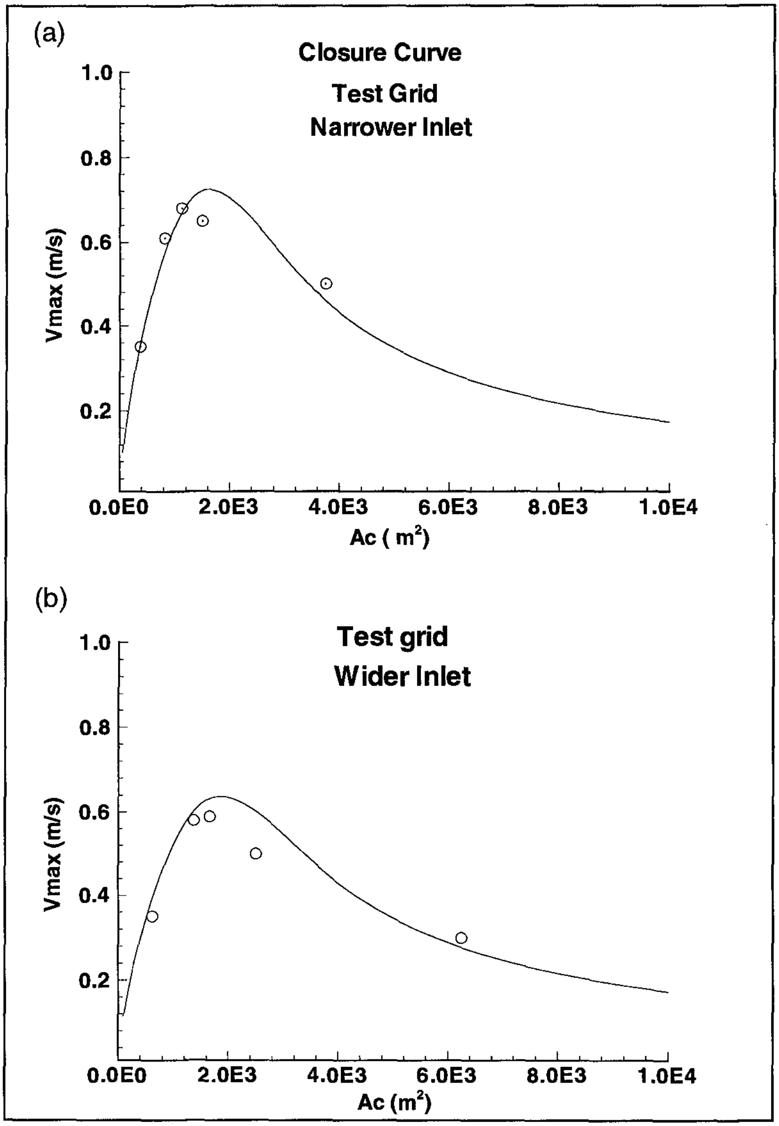

Figure 4 - Comparison between results of vertically-integrated CH3D (circles) and simple analysis (solid lines) in an idealized basin with (a) a narrower inlet and (b) a wider inlet.

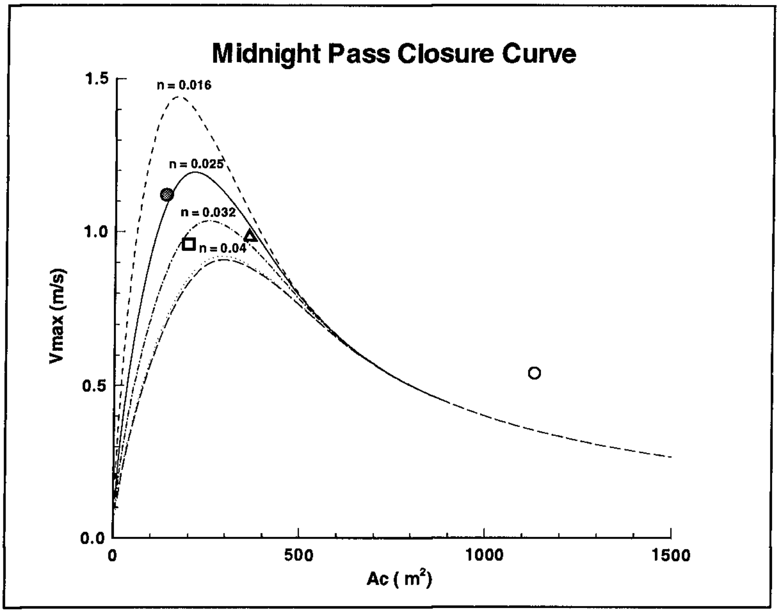

Figure 5 - Comparison between results of CH3D and the simple analysis in the Midnight Pass - Little Sarasota Bay.

Solid circle: Bay prior to intracoastal waterway dredging, narrow inlet, 1.5m deep;

Open square: Bay with the intracoastal waterway, narrow inlet, 1.5m deep;

Open triangle: Bay with the intracoastal waterway, narrow inlet, 3.0m deep;

Open circle: Bay with the intracoastal waterway, wider inlet, 3.0m deep.

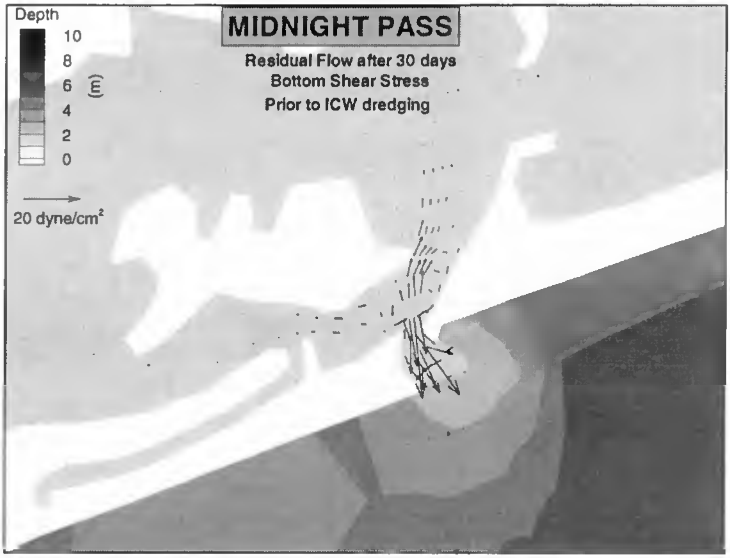

Figure 6 - Residual bottom shear stress over a 30 day simulation without intracoastal waterway but with a narrow inlet.

Figure 7 - Residual bottom shear stress over a 30 day simulation with intracoastal waterway and a narrow inlet.

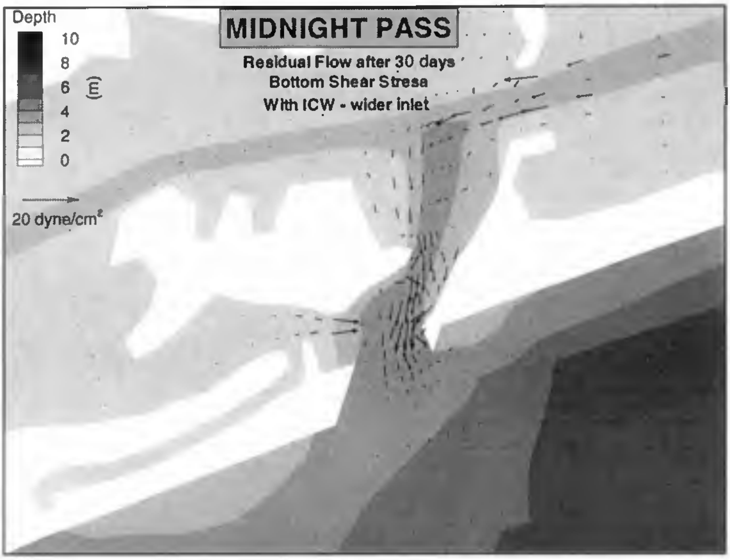

Figure 8 - Residual bottom shear stress over a 30 day simulation with intracoastal waterway and a wider inlet.

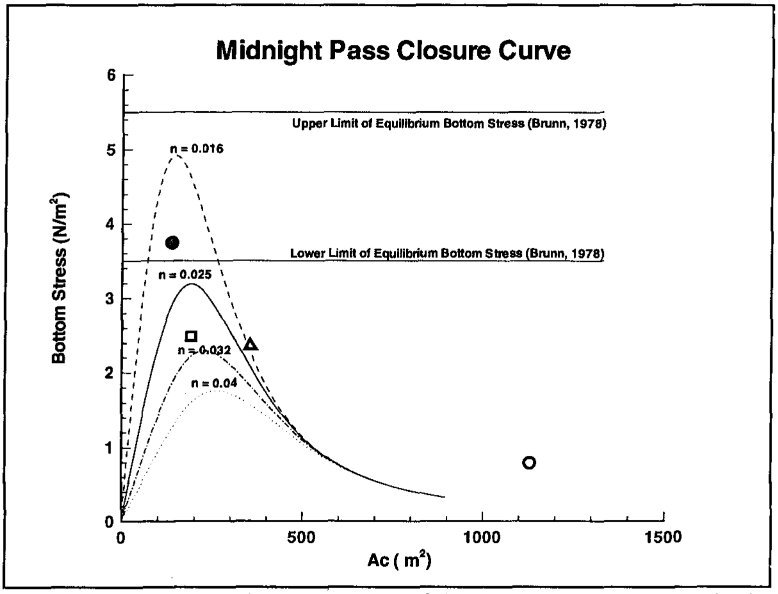

Figure 9 - Comparison between results of CH3D and simple analysis in the Midnight Pass - Little Sarasota Bay, with Bruun's equilibrium bottom shear stress added.

Solid circle:	Bay prior to intracoastal waterway dredging, narrow inlet, 1.5m deep;
Open square:	Bay with the intracoastal waterway, narrow inlet, 1.5m deep;
Open triangle:	Bay with the intracoastal waterway, narrow inlet, 3.0m deep;
Open circle:	Bay with the intracoastal waterway, wider inlet, 3.0m deep.