NUMERICAL MODEL STUDY OF TIDAL FLUSHING ALONG A NARROW CHANNEL

Balaji, R.

Assistant Professor, Department of Civil Engineering, NIT Calicut, Kerala, India.
email: rbalaji@nitc.ac.in

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Two-dimensional finite-element numerical models are developed to investigate the tidal flushing characteristics of a narrow channel along Abu Dhabi coast. The tidal hydrodynamic characteristics of the narrow channel are assessed for two different conditions, existing baseline and proposed partial blockage of the channel for bridge constructions. The boundary conditions for these local scale models are extracted from a large scale numerical model covering entire Abu Dhabi coast, developed in-house. After validating the local model against the large scale model, the effect of the partial blockage along the channel on hydrodynamic and flushing are assessed. The model results show that the tidal flow velocities are dropped down due the partial blockage that eventually delayed the natural tidal flushing by 2 days in the narrow channel.

Keywords: Abu Dhabi coast, RMA2, Telemac2D, hydrodynamics, flushing and tidal currents.

1. INTRODUCTION

The city of Abu Dhabi, situated off the North-West coast, is the political capital of the United Arab Emirates. The coast of city consists of several islands, channels and tidal streams due to which the tidal flow exhibits a mixed pattern (Figure 1). There are several navigational channels along the coast, which have constantly been dredged. In addition, several developmental activities (e.g. reclamation of man-made islands) are also going on along the coast of Abu Dhabi. These man-made changes in the coastal topography significantly alter the tidal flow, which require understanding of the tidal hydrodynamics. In general, the tide induced current velocities along the channels are significantly high, of the order of up to 1.5 m/s at some locations, the reason why some parts of the coast experiences constant erosion. It is increasingly become important to understand to the existing hydrodynamic characteristics of Abu Dhabi coastline, in order to assess the impact of any other man-made features.

With increase in the transportation needs in Abu Dhabi, several bridges are constructed across the various islands, to ease the traffic. To connect the mainland, a number of bridges are proposed to be built across Sowwah Island and some of them are already under construction. Generally, construction of these bridges needs temporary bund across the channels that partially block the tidal flow. It is also proposed to construct another bridge on the north-west side of the Sowwah Island that will create an additional obstruction to the tidal flow in the channel.

In the past, few researchers have studied the hydrodynamic characteristics of the entire Arabian Gulf region[1,2]. In recent times, notable extensive studies by[3] and[4] described the flow dynamics of the Arabian Gulf with help of a numerical model investigation. A hydrodynamic atlas[5] was developed for the Arabian Gulf that enables user friendly data visualization and extraction. Although the hydrodynamics of whole Arabian Gulf is fairly understood, to the best of the author’s knowledge, only limited investigation focused on the coast of Abu Dhabi[6,7].
In this study, the hydrodynamic and flushing conditions of the tidal channel between the mainland and Sowwah Island are investigated. For this purpose, local scale numerical models are developed to understand the effects of the temporary blockage on the flushing conditions. Local scale numerical models generally cover a relatively less area of the coastline and are effective in minimizing the computation efforts. Adoption of small mesh enables to represent the coastal features detailed and thereby enhancing the understanding of hydrodynamics. The present study is aimed to estimate the variations in the currents due to the blockage of the channel and its effect on the tidal flushing characteristics of the channel.

2. PREVIOUS NUMERICAL MODEL STUDIES

2.1 Arabian Gulf Model
Sogreah\cite{8} has developed a global regional numerical model covering entire Arabian Gulf to be able to carry out marine environment studies along its coasts in the shortest possible time and with the best possible results. The mesh used in the Arabian Gulf model, shown in Figure 2, represents a relatively fine grid near the coastline and around islands. This model helps in prediction of sea levels and currents in shorter time. The Arabian Gulf model is developed using Telemac modeling system\cite{9,10}, which is capable of simulating free-surface flows in the two dimensions of horizontal space and solves the Saint-Venant equations using the finite-element method on a computation mesh of triangular elements. Telemac modeling system is developed by the Laboratoire National d’Hydraulique et Environnement (EDF-DRD – French Electricity Board). Telemac modeling system uses an unstructured mesh technique that allows representing complex coastal features. Basically, the Telemac-2D code, part of the Telemac modeling system, solves the following hydrodynamic equations simultaneously;

Continuity
\[
\frac{\partial h}{\partial t} + \vec{u} \cdot \vec{V}(h) + h \text{div}(\vec{u}) = S_h
\]  

x-momentum
\[
\frac{\partial u}{\partial t} + \vec{u} \cdot \vec{V}(u) = -g \frac{\partial Z}{\partial x} + S_x + \frac{1}{h} \text{div}(h \nu \vec{v})
\]  

y-momentum
\[
\frac{\partial v}{\partial t} + \vec{u} \cdot \vec{V}(v) = -g \frac{\partial Z}{\partial y} + S_y + \frac{1}{h} \text{div}(h \nu \vec{v})
\]
Where;

- $h$: depth of water (m)
- $u, v$: velocity components (m/s)
- $g$: gravity acceleration (m/s$^2$)
- $\nu_t$: momentum diffusion coefficients (m$^2$/s)
- $Z$: elevation of the free surface (m)
- $t$: time (s)
- $x, y$: horizontal space co-ordinates (m)
- $S_x, S_y$: momentum source terms (m/s$^2$)

The Arabian Gulf model comprises a triangular grid, with meshes varying in size from 1km to 10km, depending on depth. The purpose of the hydrodynamic model of the entire Arabian Gulf is to provide boundary conditions for two-dimensional high-resolution local scale coastal models for performing coastal studies. This model is developed using hydrographic charts of the different sea areas around the Gulf. The boundary condition of the model is forced at the Straits of Hormuz, where each of nodes are imposed with a harmonic re-composition of the astronomical tide based on the seven main harmonics namely K1, K2, M2, N2, O1, P1 and S2. These seven main harmonics components are extracted from an earlier Arabian Gulf model study[11,12]. The model is calibrated and validated against tidal data from a large number of stations located around the Gulf. A typical comparison of computed water levels with that of predicted from the Tide Tables[13] is shown in Figure 2, for the Mina Zayed port, Abu Dhabi. The results of the Arabian Gulf model are used to provide boundary conditions for several large scale models.

### 2.2 Abu Dhabi Regional Model

Using the results of the Arabian Gulf model, several regional models are developed with finer grid sizes and bathymetries for individual coastal stretches (e.g. Bahrain, Oman, Qatar, Abu Dhabi, Dubai, Sharjah and Fujairah). These regional models are also validated with available data. Typical view of Sogreah’s[14] regional model domain covering the Abu Dhabi coast can be seen in Figure 3. This finite-element based numerical model is developed using Telemac modeling system represents the main tidal flats, deep channels and other coastal features of the Abu Dhabi coast. The hydrodynamic current circulations due to tidal variations are studied for the model domain and the engineering parameters such as velocity and water surface elevation are extracted for each node. The results obtained from the numerical model are compared with available data from tide gauge measurements along the Abu Dhabi coast. Typical comparisons of tidal constants, at selected locations, obtained from the numerical model with that of tide gauges are shown in Figure 3. Time to time, the numerical model results are also compared with the currents measured along the Abu Dhabi coast. One of such comparisons for currents measured at a location along the Mussafah channel (236899E 2702640N, WGS84, UTM Zone 40) is shown in Figure 5. It is clear from the figures that the numerical model predictions are in agreement with the available data.
3. SOWWAH ISLAND LOCAL MODEL

3.1 General

The Sowwah Island is situated adjacent to the mainland of Abu Dhabi, as can be seen Figure 1, and it is proposed to be connected by a number of bridges. In addition to the two bridges under construction on the southern side of the island, it is proposed to construct another bridge on the north-west side of the Sowwah Island, the effect of which on the tidal flushing is studied in the present study. The locations of the proposed bridge and bridges under construction are shown in Figure 1.

As the topography of Abu Dhabi coast is changing with time due to development activities, the in-house Abu Dhabi regional model is also updated in regular interval of time. However, the regional model in the study area does not include all the existing coastal features due to the coarse mesh adopted. For the purpose of validation, initially a local scale model (Model-I) of the study area close resemblance to the large scale model is developed. Then two different model meshes are developed; to represent the existing coastal features (Model-II) and proposed temporary reclamation blockages in channel (Model-III). All these three local scale models are developed using RMA2 numerical scheme\(^{[15]}\). RMA2 is a time-dependent two-dimensional depth integrated finite element hydrodynamic code developed by the U.S. Army Corps of Engineers. RMA2 can be applied to calculate water levels and flow distribution around islands due to static and dynamic boundary conditions. RMA2 is capable of simulating wetting and drying events due to the variations in the tidal elevations.

The flushing characteristics are investigated with the RMA4 numerical scheme\(^{[16]}\), which is basically a time-dependent two-dimensional finite element water quality transport numerical model developed by the U.S. Army Corps of Engineers. Although RMA4 utilizes the depth-averaged velocities from RMA2 to estimate the fate of tracers, there is no dynamic interaction between them. RMA4 is applicable for both conservative and non-conservative tracers, however, in the present study, a conservative tracer is used to study the flushing characteristics of the channel. Generally, RMA4 is used to investigate the physical processes of migration and mixing of a non-conservative substance in reservoirs, rivers, bays, estuaries and coastal zones.
3.2 Validation of the local scale model

The boundary conditions, water levels, for Model-I are extracted from the large scale model. After developing the finite element model domain, and specifying boundary conditions, the model is validated. The validation procedure ensures that the present numerical model predicts accurately what was observed in the large scale model. Several model simulations are carried out to specify a range of friction and eddy viscosity coefficients and to validate the model. Bed friction characteristics in RMA2 are basically controlled through Manning’s friction coefficient, which is initially applied as 0.03 for all the mesh elements. In the calibration process, the friction coefficients are varied systematically throughout the model domain. The final model is employed with Manning’s friction coefficients varied between 0.02 and 0.035, depending upon the regional bed features. The energy losses due to the turbulent eddy viscosity are approximated by turbulence exchange coefficients. In the present study, the automatic dynamic assignment of turbulent exchange coefficients, Peclet method, is adopted. The Peclet number, \( P \), as defined below, controls the eddy viscosity depending upon the elemental velocity and mesh size. For flow studies, Peclet number is specified between 15 and 40 \[^{[15,17]}\], where as a value of 20 or less is typically recommended for numerical stability \[^{[18]}\].

\[
P = \frac{\rho u \Delta x}{E}
\]

Where, \( \rho \) is the fluid density, \( u \) the average elemental velocity and \( E \) eddy viscosity.

The tide induced current velocities obtained from the Sowwah Island model at a location (235177E 2712529N, WGS84, UTM Zone 40, indicated as P1 in Figure 6(a)) is compared with that obtained from the Abu Dhabi regional model and presented in Figure 6(b), for a selected tidal period. It is clear from the figure that the local scale model predicts the tide induced current velocities reasonably well.

3.3 Results of existing condition

The hydrodynamic modeling of the existing baseline conditions, i.e., without the proposed blockages in the channel, requires the development of a numerical model of the area surrounding the project. A local finite-element numerical model, Model-II is developed to accommodate the detailed topographical features and to minimize the computational time. The model domain considered spans approximately 5.0Km along the tidal channel covering the entire width of the channel and including other updated coastal features. The whole domain is discretized using eight-node triangular elements. The domain is modeled with a total number of 13507 nodes making a total number of elements of 6347. The average mesh size is about 100m at the offshore boundary and size of elements is gradually decreased towards shallow waters. The size of smallest mesh along the nearshore is about 5m. Earlier studies have shown that minimum of 15 discretizations (\( \Delta x \)) are needed per tidal wave length (\( \lambda \)) \[^{[19]}\]. In the present study, the minimum tidal wavelength to mesh size ratio is greater than 100 for the entire numerical model domain. The sea bed levels for the numerical model are extracted from Admiralty chart (No.: 2889) and bathymetry survey in the vicinity of the project area. A typical view of the meshed model domain can be seen in Figure 7. The resolution of the grid is increased in the vicinity of the project area.
Figure 5 - Comparison of tidal currents with available measurements

Figure 6 - Validation of the local scale model

Figure 7 - Model mesh and bathymetry of baseline condition
Two different boundary conditions are imposed on the local scale model, representing the water surface elevations at the boundaries. The water levels for these boundary conditions are extracted from the non-curtailed large scale model domain, and can be seen in Figure 8. A selected water level time series corresponding to neap tidal period is selected for the assessment of the hydrodynamic and flushing characteristics of the existing baseline and proposed conditions. The hydrodynamic model is run for the existing baseline condition with the tidal forcing mentioned earlier. The tide induced current velocities are obtained at all the nodes and their typical distribution is presented in Figure 9. It is clear from the figures that the maximum current velocities due to the tide did not exceed 0.5m/s along the channel located adjacent to the proposed bridge site.

Based on the current velocities obtained from the hydrodynamic model, the flushing rate is estimated for the existing baseline conditions. For the water flushing study, a conservative substance of initial concentration of 100% is assumed throughout the numerical model domain. Both the boundaries of the model domain are forced with a zero concentration, to represent relatively fresh water from the incoming tide. In order to test the flushing under extreme condition, a 7-days neap tide period is considered for the present study, as the flushing rate is expected to be less during this period. The flushing conditions at different times from the start of the simulation during the neap tidal conditions can be seen in Figure 10. The numerical model results showed that the flushing in the vicinity of the project occurs within 80 hours. It is to be noted here that the PIANC guidelines recommend that the closed water area is to achieve e-folding time, time to reduce constituent to 37% of the original value, within 4 days.

3.4 Results of proposed condition

The hydrodynamic model for the proposed condition with the partial closure of the tidal channel between the Sowwah Island and the main land is modeled. The temporary closure consists of two narrow openings, 10m wide, separated by a 2m wide barrier in between. With an approximate water depth of about 6m at this location, the total water area is approximately 120m². The model meshes around the project vicinity are modified to represent the proposed temporary closure. A typical view of the meshed model domain can be seen in Figure 11, in which the resolution of the grid is increased in the vicinity of the project area. Similar to the baseline model, the two water level boundary conditions are imposed. The hydrodynamic model was run for the proposed condition and the tide induced current velocities are obtained at all the nodes and their typical distribution is presented in Figure 12. Using the hydrodynamic results, the flushing rate is estimated for the proposed condition. The flushing conditions at different times from start of simulation during the neap tidal conditions can be seen in Figure 13. The numerical model results showed that the flushing in the vicinity of the project occurs within 125 hours, which is a fair condition, according to PIANC standards.

(a) at BC1

(b) at BC2

Figure 8 - Model boundary conditions: water levels
Figure 9 - Velocity distribution for baseline condition

(a) ebb tide
(b) flood tide

(a) after 24 hours
(b) after 48 hours
Figure 10 - Flushing scenario of baseline condition at different time steps

Figure 11 - Model mesh for the proposed condition
3.5 Effect of proposed condition

To compare the numerical model results of the baseline and proposed conditions, two different points are selected (as indicated in Figure 11) from where the tidal current velocities and the concentration of the constituent are extracted. Typical comparison of current velocities of the baseline and proposed conditions, shown in Figure 14, indicate the reduction in the velocity. There is a maximum of about 30% reduction in the tidal current velocities observed due to the proposed partial closure in the channel. This reduction in the current velocities for the proposed condition resulted in delay of flushing, as can be seen in Figure 15. It is also interesting to note that, although the flushing (less than 37% of initial constituent) is initiated at some parts for the proposed channel condition at an earlier time step, these locations are completely flushed only after a long period of time.

This is due to the fact that the out gone constituent returns to the partially closed channel back with incoming tides.

4. SUMMARY

A hydrodynamic model of a narrow channel along Abu Dhabi coast was developed using a finite-element scheme. The tidal hydrodynamics and the flushing characteristics of the narrow channel with and without partial blockage were estimated. The comparison of the results showed that the tidal flow velocities are dropped down due the partial blockage which subsequently delayed the natural tidal flushing by 2 days. The proposed partial closure of the channel leads to flushing condition good to fair level, along the channel.
Figure 13 - Flushing scenario of proposed condition at different time steps

Figure 14 - Comparison of velocities
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