Tidal Inlet Bridge Scour Assessment Model

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The undermining of bridge facilities constructed in tidal inlets is a common problem. Scour mechanisms in tidal inlets are often combinations of local contraction and regional tidal inlet dynamics. A numerical model for quantitatively evaluating and assessing the scour and deposition magnitudes associated with contraction and inlet geomorphological changes has been developed. The model uses a two-dimensional, dynamic numerical hydraulic model coupled to movable bed sediment scour and deposition subroutines developed specifically for this need. The model provides for subgrid features such as pier piles, as well as limited inhomogeneity in sediment grain size. A simplistic representation for armoring associated with sediment sorting is also provided. Initial application to Johns Pass in west-central Florida indicates reasonable comparisons between model predictions and observations of scour and deposition in the pass, warranting additional testing of this approach.

Tidal inlet stabilities are influenced by extremely complex hydrodynamics and sediment dynamics. These processes may act on nearfield or farfield spatial scales, as well as on event or continuous time frames. Of paramount concern to bridge hydraulic engineers is the resulting scour and deposition processes near proposed or existing bridge pilings. In severe cases, local, contraction, and geomorphological driven scour may undermine bridge pilings, thereby resulting in structural failure.

The University of South Florida Center for Modeling Hydrologic and Aquatic Systems (USF/CMHAS) is involved in research to develop and refine a numerical model that will help engineers make decisions about situating and designing new bridges and maintaining and replacing existing structures.

METHODOLOGY

The foundation of this method was a two-dimensional, finite difference, explicit hydraulic model (referred to here as "hydraulic model") previously developed for coastal studies at USF/CMHAS (*1*). After an extensive review of applicable sediment transport theories and hydrodynamic needs, appropriate subroutines for determining wave-current interactions, sediment scour, transport, and deposition were developed and coupled to the model. This permutation of the original hydraulic model, which integrates both the hydrodynamics and sediment dynamics of tidal inlets, will be called the USF/CMHAS scour model.

The basic hydraulic equations of the USF/CMHAS scour model are developed from the Navier-Stokes equations for incompressible viscous flow, extended to turbulent flow using first-order closure techniques. Applying assumptions for shallow, well-mixed water bodies, the differential equations developed for this model are the vertically integrated equations of motion and continuity, which can be stated as follows:

- Vertically integrated equations of motion:

$$\frac{\partial U}{\partial t} + \frac{\partial\left(\frac{U^2}{d}\right)}{\partial x} + \frac{\partial\left(\frac{UV}{d}\right)}{\partial y} - \Omega V = -\frac{1}{\rho_w} d\,\frac{\partial P}{\partial x} - gd\,\frac{\partial H}{\partial x} + X - \rho_w \frac{f|Q|U}{d^2} \qquad (1)$$

$$\frac{\partial V}{\partial t} + \frac{\partial\left(\frac{V^2}{d}\right)}{\partial y} + \frac{\partial\left(\frac{UV}{d}\right)}{\partial x} + \Omega U = -\frac{1}{\rho_w} d\,\frac{\partial P}{\partial x} - gd\,\frac{\partial H}{\partial y} + Y - \rho_w \frac{f|Q|V}{d^2} \qquad (2)$$

- Vertically integrated continuity equation:

$$\frac{\partial H}{\partial t} = -\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y} + R \qquad (3)$$

where

U = vertically integrated flow per unit width in x-direction,
t = time variable,
d = depth of water,
x = southward coordinate direction,
V = vertically integrated flow per unit width in y-direction,
ρ_w = density of water,
P = atmospheric pressure,
y = eastward coordinate direction,
Ω = Coriolis factor,
g = acceleration due to gravity,
H = height of tide above mean low water used in equations of motion,
X = x-component of wind stress per unit mass of water,
f = friction factor,
Q = fluid transport per unit width,

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Y = y-component of wind stress per unit mass of water, and
R = sources and sinks of water.

Employing a grid-based finite difference approach and applicable boundary conditions, the three equations can be discretized to algebraic expressions that can be explicitly solved to describe the water surface elevation and U and V transports (discharges per unit width) as functions of time and spatial position. As with other models of this type, proper model calibration must occur with each application.

One advantage of the USF/CMHAS scour model is the provision for subgrid features required for evaluating bridge pier management alternatives (*1*). The model allows for the incorporation of features considerably smaller than the grid dimension, such as bridge piers, bascules, and small channels.

The contribution of waves to the tidal inlet system is incorporated into the model through subroutines employing the equations from the popular linear or airy wave theory. Discussions of the equations and logic by which the scour model solves for wave heights, lengths, orbital dimensions, and velocities can be found in work by Vincent and Ross (*2*) and Vincent (*3*).

In addition to fluid velocities, sediment transport equations are also a function of the shear stress at the bed, which in turn is a function of the combined friction factor at the bed. The scour model determines the friction due to currents and the friction due to waves following the approaches of Manning-Strickler (*4*) and Swart (*5*). From these two terms the combined friction factor can then be found using the method of Jonsson (*6*). These equations are

$$f_c = 0.122\left(\frac{k_s}{d}\right)^{1/3} \tag{4}$$

$$f_w = .00251 \exp^{\left[5.21\left(\frac{\zeta}{ky}\right)-0.19\right]} \tag{5}$$

$$f_{cw} = \frac{u_c f_c + u_b f_w}{u_c + u_b} \tag{6}$$

where

f_c = current friction factor;
k_s = Nikuradse roughness number;
f_w = wave friction factor;
ζ = wave excursion number;
f_{cw} = combined friction factor due to currents and waves;
u_c = depth-integrated velocity, unidirectional current magnitudes at bed; and
u_b = wave orbital velocity at bed.

Once the combined friction factor due to waves and currents has been determined, the combined shear stress at the bed is calculated by the quadratic stress law as

$$\tau_{cw} = \frac{\rho f_{cw}\, u_{cw}^2}{2} \tag{7}$$

where τ_{cw} is the shear stress due to currents and waves and u_{cw} is the resultant velocity due to currents and waves.

A comprehensive screening and literature review of applicable sediment transport equations was conducted to ensure the selection of a competent and tested method for the scour model. Consistently ranked as among the most accurate in investigations was the Engelund and Hansen equation (*7*). This approach was selected because of its consistent performance in laboratory and field tests, as well as success in tidal inlet modeling endeavors by Ross (*8*) and Zarillo and Park (*9*). The total sediment load can be expressed by the Engelund and Hansen equation as

$$q_t = 0.05\, u_c^2 \left[\frac{D_{50}}{g(S_s - 1)}\right]^{1/2} \left[\frac{\tau_{cw}}{(\rho_s - \rho_w) g D_{50}}\right]^{3/2} \tag{8}$$

where

q = fluid transport per unit area,
D_{50} = sediment grain diameter such that 50 percent of bed material is finer,
S_s = density of sediment relative to water, and
ρ_s = density of sediment.

The scour model uses a series of tests to determine the condition of transport or deposition within each grid. One of the principal methods applied by the code is the Hjulstrom curve, which provides a graphical relationship of the velocities needed for erosion, transport, and deposition, as a function of grain size (*10*).

A second test for potential scour is conducted by the equilibrium depth promoted by Bruun (*11*). This test, which is also used in the Corps of Engineers HEC 6 model, can be expressed as

$$d_{\mathrm{EQ}} = \left[\frac{q}{10.21 D_{50}^{1/3}}\right]^{6/7} \tag{9}$$

where d_{EQ} is the maximum depth at which scour can occur for given grain size and flow condition.

The model also allows for the natural armoring of the inlet bed due to nonhomogeneous sediments following the method of Borah (*12*) as

$$T_{\mathrm{AL}} = \frac{D_{\mathrm{AR}}}{(1 - \varepsilon) F_{\mathrm{AR}}} \tag{10}$$

where

T_{AL} = thickness of active layer of sediment bed,
D_{AR} = grain size of bed armoring material,
ε = porosity of bed sediment, and
F_{AR} = fraction of armor material.

In this approach, T_{AL} is defined as the active layer, which is the allowable depth of scour expressed as a function of the porosity, size, and fraction of armor size sediment.

At specified time increments, a continuity equation relates the volumetric rate of transport to the change in bed depth over time following

$$\frac{\partial q_{sx}}{\partial x} + \frac{\partial q_{sy}}{\partial y} = -(1 - \varepsilon)\frac{\partial z}{\partial t} \tag{11}$$

where

q_{s_x} = sediment transport flux in x-direction,
q_{s_y} = sediment transport flux in y-direction, and
z = vertical coordinate direction.

Boundary conditions and input data used by the scour model include initial bathymetry, tidal driving function at the open water boundaries, wind speeds and directions, offshore wave conditions, sediment characteristics, and specification of subgrid features. Model output includes arrays of all pertinent data (i.e., bathymetry or scour depths, velocities, etc.) at user-specified time increments.

A flow chart depicting the order of analysis used in the scour model is provided in Figure 1.

APPLICATION

To date, the USF/CMHAS scour model has been employed in several tidal inlet engineering investigations, including a bridge and channel design study for Clearwater Pass (*8*) and a bridge maintenance and replacement study for Johns Pass (*2*). Both of these inlets are located along littoral drift shorelines of the west-central coast of Florida. The application to Johns Pass will be discussed briefly in this paper.

In 1971 the new Johns Pass Bridge connecting Treasure Island and Madeira Beach was completed. As early as 1976, Florida Department of Transportation (FDOT) officials noted severe scour in the vicinity of the bridge. By 1984 the tips of three of the pilings, which had been driven 6.1 m (20 ft) below the original bed, had become exposed; others were within 1 m (1 to 2 ft) of exposure. In attempts to stabilize the bridge pilings and the surrounding bed, FDOT installed additional crutch pilings, fenders, and riprap rubble. Subsequent monitoring has indicated that these improvements may have further aggravated the scour conditions at the bridge. As of 1987 the bed beneath the bridge was eroding at an annual rate of 0.5 m (1.5 ft).

The objective of the Johns Pass investigation was to explore the cause of existing scour problems, the intensity and maximum extent of the present scour condition, and possible remediation alternatives. No attempt was made to explore the behavior of the inlet associated with a particular design magnitude return storm, but this would be an additional and useful application of the model.

For the Johns Pass Bridge scour investigation, 14 existing and hypothetical conditions were modeled. These were composed of combinations of two distinct seasonal scenarios, average winter-spring and summer-fall conditions, coupled with seven different structural alternatives described as follows:

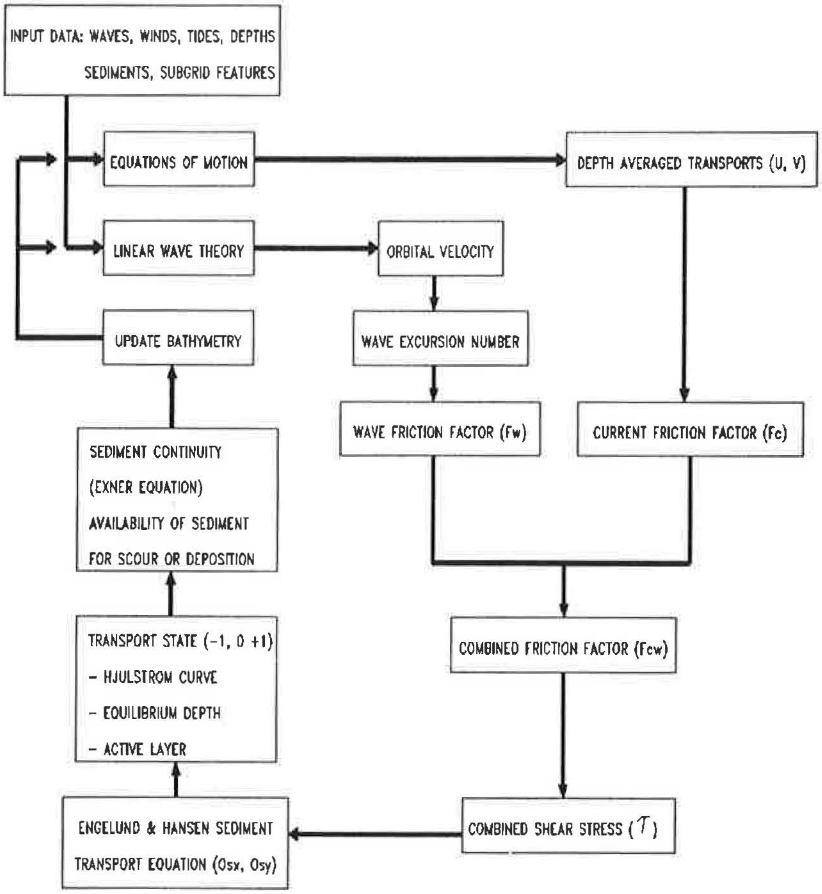

FIGURE 1 Flow chart of scour logic and equations.

1. No build: this model test was designed to obtain a baseline magnitude of existing scour rates if no improvements were implemented.
2. Future scour (future depths): existing depths were increased in accordance with the observed trends to determine if the scour rate significantly diminishes as the cross section deepens.
3. Addition of southern bent: this configuration evaluates the effectiveness of continuing the present course of remedial action of installing crutch bents when pile structural integrity is threatened.
4. Removal of all pilings: an unreasonable remedial alternative that is only of academic interest in evaluating the overall contribution of the bridge profile on the inlet geomorphology.
5. Removal of southern pilings: also a largely academic alternative, nevertheless one that is of interest because of the proximity and persistence of the south scour hole.
6. Half armor: there has been a casual discussion of armoring the inlet throat near the persistent scour hole along the southern half of the bridge. This alternative is easy to evaluate in the model but would require many other considerations.
7. Full armor: this condition is similar to the half-armor run condition but would continue completely across the inlet. It is also highly unlikely to implement successfully and very unpopular with other agencies.

A 10 × 15 array of grids 30.5 m^2 (100 ft^2) was developed to simulate Johns Pass. This configuration covers the entire inlet from the Gulf of Mexico to Boca Ciega Bay. The grid size was selected as the optimum to provide both the necessary detailed resolution of critical areas as well as to allow reasonable computation time. By the Courant-Fiedrich-Levy stability criteria, a time step of 1.5 sec was selected. The inlet bathymetry and subgrid features (bridge bascules, pilings, and crutchbents) are depicted in Figures 2 and 3, respectively.

RESULTS

One of the key sets of output data from the scour model is the DELZB arrays, which contain the net bottom elevation change from scour or deposition within each individual grid of the model during the course of a run. From this information, sediment dynamic trends along various portions of the bridge structure can be identified.

To aid in the interpretation of this information, data from the DELZB arrays were converted into inlet cross sections along the bridge centerline. These centerline stations were selected to coincide with approximate centers of model grids beneath the bridge. Beginning at the southern revetment, the stations proceed northeast at locations of 0, 15, 52, 91, 128, 159, 195, and 213 m (0, 50, 170, 300, 420, 520, 640, and 700 ft). Of particular interest to this study were the data from

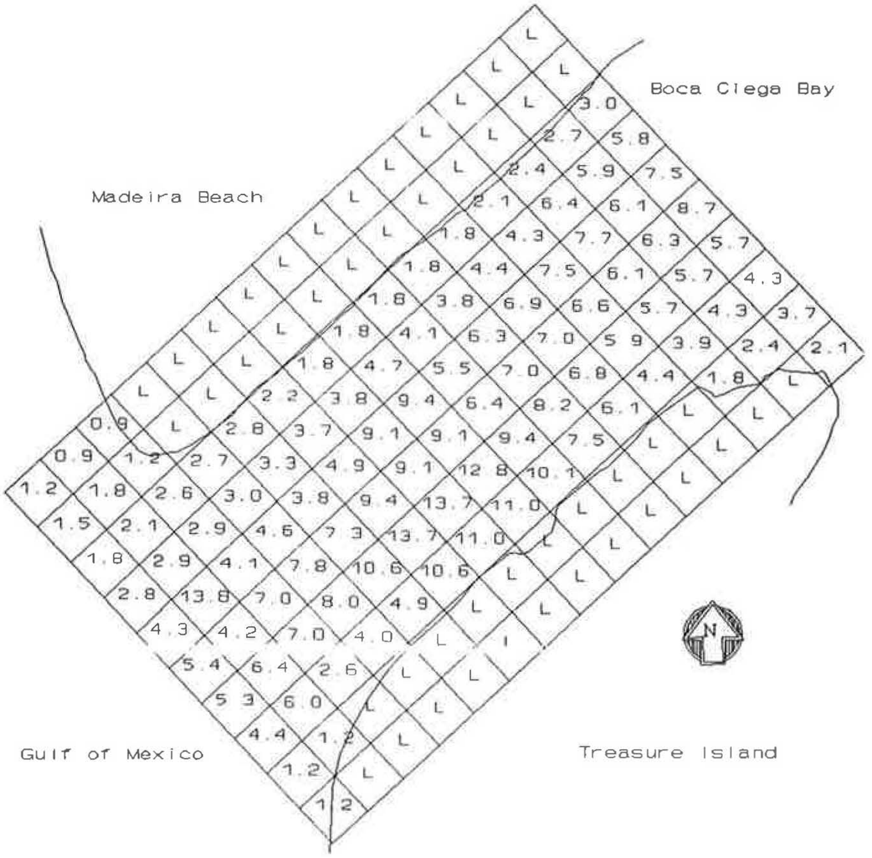

FIGURE 2 Johns Pass grid depths (m).

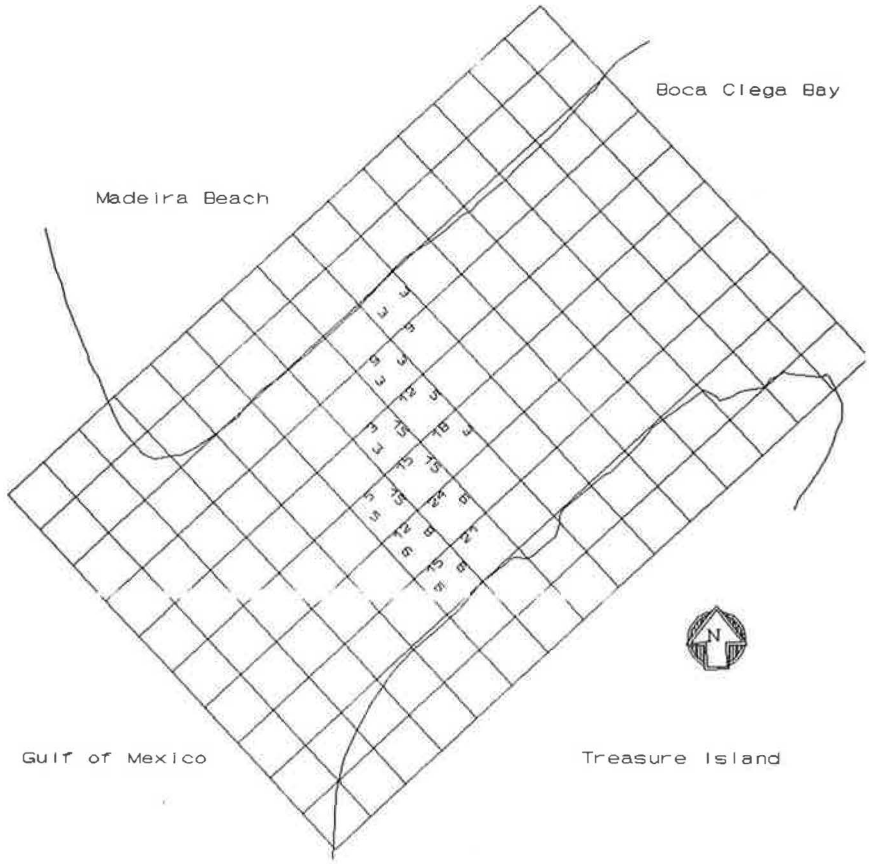

FIGURE 3 Johns Pass subgrid features (m).

Station 52, which is the deepest area beneath the bridge, with depths of 13.7 m (45 ft), and a location of persistent scour presence.

Given the constraints of even the most prominent sediment transport equations (7), the model results should be interpreted as scour-deposition trends (versus absolute rates), perhaps only within an order of magnitude in absolute accuracy. Furthermore, extrapolation of such rates should be done with caution, inasmuch as during extended time periods, bottom areas may become structurally or hydraulically stable (e.g., via deposits of natural shell lag, erosion down to strongly cohesive sediment or hardened bedrock, or reduced shear stress from deepening).

Figure 4 illustrates extrapolated results from two combined run scenarios: winter-spring and summer-fall conditions with the no-build option, as an example of model utility. Figure 5 summarizes the annual scour and deposition rates from all seven structural configurations.

DISCUSSION OF RESULTS

The bridge over Johns Pass has been seen to experience seasonal and annual variability in scour magnitude, with definite long-term trends toward increasing depths next to the southern bascules and nearby pier foundations. Application of the model using seasonal average conditions of summer quiescent periods followed by winter storms indicates that the order of magnitude of the scour rates and location are in general agreement with observed conditions. Scour depths of several feet per year under normal conditions have been observed and are predicted by the numerical model. As pointed out previously, many support piles at the Johns Pass Bridge have been undermined and a problem persists in the south span. The problem appears to be largely a result of contraction scour associated with the placement of the bridge and especially with the relatively large (10-m diameter) bascule support structures.

Preliminary runs with the model using estimated, extrapolated bathymetry—including up to 1.5 m (5 ft) of deepening—suggests that the present scour rates will continue at approximately the same rate. Bottom armoring scenarios indicated that the location of scour would merely shift immediately adjacent to the armor mats, and the scour rate could intensify, thereby potentially undermining the armor. In this regard the armoring of the inlet beneath the bridge does not appear to be a prudent alternative.

SUMMARY AND RECOMMENDATIONS

The potential utility of this model for tidal inlet scour assessment was demonstrated through application to the Johns Pass Bridge in Pinellas County, Florida. Simulations of 14 distinct seasonal and structural scenarios were conducted to evaluate the present and future scour deposition trends in areas of severe erosion along the bridge pilings. The simulated

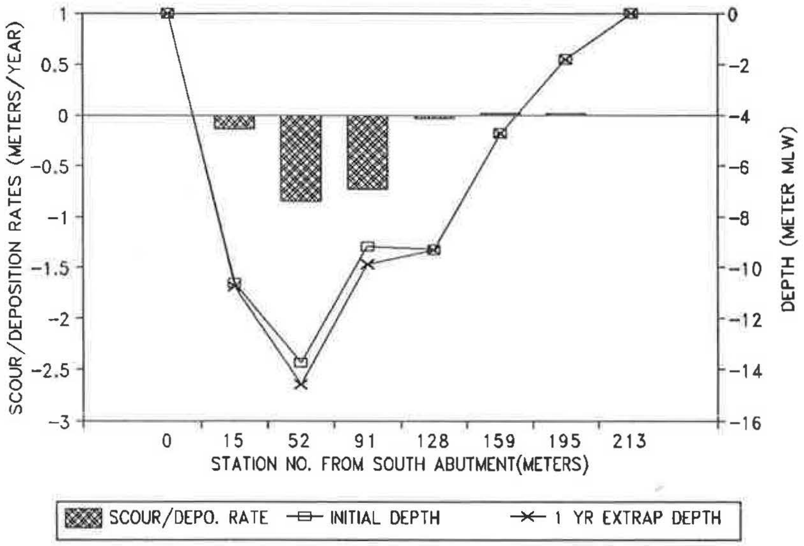

FIGURE 4 Annual no-build scenario.

hydrodynamics and sediment dynamic trends for existing conditions were in general agreement with documented observations, supporting further testing of this approach.

To date, the USF/CMHAS scour model has shown promise as a beneficial design and management tool for engineering evaluation of bridge scour and deposition in tidal inlets. However, the extreme complexity of sediment transport in coastal systems warrants continued aggressive research in both the laboratory and the field.

Unfortunately, many of the model components, although acceptable approaches for specific applications, were predicated on experiments using small flumes with conditions of uniform sediment grains, plain beds, and uniform steady flow. Moreover, most friction and shear stress equations as yet do not consider the compounding effects of sediment in motion.

An urgent need is seen here for model improvements to incorporate the transport of graded sediments, as well as spatial and temporal variability in sediment mixtures, bed forms, and bed armoring. Another potentially important feature that would complement the contraction scour processes that the model now handles would be the incorporation of equations for predicting subgrid local scour due to separation.

Although considerable theoretical and modeling improvements are needed, the USF/CMHAS scour model shows merit as a tool to be used in management and design studies as well as a vehicle for understanding basic processes and responses of tidal inlets.

The Fortran 77–based program runs on high-speed minicomputers as well as the desktop personal computers used in most engineering consulting and research facilities.

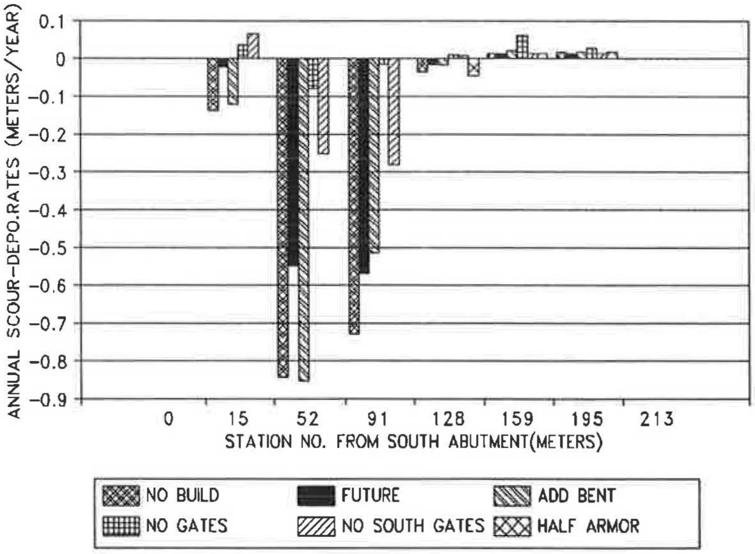

FIGURE 5 Comparison of annual scour rates.

ACKNOWLEDGMENTS

The authors gratefully acknowledge FDOT for funding this research and especially coauthor Bernard E. Ross for his leading role in the development of the USF/CMHAS hydraulic and scour models.

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