Implementation of Structures in the CMS: Part IV, Tide Gate

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the mathematical formulation, numerical implementation, and input specifications of tide gates in the Coastal Modeling System (CMS) operated through the Surface-water Modeling System (SMS). A coastal application at an idealized inlet is provided to illustrate the implementation procedure and demonstrate the model capability.

INTRODUCTION: A tide gate is an opening structure built across a river or a channel in an estuarine system. By preventing saltwater intrusion to farm land and allowing freshwater drainage to the estuary, tide gates are commonly used for flow and flooding control, and salinity and sediment management (Figure 1). Because a tide gate is a significant component of hydrodynamic and sediment transport controls in the coastal zone, it is important to incorporate the structure and to simulate its effect in the CMS.

Figure 1. West River tide gate, New Haven, Connecticut: (a) Low outgoing tide; (b) High incoming tide (*http://www.flickr.com/photos/sts-noaa/*).

COASTAL MODELING SYSTEM: The CMS, developed by the Coastal Inlets Research Program (CIRP), is an integrated suite of numerical models for simulating water surface elevation, current, waves, sediment transport, and morphology change in coastal and inlet applications. It consists of a hydrodynamic and sediment transport model, CMS-Flow, and a spectral wave model CMS-Wave (Sanchez et al. 2011a; Sanchez et al. 2011b; Lin et al. 2011). Both are described in Part I of this series (Li et al. 2013).

	Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE **AUG 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**	
4. TITLE AND SUBTITLE **Implementation of Structures in the CMS:Part IV, Tide Gate**		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Engineer Research and Development Center,Vicksburg,MS, 39180**		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**			
13. SUPPLEMENTARY NOTES			
14. ABSTRACT			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

MATHEMATICAL FORMULATION: Similar to the weir implementation (Wu 2012 ; Li et al. 2013a), two approaches are developed to implement tide gate structures in the CMS. In the first approach the orifice flow equation is used and the underflow through tide gates is calculated as follows:

$$Q = A_o K_v \sqrt{2g(h_1 - h_2)} \qquad (1)$$

where A_o is the opening area, K_v is the gate discharge coefficient, g is the acceleration of gravity, and h_1 and h_2 are the upstream and downstream water levels, respectively. The opening area, A_o, is determined by the opening height of the gate, e_o, and the width of the gate. The discharge coefficient, K_v, is a user-specified parameter that depends on the geometric characteristics of the gate and its opening, and the type of flow (submerged or nonsubmerged) (Graf and Altinakar 1998). A definition schematic for the flow and related parameters is provided in Figure 2.
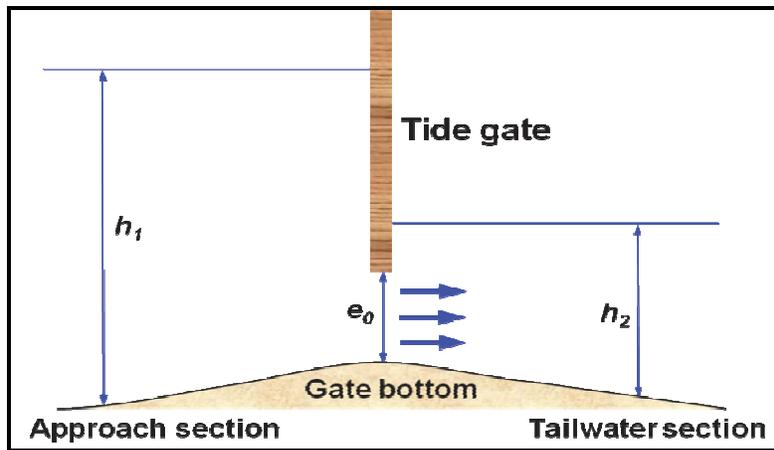

Figure 2.   Schematic showing flow through a tide gate.

The second approach treats the structure cells as other internal cells by adding the *x*- and *y*-components of the resistance force terms M_x and M_y induced by tide gates in the depth-averaged momentum equations. The resistance forcing is represented by a quadratic drag law and the Manning's (n) needs to be specified as the drag coefficient.

Different from other coastal structures, tide gates are tide-regulated and operation schedules are needed for the opening/closing of a tide gate. Here, four types of schedules are considered in the CMS. The first schedule is to open the gate in a regular time interval, for example six hours from 0800 to 1400 every day. The second schedule is to open the gate in designated time periods, for example three hours from 0800 to 1100 the first day and seven hours from 1000 to 1700 the second day. The third schedule is to open the gate for ebb tide and close for flood tide, which mimics the function of a flap gate at the sea side. The fourth schedule is for an uncontrolled tide gate that allows the flow to go back and forth with tidal phase changes.

NUMERICAL IMPLEMENTATION: Multiple tide gates can be specified in the CMS. Each tide gate is implemented on a line of cells (cell string). The same flux is assumed for the upstream and downstream faces of tide gate cells and the flux at each cell face, based on the orifice flow equation (1), can be calculated as:

$$q = e_o K_v C_{gl} \sqrt{2g(h_1 - h_2)} ds \qquad (2)$$

where C_{gl} is a user-specified coefficient of distribution of flow discharge over the cells of each gate structure. Since $\sum q = Q$, the following constraint should be applied to C_{gl}:

$$\sum C_{gl} e_o ds = A_o \qquad (3)$$

The summation in equation (3) is applied over all the cells of a tide gate structure. If a constant C_{gl} is assumed, $C_{gl} = A_o / \sum e_o ds$, but C_{gl} may also be specified as varying values for different gate cells.

Using the second approach for the tide gate implementation in the CMS, the same SIMPLEC algorithm as that for a weir is applied to solve the continuity and momentum equations near a tide gate (Wu and Zhang 2011).

In the simulations of salinity or sediment transport with tide gates, the salinity and suspended sediment will be transported over tide gate structures, but the bed load will be trapped if the tide gate has an elevated bottom.

INPUT SPECIFICATIONS: An advanced card is designed for the specifications of tide gate structures (Wu 2012) by using the modular format in the SMS-CMS interface, which starts with "TIDE_GATE_BEGIN" and ends with "TIDE_GATE_END". A description of the tide gate parameters is shown in Table 1.

Table 1. Specifications of tide gate parameters in the CMS.		
Input	**Format**	**Note**
Number of Tide Gate	[card=NUMBER_TIDE_GATE] [name=NumTideGate, type=integer]	Number of tide gate structures
Number of Cells of Each Tide Gate	[card=NUM_CELL_TIDE_GATE] [name=NTideGate, type=integer]	Number of cells of each tide gate
Cell ID	[card=CELLS] [name=IDTideGate, type=integer]	IDs of cells occupied by all tide gate structures (the ID is the cell counter on the flow grid)
Distribution Coefficient	[card=DISTRIBUTION_COEFFICIENT] [name=CoefWeirLateral, type=float]	Lateral distribution coefficient Cgl
Orientation of Tide Gate	[card=ORIENTATION] [name=OrientTideGate, type=integer]	Orientation of tide gate, defined as the direction of sea side: 1=north, 2=east, 3=south, 4=west
Flow Coefficient	[card=FLOW_COEFFICIENT] [name=CoefTideGate, type=float]	A pair of coefficients, Kv, for flow through tide gate from the bay to sea side and from the sea to bay side
Gate Opening Height	[card=OPEN_HEIGHT] [name=OpenHgtTideGate, type=float]	Opening height of each tide gate, eo
Bottom Elevation of Tide Gate	[card=BOTTOM_ELEVATION] [name=ElevTideGate, type=float]	Bottom elevation of each tide gate relative to the Mean Water Level (positive is upward)
Method	[card=METH] [name=MethTideGate, type=integer]	Method to calculate the flux through tide gate: 1=Approach 1, 2=Approach 2

The operation schedules of tide gate structures are specified within the module of the advanced card as shown in Figure 3. This block starts with "SCHEDULE_BEGIN' and ends with "SCHEDULE_END". Table 2 lists the schedule parameters of tide gates.
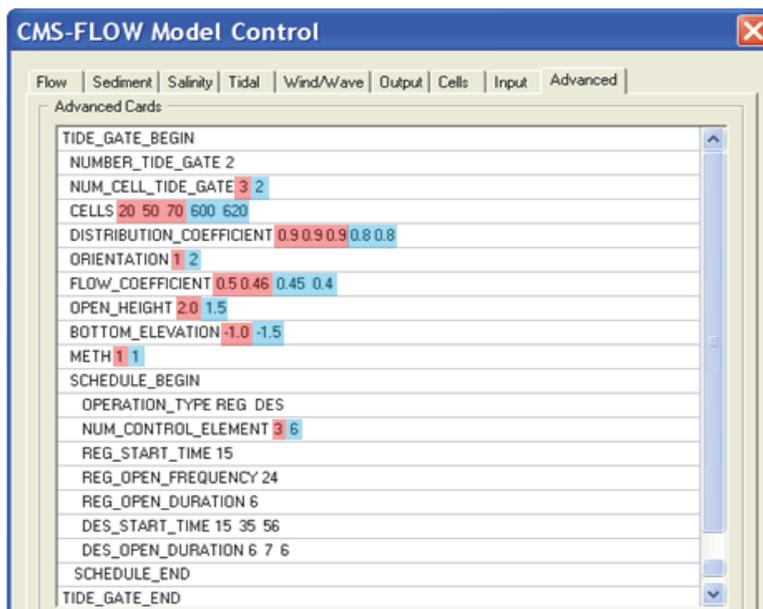

Figure 3.   Tide Gate Specifications in the SMS/CMS.

Table 2. Specifications of opening schedules of tide gates in the CMS.		
Input	**Format**	**Note**
Type of Operation	[card=OPERATION_TYPE] [name=OperationType, type=char]	Different types of tide gate operation schedules: REG: open the gate in a regular time interval DES: open the gate in designated time periods EBB: open the gate for ebb tide and close for flood tide UCG: uncontrolled tide gate
Number of Controlled Elements for Each Tide Gate Schedule	[card=NUM_CONTROL_ELEMENT] [name=NElement, type=integer]	Number of elements for controlling each tide gate operation schedule REG: 3 DES: user-specified EBB: 0 UCG: 0
Starting Time for REG Schedule	[card=REG_START_TIME] [name=RegStartTime, type=integer]	Opening startimg time for regular opening schedule (hour)
Opening Frequency for REG Schedule	[card=REG_OPEN_FREQUENCY] [name=RegOpen Frequency, type=integer]	Opening frequency for regular opening schedule (hour)
Opening Duration for REG Schedule	[card=REG_OPEN_DURATION] [name=RegOpenDuration, type=integer]	Opening duration for regular opening schedule (hour)
Starting Time for DES Schedule	[card=DES_START_TIME] [name=DesStartTime, type=integer]	Opening starting time for designated opening schedule (hour)
Opening Duration for DES Schedule	[card=DES_OPEN_DURATION] [name=DesOpenDuration, type=integer]	Opening duration for designated opening schedule (hour)

Similar to the rubble mound and weir structures specified in the CMS (Li et al. 2013), tide gate structures are divided into segments, and each segment consists of the IDs of cells occupied by one tide gate structure. For example, the simulation case with two tide gate structures, A and B, are considered here. Tide gate A distributes on the cells with ID numbers 20, 50, and 70, and tide gate B distributes on the cells with ID numbers 600 and 620. Therefore, NumTideGate = 2, NTideGates = 3 and 2, respectively (Table 1). Accordingly, the IDs, IDTideGate, consists of cells 20, 50, 70, 600, and 620. The first 3 elements are IDs of tide gate A's cells, and the last 2 elements are IDs of tide gate B's cells.

Assume the coefficient C_{gl} has a value of 0.9 on all the three cells of tide gate A, a value of 0.8 on the two cells of tide gate B. The other properties of gate A are: $K_v = 0.50$ for flow from bay to sea side and 0.46 for flow from sea to bay side, bottom elevation of -1.0 m (ElevTideGate = -1.0), opening height of 2.0 m (OpenHgtTideGate = 2.0), and sea side facing to north (OrientTideGate = 1). The other properties of gate B are: $K_v = 0.45$ for flow from bay to sea side and 0.40 for flow from sea to bay side, bottom elevation of -1.5 m (ElevTideGate = -1.5), opening height of 1.5 m (OpenHgtTideGate = 1.5), and sea side facing to the east (OrientTideGate = 2). Approach 1 (MethTideGate = 1) is used for both tide gates. The advanced card is given in Figure 3 with red marked for tide gate A and blue for tide gate B.

IDEALIZED INLET WITH A TIDE GATE: The CMS domain is configured for demonstrating the implementation of tide gate structures. The domain has a size of 3.4 × 2.2 km, and an idealized inlet connects the open ocean side to an embayment. In the application, a tide gate is specified across the 175-m-wide inlet, and a semi-diurnal tide with amplitude of 1.0 m is driving the CMS along the open ocean boundary in hydrodynamic simulations.

Figure 4 shows the CMS domain and the tide gate at the idealized inlet. Two locations (points 1 and 2 in Figure 4) are selected on the sea side and on the bay side of the tide gate, respectively, and water depths at the locations are 2.75 m. Time series of water surface elevations, currents, and fluxes are compared for the numerical experiments with the tide gate structures.
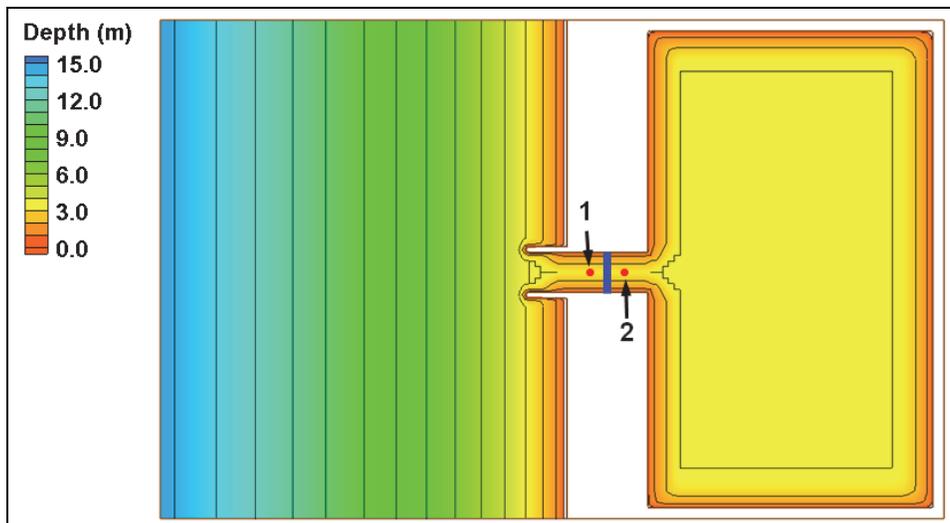

Figure 4. CMS domain: Idealized Inlet and the surrounding area. The blue bar denotes the tide gate and the red dots represent the selected time series locations.

Figure 5 shows the specifications of the tide gate parameters at the inlet in a SMS/CMS advanced card and a sketch of the cross-inlet transect corresponding to the tide gate. The gate consists of 7 cells. Using Approach 1, detail features of the tide gate structure are listed as follows. The distribution coefficients of flow discharge over the cells of the gate, C_{gl}, are constant and equal to 0.9. The discharge coefficient, K_v is equal to 0.50 for flow from bay to sea side and 0.46 for flow from sea to bay side. The bottom elevation of the gate is 1.2 m below the mean water level and the gate opening height is 1.2 m. The specification of this case indicates that when the gate is open, it is lifted all the way to water surface. The regular opening schedule is adopted, and the gate is open every 18 hours with an opening duration of 6 hours.
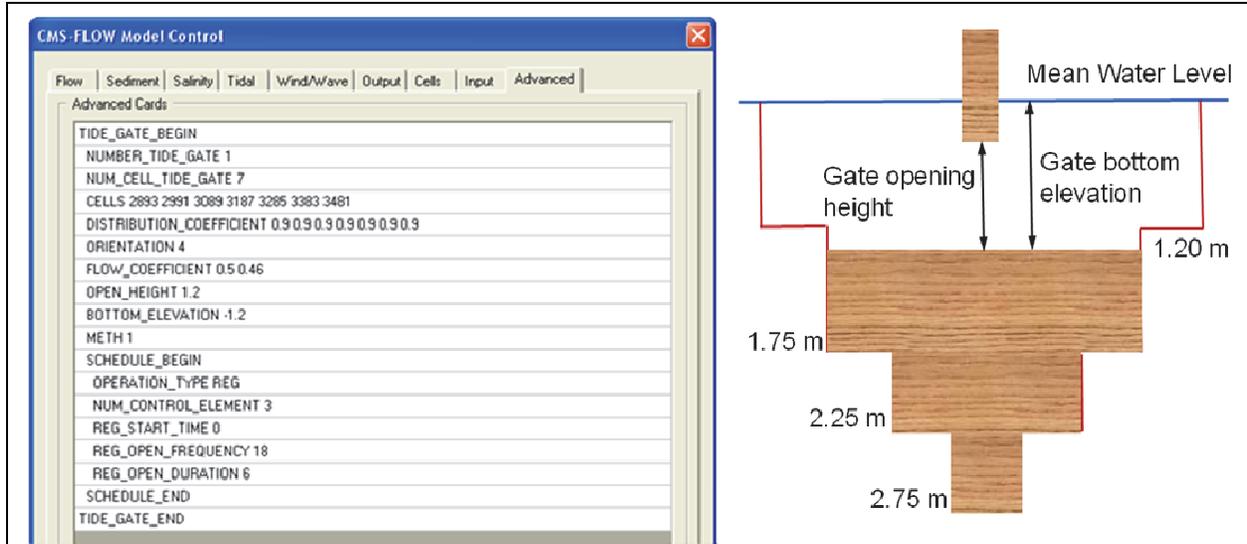

Figure 5.   Tide gate specifications at the idealized inlet.

Similar to the weir case, Approach 1 is used for the gate implementation because the CMS can produce more stable results and better incorporate supercritical flow around a tide gate into model simulations. Therefore, the setup of this approach is treated as the base case in the study. Different gate specifications for other experiments are listed in Table 3. The hydrodynamic variables are compared between different cases (base, and S0 through S6) at points 1 and 2.

Table 3. Tide gate specifications in the CMS.				
	Parameter			
Tide Gate Simulation	Distribution Coefficient	Discharge Coef (Mannings (n))	Opening Height (m)	Approach
Base	0.9	0.50/0.46	1.2	1
0	0.5	0.50/0.46	1.2	1
1	0.9	0.60/0.60	1.2	1
2	0.9	0.30/0.30	1.2	1
3	0.9	0.50/0.46	0.6	1
4	0.9	0.50/0.46	1.2	2
5	0.9	0.05	1.2	2
6	No Gate			

Using the orifice flow equation (Approach 1) one may specify different values for the distribution coefficient on the cells according to their locations, bottom elevations, etc. For example, a smaller value can be given to the cells near the banks, and zero for those cells where the tide gate is blocked by structure or land. As a sensitivity test, the distribution coefficient is reduced by 44 percent over the gate cells. Figure 6 shows the comparisons of water surface elevation and current between the base case and S0 at the seaside (Point 1) and the bayside (Point 2) locations of the tide gate. Corresponding to the reduced distribution coefficient both water surface elevation and current at Point 2 indicate that less water passes through the inlet when the tide gate is open.
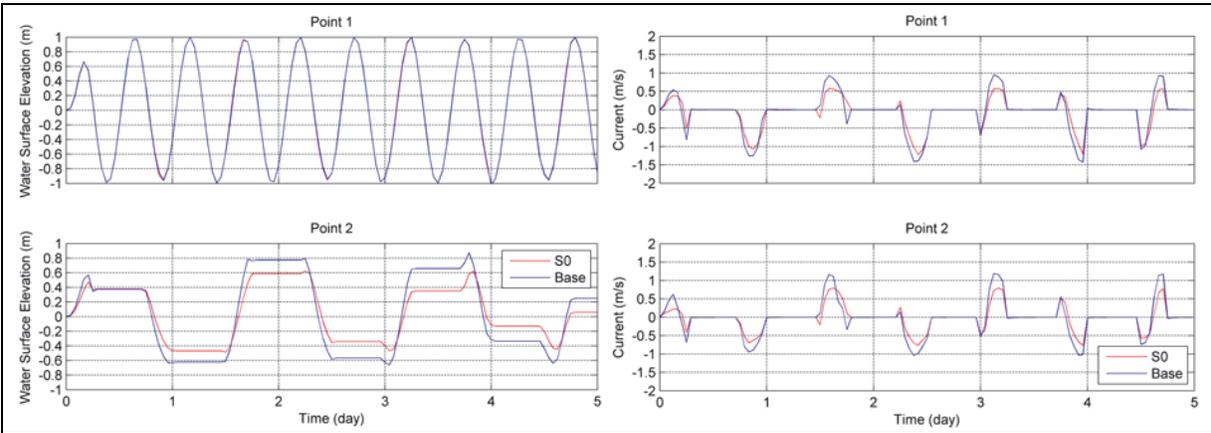
Figure 6. Water surface elevation and current comparisons between the base case and simulation S0 at the seaside (Point 1) and the bayside (Point 2) of the tide gate.

In the CMS implementation, different discharge coefficients can be specified for the tide gate structure. Depending on the design of a tide gate, the coefficient has an upper limit of 0.61 (Graf and Altinakar 1998). The water surface elevation and current comparisons between the base case and the cases with varying discharge coefficients are shown in Figures 7 (S1) and 8 (S2). It can be seen from the figures that a larger (smaller) discharge coefficient results in relatively larger (smaller) flows through the inlet and larger (smaller) elevation change at the bayside location.
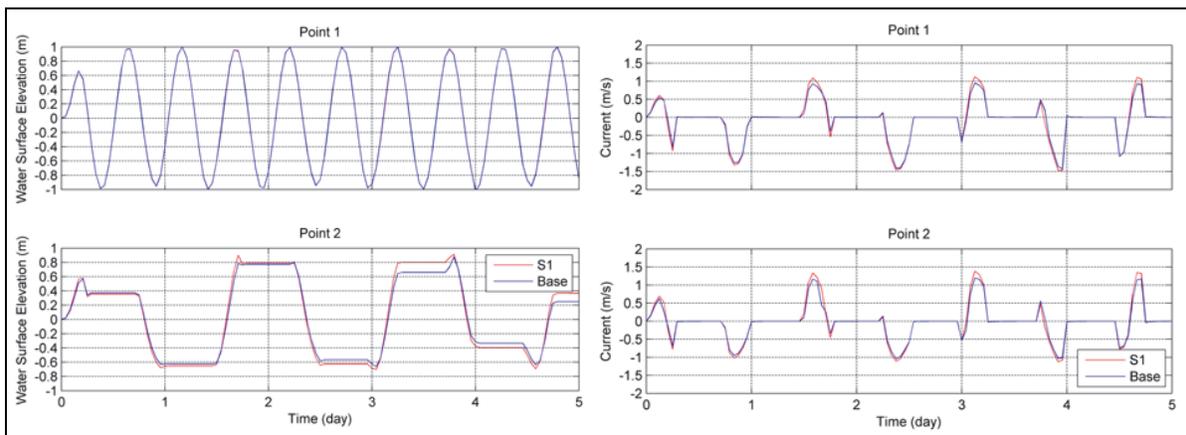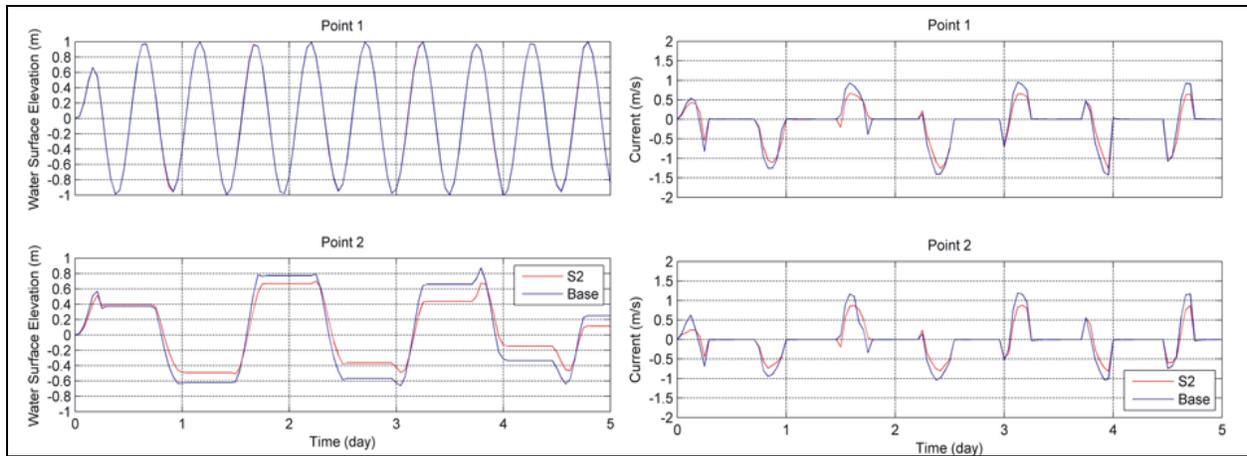

Figure 7. Water surface elevation and current comparisons between the base case and simulation S1 at the seaside (Point 1) and the bayside (Point 2) of the tide gate.
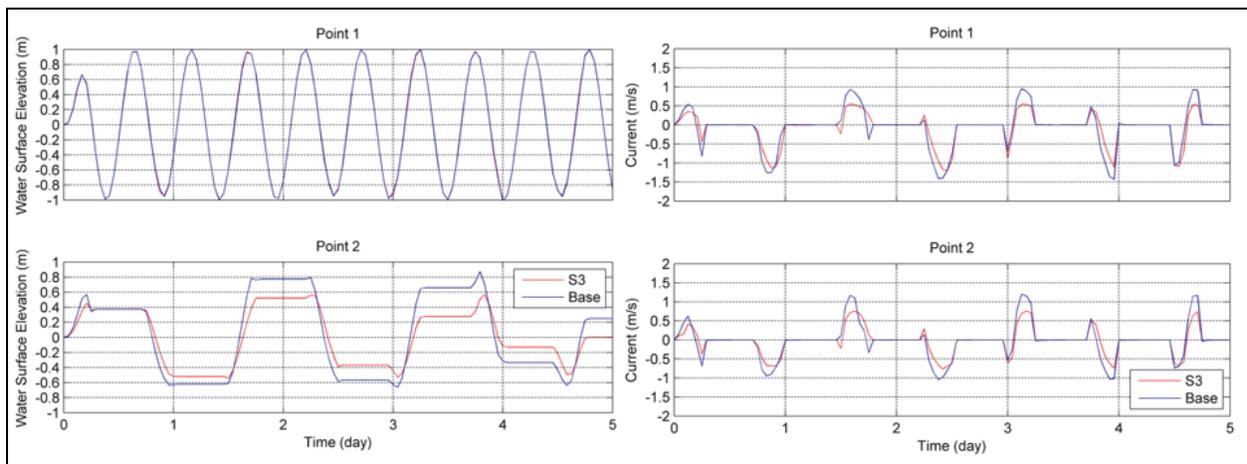
Figure 8.   Water surface elevation and current comparisons between the base case and simulation S2 at the seaside (Point 1) and the bayside (Point 2) of the tide gate.

Flows through a tide gate are also controlled by the gate opening height. In S3, the gate opening height is reduced to 0.6 m from 1.2 m for the base experiment (Figure 9). Comparing with other cases, the results of the S3 simulation correspond to the largest water surface elevation change at Point 2 and show the flows entering/exiting the embayment are more sensitive to this parameter.

Figure 9.   Water surface elevation and current comparisons between the base case and simulation S3 at the seaside (Point 1) and the bayside (Point 2) of the tide gate.

For Approach 2, Manning's (n) is specified in the place of the discharge coefficient but it functions differently because the parameter is adding extra resistance to the momentum equation due to the tide gate structure. As shown in Figures 10 and 11, the same values of discharge coefficients as in the previous cases (0.5/0.46) will greatly decrease the flows through the inlet at both the seaside and the bayside locations. The large Manning's (n) at the tide gate even damps the water surface elevation at the seaside location. A more reasonable Manning's (n) of 0.05 in simulation S5 produces the flow results more compatible to those by Approach 1 (Figure 11).
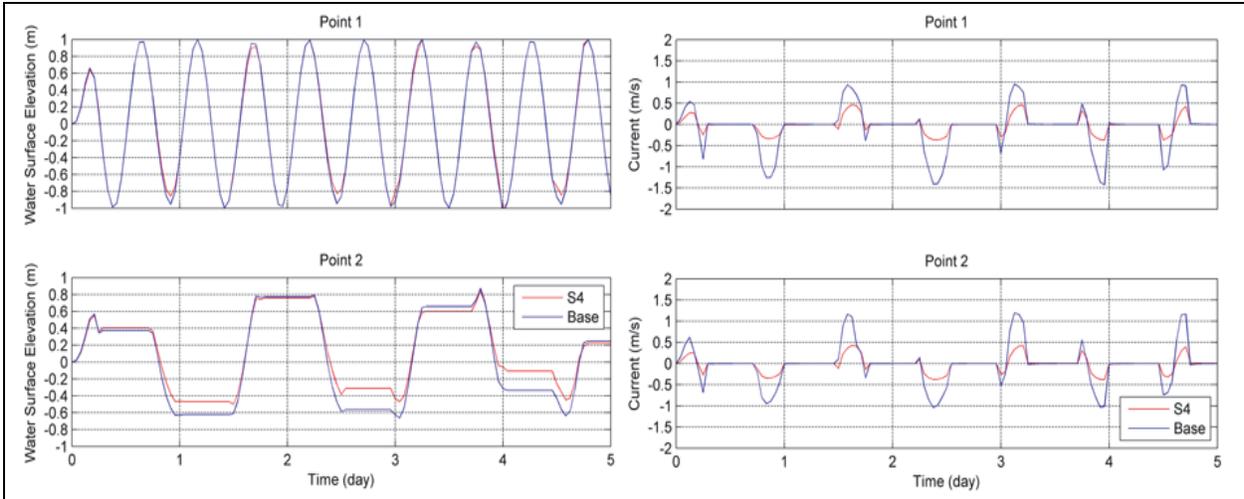
Figure 10. Water surface elevation and current comparisons between the base case and simulation S4 at the seaside (Point 1) and the bayside (Point 2) of the tide gate.
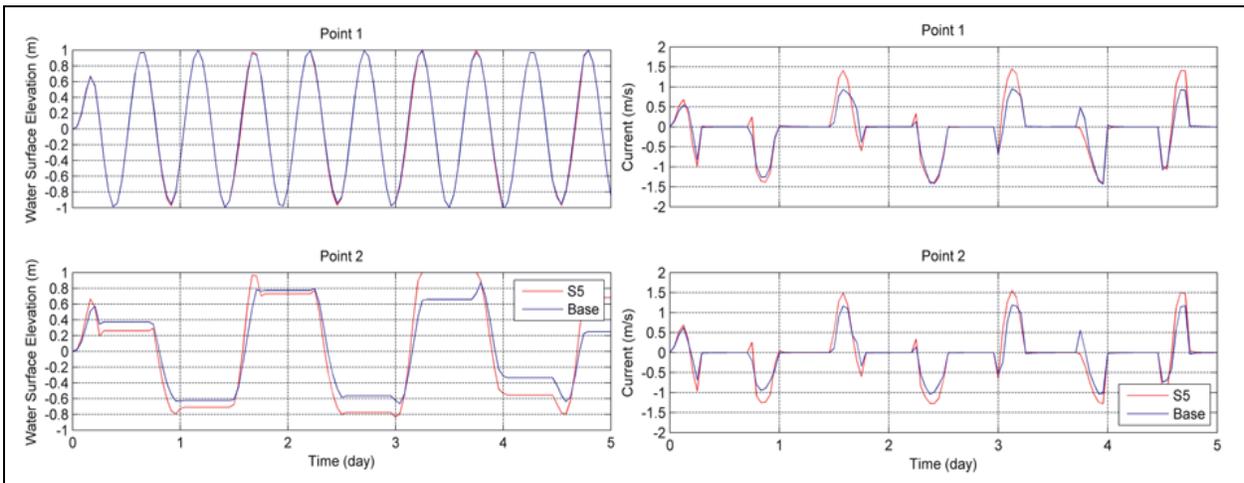

Figure 11. Water surface elevation and current comparisons between the base case and simulation S5 at the seaside (Point 1) and the bayside (Point 2) of the tide gate.

Figure 12 is the water surface elevation and flow comparisons between the base case and S6 (no gate). Apparently the installation of a tide gate slows down tidal propagation at the seaside and reduces tidal range at both sides of the tide gate.

SUMMARY: Tide gate structures are incorporated into the CMS and the implementation procedure was described in this note. The application of the algorithms and selection of the parameters in the CMS are demonstrated and water surface elevations and flows through an idealized inlet are compared at the seaside and the bayside of the inlet. The results indicate that the orifice flow equation is more appropriate in the CMS implementation of tide gate structures.
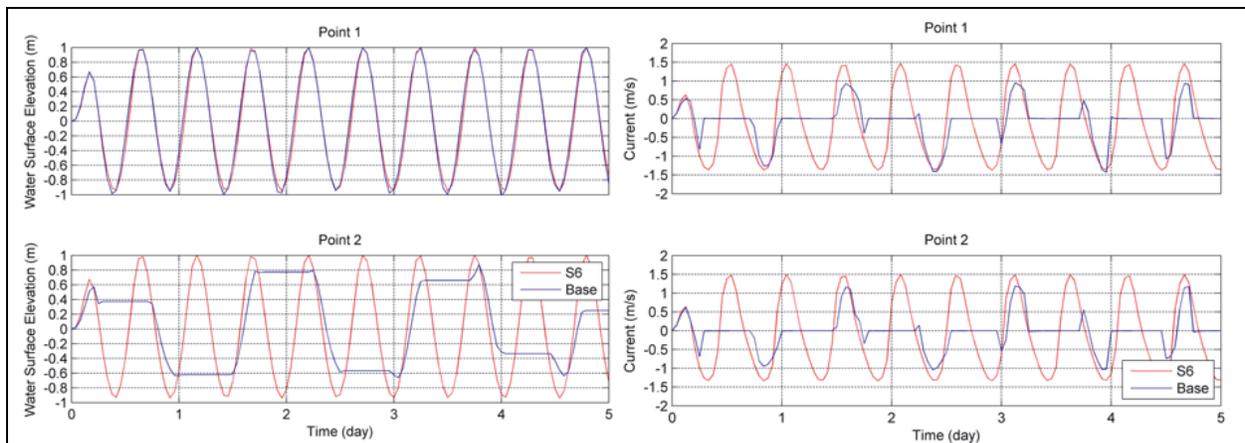
Figure 12. Water surface elevation and current comparisons between the base case and simulation S6 at the seaside (Point 1) and the bayside (Point 2) of the tide gate.

ADDITIONAL INFORMATION: This CHETN was prepared as part of the CIRP and was written by Dr. Honghai Li (*Honghai.Li@usace.army.mil*, voice: 601-634-2840, fax: 601-634-3080), Alejandro Sanchez of the US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Dr. Weiming Wu of University of Mississippi, and Dr. Christopher W. Reed of URS. The CIRP Program Manager, Dr. Julie D. Rosati (*Julie.D.Rosati @usace.army.mil*), the assistant Program Manager, Dr. Zeki Demirbilek, and the Chief of the Coastal Engineering Branch at CHL, Dr. Jeffrey P. Waters, reviewed this CHETN. Files for the study may be obtained by contacting the author. This CHETN should be cited as follows:

> Li, H., A. Sanchez, and W. Wu. 2013. *Implementation of structures in the CMS: Part IV, Tide Gate*. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-IV-96. Vicksburg, MS: US Army Engineer Research and Development Center.

An electronic copy of this CHETN and I/O files for the example are available from: *http://chl.wes.army.mil/library/publications/chetn/*

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