Numerical investigation of effective harbor geometry parameters on sedimentation inside square harbors

†M. Mojabi; ‡K. Hejazi; †M. Karimi

1 Department of Civil Eng., K.N. Toosi University of Technology, Tehran, Iran
2 Faculty Member, K.N.Toosi University of Technology, Tehran, Iran

ABSTRACT: Sedimentation is one of the most important problems in harbors that results in considerable economic costs. Harbor planforms affects the flow pattern in the harbor basin and consequently, plays an important role in sediment transport and sedimentation. In the present study, a two dimensional depth-averaged hydrodynamic and sediment transport model has been developed to investigate the effect of harbor planform on sedimentation and sediment transport in harbor basin. Various planforms have been examined by the numerical model and results are plotted for alternative harbor planform geometry parameters, namely, planform aspect ratio, entrance location and entrance width which are presented in a dimensionless form. Results suggest that planform aspect ratios less than unity, leads to less sedimentation inside the harbor basin. In addition, it can be observed that, while entrance location dose not seriously affect suspended sediment transport rate through the harbor entrance, entrance locations closer to the corner of the basin lead to less sedimentation.

Keywords: Harbor Planform; Depth-Averaged Model; Sediment Transport; Alternating Direction Implicit (ADI) method; Finite Volume method (FVM)

INTRODUCTION

Sedimentation is a common problem in harbors, which reduces the required navigation depth and disturbs the vessels passage. In order to provide safe passage for vessels, frequent maintenance dredging in harbors is needed. The amount of maintenance dredging, which is the most expensive item in running costs of harbors, depends on the rate of sedimentation in harbor basin. For example, annual dredging costs of marinas in The Netherlands are estimated about M€500, as reported in (Ommen and Schaap, 1995). As another case in point, the average annual dredging costs of federal navigation projects in United States between 1995 and 2000 was estimated to be about M$500, as reported in (Parchure and Teeter, 2002). Therefore, minimizing sedimentation in harbors is one of the major considerations in harbor design. Generally, sediments, transported into harbors by the action of currents and waves, are deposited in parts of the harbor where currents and waves are not strong enough to keep sediments in motion, and reduce water depth. Therefore, harbor geometry, which considerably affects flow pattern inside the harbor, plays a crucial role in sediment transport and deposition pattern inside the harbor basin.

Recently, many attempts have been made to study sediment transport and measures for the reduction of sedimentation in harbor basins. Yin et al. (2000) conducted an experimental study on water and sediment movements inside square harbors under the effect of tidal and steady currents and suggested some general criteria that enhance flushing process in the harbor and consequently reduce the need for dredging therein. Winterwerp (2005) gives a summary of measures for the reduction of sediment deposition reduction measures in harbors for various environmental conditions. Kuijper et al. (2005) discussed the effects of harbor geometry on sediment deposition in harbor basin, together with the application of CDW (Current Deflection Wall) as a type of geometrical modification to reduce sediment deposition in a harbor basin of the port of Hamburg (Germany). Yüksek (1995), conducted an experimental study on the effects of layouts of breakwaters on sedimentation pattern in harbor basins.
and suggested some design criteria in a form of dimensionless geometrical parameters of breakwaters. Donnelly and MacInnis (1968), studied sedimentation in Dingwall harbor (Canada) and proposed that changing the shape of harbor entrance may influence sedimentation inside the harbor. Stoschek and Zimmermann (2006) conducted a numerical investigation on the effects of harbor geometry on sediment exchange and sedimentation in an estuarine tidal harbor. Van Rijn (2004) discussed the sedimentation problem in estuarine and coastal environments including harbors, and suggested practical engineering solutions based on the field measurements, physical models and numerical model results. Van Maren et al. (2009) investigated the effect of dock length on siltation in a harbour basin, using a high resolution numerical model for Deurganckdok in the port of Antwerp (Belgium) and concluded that, depending on other environmental conditions in the estuary, changing in dock length may have different effects on siltation. Previous works have rarely focused on the effective geometric parameters that can be used as design criteria in harbor design. The main purpose of the present study is to provide deeper insight into the effect of harbor planform on sedimentation and sediment transport inside the harbor basin, and suggest the geometric parameters to be used as preliminary design criteria, which reduce sedimentation inside the harbor basin. Therefore, a 2D depth averaged finite volume hydrodynamic and sediment transport model is developed and validated against experimental data and analytical solutions. Then, the planform effects on sedimentation volume are investigated through examining various planforms by the numerical model, and comparing the amount of sedimentation volume, each associated with a specific harbor planform.

MATERIALS AND METHODS

Numerical model formulation
The model developed herein, consists of hydrodynamic, and suspended sediment transport and morphodynamic modules. Hydrodynamic module, predicts water depth and depth integrated flow velocity through solving shallow water equations. Using results of hydrodynamic module, suspended sediment transport and morphodynamic module predicts suspended sediment concentration via solving advection - diffusion equation, and predicts bed level changes, by solving sediment mass conservation equation. In the present model, governing equations are discretized using finite volume method on a uniform rectangular staggered grid. Convective terms are discretized using conservative formulation and the high resolution SDPUS-C1 scheme (Lima et al., 2010), has been utilized to interpolate cell face values from cell centered quantities. Diffusive terms are also discretized using the second order central difference scheme (CDS), and time derivative terms have been discretized using the first order Euler backward scheme. In the present model, the solution of full two dimensional set of algebraic equations, has been approached by the use of alternating direction implicit method (ADI). At each step, Thomas Algorithm has been utilized to solve tri-diagonal matrices.

Hydrodynamic module
Hydrodynamic module is based on shallow water equations, consisting of continuity and momentum equations which include effects of turbulence, bottom stress and wind friction, and are represented as follows:

\[
\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0
\]  
(1)

\[
\frac{\partial (uh)}{\partial t} + \frac{\partial (uuh)}{\partial x} + \frac{\partial (vah)}{\partial y} =
\]

\[- gh \left( \frac{\partial (h + z_b)}{\partial x} + \frac{1}{\rho} \frac{\partial (hT_{sx})}{\partial x} + \frac{1}{\rho} \frac{\partial (hT_{sy})}{\partial y} \right) \frac{\tau_{bx}}{\rho} + \frac{\tau_{sx}}{\rho}
\]

\[
\frac{\partial (vh)}{\partial t} + \frac{\partial (uvw)}{\partial x} + \frac{\partial (vvh)}{\partial y} =
\]

\[- gh \left( \frac{\partial (h + z_b)}{\partial y} + \frac{1}{\rho} \frac{\partial (hT_{yx})}{\partial x} + \frac{1}{\rho} \frac{\partial (hT_{yy})}{\partial y} \right) \frac{\tau_{by}}{\rho} + \frac{\tau_{sy}}{\rho}
\]

where \(u\) and \(v\) are depth-averaged horizontal velocities in \(x\) and \(y\) directions respectively, \(h\) is the water depth, \(z_b\) is bed elevation, \(T_{sx}, T_{sy}, T_{yx}\) and \(T_{yy}\) are depth-averaged turbulent stresses, \(\tau_{bx}, \tau_{by}\) are bed shear stresses in \(x\) and \(y\) directions respectively, \(\rho\) is water density and \(g\) is the gravity acceleration. Bed shear stresses, using simple quadratic friction law, are determined and represented by Eq. 4, in which \(C\) is the Chezy coefficient, \(\tau_{bx}, \tau_{by}\) are wind shear stresses, acting on the water surface, as expressed by Eqs.5, in which \(u_w\) and \(v_w\) are wind velocity components at the location of 10 meters above water surface, in \(x\) and \(y\) directions respectively, \(\rho_a\) is the air density and \(C_a\) is wind drag coefficient.
\[\begin{align*}
\tau_{bx} &= \rho g C^2 \left( \frac{u^2}{u^2 + v^2} \right)^{\frac{1}{2}} \left[ T_x \right] \\
\tau_{by} &= \rho g C^2 \left( \frac{v^2}{u^2 + v^2} \right)^{\frac{1}{2}} \left[ T_y \right]
\end{align*}\]  
(4)

\[\begin{align*}
\tau_{sx} &= \rho k_w \left( \frac{u_w^2}{u_w^2 + v_w^2} \right)^{\frac{1}{2}} \left[ T_x \right] \\
\tau_{sy} &= \rho k_w \left( \frac{v_w^2}{u_w^2 + v_w^2} \right)^{\frac{1}{2}} \left[ T_y \right]
\end{align*}\]  
(5a)

\[k_w = \frac{\rho_a}{\rho} C_a\]  
(5b)

Turbulent shear stresses are calculated using simple Boussinesq assumption (Rodi, 1993):

\[T_{xx} = 2\rho (v + v_T) \left( \frac{\partial u}{\partial x} \right) - \frac{2}{3} \rho k\]  
(6a)

\[T_{xy} = T_{yx} = \rho (v + v_T) \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)\]  
(6b)

\[T_{yy} = 2\rho (v + v_T) \left( \frac{\partial v}{\partial y} - \frac{2}{3} \rho k\right)\]  
(6c)

where \(v\) is water kinematic viscosity, \(v_T\) is turbulent eddy viscosity, \(k\) is turbulent kinematic energy which is dropped from Eq. 6a and Eq. 6b, if zero equation turbulence closure is applied. In order to calculate eddy viscosity, a zero equation depth averaged parabolic model has been used, as represented by Eq. 7 respectively. Here \(\alpha\) is an empirical coefficient that may vary from 0.15 to 1.5.

\[v_T = \alpha h \sqrt{\frac{g}{C}} \left( u^2 + v^2 \right)\]  
(7)

**Suspended sediment transport and morphodynamic module**

Total sediment load has been divided into suspended sediment part and bed load, each part is treated separately. Suspended sediment concentration is described, using depth averaged advection diffusion equation, as expressed by Eq. 8.

\[\frac{\partial (c h)}{\partial t} + \frac{\partial (u c h)}{\partial x} + \frac{\partial (v c h)}{\partial y} = \frac{\partial}{\partial x} \left( \varepsilon_x h \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( \varepsilon_y h \frac{\partial c}{\partial y} \right) + E_b - D_b\]  
(8)

Where, \(c\) is the depth-averaged suspended sediment concentration, \(\varepsilon_x = \varepsilon_y = v/6\) are sediment diffusion coefficients in \(x\) and \(y\) directions respectively, \(\sigma\) is turbulent Schmidt number (varies between 0.5 to 1.0), \(E_b\) is sediment erosion rate, and \(D_b\) is sediment deposition rate. The term \((E_b - D_b)\) on the right hand side of the Eq. 8, represents suspended sediment exchange rate between bed material and water column. In the present model, suspended sediment exchange rate is calculated by using Krone (1962) and Partheniades (1965) formulas, as represented by Eq. 9 and Eq. 10 respectively, where \(\tau_b\) is bed shear stress, \(\tau_{cd}\) is critical stress for deposition, \(\tau_{ce}\) is critical stress for erosion, \(w_s\) is settling velocity, and \(M\) is erosion constant.

\[\begin{align*}
D_b &= \begin{cases} 
\frac{w_s c(1 - \frac{\tau_b}{\tau_{cd}})}{n} & \text{for } \tau_b < \tau_{cd} \\
0 & \text{for } \tau_b > \tau_{cd}
\end{cases}\]  
(9)

\[\begin{align*}
E_b &= \begin{cases} 
M(\frac{\tau_b}{\tau_{ce}} - 1) & \text{for } \tau_b > \tau_{ce} \\
0 & \text{for } \tau_b < \tau_{ce}
\end{cases}\]  
(10)

Bed level changes due to both suspended and bed load Transport are calculated, by solving the sediment mass conservation equation, which is represented by Eq. 11, where \(z_b\) is bed level, \(q_{bx}\) and \(q_{by}\) are bed load volumetric transportation rate in \(x\) and \(y\) directions respectively, and \(n\) is bed material porosity. Since bed load transport is negligible in the case of the transport of fine sediments transport, in the present study bed load transport is not taken into account. Thus, sediment mass conservation equation is simplified into Eq. 12.

\[\begin{align*}
\frac{\partial z_b}{\partial t} + \frac{\partial q_{bx}}{\partial x} + \frac{\partial q_{by}}{\partial y} - (E_b - D_b) &= 0 \\
\frac{\partial z_b}{\partial t} &= E_b - D_b
\end{align*}\]  
(11)

(12)

**Numerical model validation**

**Tide induced circulation in a square harbor**

The numerical model prediction of tide induced depth integrated velocity distribution along central axes of a square harbour, has been compared with experimental measurements of Nece and Falconer (1995). In the
Numerical investigation of effective harbor geometry parameters

Numerical simulations, the depth averaged parabolic turbulence model has been proposed by Nece and Falconer (1995). A constant Chezy coefficient and initial depth for entire domain are set to 60 m^0.5/s and 0.15 m, respectively. A sinusoidal tidal wave with an amplitude of 0.05m and period of 708 s is specified at the open boundary parallel to harbor entrance, and zero lateral velocity gradient boundary condition is applied at two open boundaries which are perpendicular to harbor entrance Fig. 1. A comparison between the numerical model predictions of flow velocity inside the harbour and experimental measurements (Nece and Falconer, 1989) is represented by Fig. 2, which shows a good agreement.

Analytical solution for advection-dispersion equation including source-sink term

Assuming certain initial and boundary conditions as expressed in (Wexle, 1992), Wexler (1992) proposed an analytical solution for advection-diffusion equation, as presented in Eq. 13. where $L$ and $W$ are length and width of computational domain respectively. Velocity and diffusion coefficients are assumed to be constant over computational domain. Results for unit depth, $u = 1$ ft/day, $v = 0$, $k_x = 200$ ft/day², $k_y = 60$ ft/day² and $\lambda = 0.001$ are shown in Fig. 3, that confirm the accuracy of advection-diffusion simulation. Dots and lines represent analytical solution and numerical model predictions, respectively.

Fig. 1: A description of numerical model configuration

Fig. 2: effect of velocity along x axis of mean level ebbtide
   a) u velocity           b) v velocity
\[
\frac{\partial (ch)}{\partial t} + \frac{\partial (uch)}{\partial x} + \frac{\partial (vch)}{\partial y} = \frac{\partial}{\partial x} \left( \varepsilon \frac{h}{\partial x} \right) + \frac{\partial}{\partial y} \left( \varepsilon \frac{h}{\partial y} \right) - \lambda c
\]

[13]

\[
\frac{\partial (ch)}{\partial t} + \frac{\partial (uch)}{\partial x} + \frac{\partial (vch)}{\partial y} = \frac{\partial}{\partial x} \left( \varepsilon \frac{h}{\partial x} \right) + \frac{\partial}{\partial y} \left( \varepsilon \frac{h}{\partial y} \right) - \lambda c
\]

Sediment mass conservation test

The sediment mass conservation test is designated to evaluate the numerical model capability of simulating sediment transport, while maintaining sediment mass conservation. Assuming constant bed shear stress of \( \tau_b = 2.0 \text{ N/m}^2 \), critical shear stress for erosion of \( \tau_{cr} = 0.2 \text{ N/m}^2 \) and erosion constant of \( M = 3.77 \times 10^{-9} \text{ m/s} \), analytical solution of Eq. 12 yields \( \Delta z = 5.66 \times 10^{-8} \text{ m} \).

Fig. 4 represents a comparison between analytical solution and numerical model predictions of bed level changes for aforementioned assumed conditions, which shows an excellent agreement. In order to evaluate the model capability in simulating sediment transport while maintaining sediment mass conservation, a numerical simulation of sediment transport on a rectangular \( 12 \text{ km} \times 4 \text{ km} \) domain, with a simple sloped bottom, Fig. 5, has been carried out. Except for critical shear stresses for erosion and deposition, other parameters are same as those used in (Pandoe and Edge, 2004) which include the flow boundary condition with the discharge of \( u_h = 2.25 \text{ m}^2/\text{s} \) per unit width on the left hand open boundary, and a constant water elevation of \( (h = 20 \text{ m}) \) on the right hand side open boundary. Other two boundaries are assumed to be land boundaries and the simulation time has been 24 hours. To maintain sediment mass conservation, net erosion volume (erosion + deposition) has to be equal to the sum of suspended sediment volume and sediment volume that leaves the channel from right hand side boundary. Fig. 6 shows bed erosion/deposition per unit width along the centerline of the channel. Results, presented in Table 1, show an error of about 0.41% for sediment mass conservation after 24-hour simulation.

\[
\begin{align*}
\text{Net Erosion} & = 2450.26 \text{ m}^3 \\
\text{Suspended Sediment} & = 1819.80 \text{ m}^3 \\
\text{Sediment Inflow} & = \text{Zero} \\
\text{Sediment Outflow} & = 639.95 \text{ m}^3 \\
\text{Error} & = 0.41%
\end{align*}
\]

Table 1: Sediment deposition along the channel centreline
Study approach
The validated model has been investigated for various planform and geometric effects on sedimentation inside typical square harbour basins. Entrance width, entrance location and harbour aspect ratio are the parameters which have been chosen for this investigation. The typical harbour is the same as presented in Fig. 1, as that has been described in the work of Nece and Falconer (1989). Since Making use of zero equation turbulence closure leads to sufficiently good results, as has been used has been used in the simulation of the work conducted by Nece and Falconer (1989), and saves considerable computational time, in all simulations zero equation turbulence closure has been employed.

Engineering criterion for sedimentation inside harbors
To evaluate, suspended sediment mass balance, schematic harbor basin, as shown in Fig. 7, where $c_a$ is suspended sediment concentration in ambient waters, $Q_e$ is suspended sediment exchange rate between harbor basin and ambient water, $L$ is harbor length, $B$ is harbor breadth, $W$ is entrance width and $X$ is the distance at which entrance is located (measured from the left corner of the basin). Sediment mass conservation equation in the harbor basin may be expressed by Eq. 14, in which $V_s$ is suspended sediment volume and $Q_d$ is the sedimentation rate inside the harbor basin.

\[
\frac{dV_s}{dt} = Q_e - Q_d \quad (14)
\]

Integrating Eq. 14 over time, the total suspended volume changes inside the harbor basin would be represented by Eq. 15 in which $\Delta V_{in}$ is suspended sediment volume, transported into the basin during flood periods, $\Delta V_{out}$ is suspended sediment volume flushed out of the basin during ebb periods and $\Delta V_d$ is suspended sediment deposition volume inside the harbor basin.

\[
\Delta V_d = \Delta V_{in} - \Delta V_{out} - \Delta V_s \quad (15)
\]

Eq. 15 suggests that, for a constant value of $\Delta V_{in}$, the more $\Delta V_s$ or $\Delta V_{out}$, results in less sedimentation volume. In order to calculate $\Delta V_{in}$ over a tidal period, suspended sediment flux into the harbor basin through the entrance is integrated over time. For the sake of simplicity, in the present study, $c_a$ is assumed to be constant over time and space.

\[
\Delta V_{in} = \int_0^t \int_0^X q_{in} c_a dx dt = \int_0^t \int_0^X q_{in} dx dt \quad (16)
\]

\[
q_{in} = \begin{cases} 
(\chi h)_{y=B} & v < 0 \quad (flood) \\
0 & v \geq 0 \quad (ebb) 
\end{cases} \quad (17)
\]

The term $\int_0^t \int_0^X q_{in} dx dt$ equals to the change of water volume inside the harbor basin, during the tidal flood period. Assuming that the harbor basin experiences the regular sinusoidal tides, temporal variation of water volume inside the harbor can be expressed by Eq. 18, as suggested by Barber and Wearing (2002), in which $V(t)$ is water volume inside the harbor, $V_m$ is water volume inside the harbor at mean level tide, $T$ is tidal period, $A$ is tidal amplitude and $S = LB$ is the surface area of harbor basin. Fig. 8 shows the excellent agreement of numerical model predictions and graphical demonstration of Eq. 18 which confirms the sinusoidal assumption of variation of volume of the water inside the harbor basin. Hence, during the flood interval, the suspended sediment volume transported into the basin during tidal flood periods, is calculated, as in Eq. 19.

\[
V(t) = V_m + \frac{SA}{2} \sin \left( \frac{2\pi}{T} t \right) \quad (18)
\]

\[
\Delta V_{in} = \int_0^t \int_0^X q_{in} dx dt = ASc_a \quad (19)
\]

Since the basin experiences the repetitive tidal cycles and $c_a$ is assumed to be constant over time, after $n$ tidal periods, $\Delta V_{in}$ would be equal to $n$ times the calculated amount for one tidal cycle. The total deposition volume inside the basin is calculated by Eq. 20, where $z_s$ is the final bed level after $n$ tidal cycle, calculated by the numerical model, and $z_{i0}$ is initial bed level. In the present study the fraction of deposited sediment to the total sediment transported in the basin, $\alpha$, has been chosen as a dimensionless parameter that represents the trapping efficiency of a harbor, which is the criterion parameter which has been used for the investigation and engineering judgment, Eq. 21.
\[ \Delta V_d = \int_{0}^{L} \left( z_b - z_{b0} \right) dx \, dy \]  
\[ \alpha = \frac{\Delta V_d}{\Delta V_{in}} = 1 - \left[ \frac{\Delta V_{in}^{s} + \Delta V_{out}^{s}}{\Delta V_{in}^{s}} \right] \]  

**RESULTS AND DISCUSSION**

In the present study, 30 harbor configurations, varying in entrance location, entrance width and aspect ratio have been examined. In order to make a basis for comparisons between various planforms, the amount of transported sediment volume into the basin \( (\Delta V_{in}) \) has been kept constant in all tests (i.e. \( L \times B = \text{Constant} \)). The dimensionless parameter of harbor trapping efficiency \( (\alpha) \), reflects how a specific planform affect the suspended sediment deposition inside the harbor. In the present study the planform area has been taken to be constant, and the geometric parameters of harbor planform have been represented in dimensionless form. The dimensionless geometric parameters considered in this study, are \( L/B, W/L \) and \( (0.5W+X)/L \), which denote the aspect ratio, entrance width and entrance location respectively.

Eq.[19] for a harbor dimensions of \( 1.08m \times 1.08m \), tidal height of \( 0.1m \) and suspended sediment concentration in ambient waters equal to \( 0.3kg/m^3 \), as used in this study, and after 8 tidal period yields:

\[ V_{in} = 8 \times 0.3 \times 2650 \times 1.08^2 \times 0.1 = 1.03 \times 10^{-4} \, m^3. \]

The hydraulic and sediment transport parameters, together with a sketch of typical harbor geometry have been tabulated in Table 2. Results of numerical simulations, associated with various planform geometries, are tabulated in Table 3.

**Effect of Entrance Location**

The effect of entrance location on suspended sediment deposition inside the harbor basin, for various entrance widths, is represented by Fig.9 (a), (9b), (9c) and (9d). Fig.s show that entrances located close to the corner, compared to the entrances located close to the centerline of the harbor (i.e. \( X_c/L \approx 1/2 \)), the entrances located near the corner result in less sedimentation. Generally, entrance location is found to have a negligible effect on overall suspended sediment exchange rate.

<table>
<thead>
<tr>
<th>Table 2: hydrodynamic and sediment transport parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_0 ) (kg/m(^3))</td>
</tr>
<tr>
<td>( c_s ) (kg/m(^3))</td>
</tr>
<tr>
<td>( W_s ) (m/s)</td>
</tr>
<tr>
<td>( V_{in} )</td>
</tr>
</tbody>
</table>

Fig. 8: Tidal variation of water volume inside the harbor basin
Table 3: Numerical simulation parameters and predictions

<table>
<thead>
<tr>
<th>Test</th>
<th>L(mm)</th>
<th>B(mm)</th>
<th>L/B</th>
<th>W/L</th>
<th>Xc/L</th>
<th>100α</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>360</td>
<td>3240</td>
<td>1/9</td>
<td>2/9</td>
<td>7/18</td>
<td>1/2</td>
</tr>
<tr>
<td>2</td>
<td>360</td>
<td>3240</td>
<td>1/9</td>
<td>2/9</td>
<td>1/6</td>
<td>5/18</td>
</tr>
<tr>
<td>3</td>
<td>540</td>
<td>2160</td>
<td>1/4</td>
<td>2/9</td>
<td>7/18</td>
<td>1/2</td>
</tr>
<tr>
<td>4</td>
<td>540</td>
<td>2160</td>
<td>1/4</td>
<td>2/9</td>
<td>7/18</td>
<td>1/2</td>
</tr>
<tr>
<td>5</td>
<td>720</td>
<td>1620</td>
<td>4/9</td>
<td>2/9</td>
<td>1/2</td>
<td>7/18</td>
</tr>
<tr>
<td>6</td>
<td>720</td>
<td>1620</td>
<td>4/9</td>
<td>2/9</td>
<td>1/6</td>
<td>5/18</td>
</tr>
<tr>
<td>7</td>
<td>1620</td>
<td>720</td>
<td>9/4</td>
<td>2/9</td>
<td>7/18</td>
<td>1/2</td>
</tr>
<tr>
<td>8</td>
<td>1620</td>
<td>720</td>
<td>9/4</td>
<td>2/9</td>
<td>1/6</td>
<td>5/18</td>
</tr>
<tr>
<td>9</td>
<td>2160</td>
<td>540</td>
<td>4</td>
<td>2/9</td>
<td>7/18</td>
<td>1/2</td>
</tr>
<tr>
<td>10</td>
<td>2160</td>
<td>540</td>
<td>4</td>
<td>2/9</td>
<td>1/6</td>
<td>5/18</td>
</tr>
<tr>
<td>11</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>1/9</td>
<td>1/6</td>
<td>2/9</td>
</tr>
<tr>
<td>12</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>1/9</td>
<td>1/3</td>
<td>7/18</td>
</tr>
<tr>
<td>13</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>1/9</td>
<td>5/12</td>
<td>17/36</td>
</tr>
<tr>
<td>14</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>1/9</td>
<td>1/2</td>
<td>5/9</td>
</tr>
<tr>
<td>15</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>1/9</td>
<td>5/9</td>
<td>11/18</td>
</tr>
<tr>
<td>16</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>2/9</td>
<td>1/6</td>
<td>5/18</td>
</tr>
<tr>
<td>17</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>2/9</td>
<td>4/9</td>
<td>3.467</td>
</tr>
<tr>
<td>18</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>2/9</td>
<td>1/2</td>
<td>7/18</td>
</tr>
<tr>
<td>19</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>2/9</td>
<td>5/12</td>
<td>19/36</td>
</tr>
<tr>
<td>20</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>2/9</td>
<td>1/2</td>
<td>11/18</td>
</tr>
<tr>
<td>21</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>3/9</td>
<td>1/6</td>
<td>1/3</td>
</tr>
<tr>
<td>22</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>3/9</td>
<td>5/4</td>
<td>7/27</td>
</tr>
<tr>
<td>23</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>3/9</td>
<td>1/3</td>
<td>1/2</td>
</tr>
<tr>
<td>24</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>3/9</td>
<td>5/12</td>
<td>7/12</td>
</tr>
<tr>
<td>25</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>3/9</td>
<td>1/2</td>
<td>2/3</td>
</tr>
<tr>
<td>26</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>4/9</td>
<td>1/6</td>
<td>7/18</td>
</tr>
<tr>
<td>27</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>4/9</td>
<td>2/27</td>
<td>8/27</td>
</tr>
<tr>
<td>28</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>4/9</td>
<td>1/3</td>
<td>5/9</td>
</tr>
<tr>
<td>29</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>4/9</td>
<td>5/12</td>
<td>23/36</td>
</tr>
<tr>
<td>30</td>
<td>1080</td>
<td>1080</td>
<td>1</td>
<td>4/9</td>
<td>1/2</td>
<td>13/18</td>
</tr>
</tbody>
</table>

Fig. 9a: Entrance location effect on sedimentation

W/L = 1/9

Fig. 9b: Entrance location effect on sedimentation

W/L = 2/9
**Fig. 9c:** Entrance location effect on sedimentation  
W/L = 3/9

**Fig. 9d:** Entrance location effect on sedimentation  
W/L = 4/9

**Effect of entrance width**  
Fig.s (10a), (10b) and (10c), represent the effect of harbor entrance width on sedimentation inside the basin for various entrance locations. Based on the numerical simulation results, it may be concluded that, although the suspended sediment flushing rate is not reduced for larger entrance width, wider entrances lead to more sedimentation inside the basin. Therefore, wider entrance reduces the overall strength of currents inside the basin and consequently, results in more sedimentation.

**Fig. 10a:** Entrance width effect on sedimentation X/L=1/6  
**Fig. 10b:** Entrance width effect on sedimentation X/L=1/3

**Fig. 10c:** Entrance width effect on sedimentation  
X/L=5/12

**Planform aspect ratio effect**  
Fig.s (11a) and (11b), present the aspect ratio effect on suspended sediment exchange rate through harbor entrance. For L/B<1, increasing the aspect ratio reduces the flushing rate through the entrance in both symmetric and asymmetric single entrance harbors. Meanwhile, for L/B>1, larger aspect ratios increases the flushing rate. Therefore, L/B=1 for intermediate entrance width (W/L=2/9), may be considered as a crucial point for basin flushing performance.

**CONCLUSION**  
In the present study a two dimensional depth averaged hydrodynamic and sediment transport model has been developed and validated against both analytical solutions and experimental measurements and showed very good agreement. 30 various harbor planforms have been examined by the numerical model and results have been presented by making use of dimensionless geometric parameters. The fraction of deposited sediment to the sediment transported in the basin, \( \alpha \), has been chosen as a criterion parameter which has been used for the investigation and engineering judgment.

In order to investigate the effect of planform geometry on sediment transport and sedimentation inside square harbors, aspect ratio, entrance location and entrance width have been chosen as geometry parameters to be varied in this investigation. Numerical investigation results suggest that planform aspect ratios less than unity, result in less sedimentation and more flushing rate inside the harbor basin. In addition, while entrance location dose not seriously affect suspended sediment exchange rate, entrance locations closer to the corner of the basin lead to less sedimentation.

In conclusion, results of the numerical tests can be summarized as follow:

- For both narrow and wide entrances, ranging from W/L=1/9 to W/L=4/9 the entrance location closer the corner leads to less sedimentation inside the basin.
- For \( \frac{1}{9} \leq \frac{W}{L} \leq \frac{4}{9} \), the increase of entrance width results in more sedimentation.

- For \( \frac{L}{B} < 1 \), the increase of aspect ratio leads to more sedimentation inside the basin and reduces the flushing rate.

Fig. 11: Aspect ratio effect on sedimentation, a) \( \frac{X_c}{L} = \frac{5}{18} \), b) \( \frac{X_c}{L} = \frac{1}{2} \)

Fig. 12a: The Effect of Aspect Ratio on Suspended Sediment Exchange Rate for Central Entrance

\[
\text{Sediment Exchange Rate} (m^2/\text{a})
\]

\[
\text{Flushing}
\]

\[
\text{Time (s)}
\]

\( \frac{X_c}{L} = \frac{1}{2} \) & \( \frac{W}{L} = \frac{2}{9} \)

\( \bullet \frac{L}{B} = 1/9 \) - \( \odot \frac{L}{B} = 1/4 \) - \( \blacklozenge \frac{L}{B} = 4/9 \)
Fig. 12b: The Effect of Aspect Ratio on Suspended Sediment Exchange Rate for Corner Entrance

REFERENCES


Siltation., Continental Shelf Research, 29 (11-12), 1410-1425.

**How to cite this article: (Harvard style)**