HYDRODYNAMIC MODELLING OF TIDAL INLETS IN HUE, VIETNAM

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ABSTRACT
Application of an one-dimensional numerical model for hydrodynamic simulation of a complex lagoon-inlet system in Vietnam is presented. Model results help to get a better understanding on the behaviour of the system. Based on the numerical model results and analytic solutions, stability of tidal inlets is evaluated.

1. INTRODUCTION

The tidal inlets of Hue, namely Thuan An and Tu Hien, connect the Tam Giang-Cau Hai lagoon to the South China Sea. Hydrodynamics and morphology of the inlets are strongly influenced by both marine and continental factors in a tropical monsoon region. In rainy season from September to December, floods from rivers can cause sudden changes like widening existing inlets or breaking the narrow sand dune barrier to open new inlets. In dry season lasting from January to August, marine effects are dominant. Longshore sediment transports tend to close the inlets while tidal flushing and river flow try to maintain them. Small tidal ranges and small river flows in the season make more difficult for maintenance the inlets. The inlets are usually shoaling, migrating and even closed. Instability of the inlets has negative effects on socio-economic development and environment in the area. Shoaling of the Thuan An inlet and closure of the Tu Hien inlet produce difficulties and problems for navigation, fishery, aquaculture, flood evacuation and environment of the lagoon. The opening of a new inlet at Hoa Duan (4 km south of the Thuan An inlet) in November 1999 reduces the flushing ability of the Thuan An inlet. It also has adverse effects on transportation of habitants in the sand barrier and ecosystem of the lagoon. Study on hydrodynamics of the system is necessary to provide a better understanding on the system's behaviour and to provide a basis for decision making process.

2. NUMERICAL MODEL

Hydrodynamics of the system depends on a combination of complex boundary conditions including inlet configuration, variation of channel cross-section and contribution of tributary inflows. It can be represented by the system of one-dimensional shallow water equations

$$B\frac{\partial \eta}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+gA\frac{\partial \eta}{\partial x}+g\frac{|Q|Q}{C^2AR}=0 \tag{2}$$

The system (1) and (2) has analytic solutions for only simple systems with simplified assumptions. For proper hydrodynamic simulation of the system, a numerical model is employed using DUFLOW (IHE, 1995). The numerical model will help to investigate the behaviour of the system under different boundary conditions. It also provides some basic information on the system that will be used for insight looking on the principles of system stability based on analytical solutions.

2.1. Model schematisation and boundary conditions

Difficulties arise during modelling process. Data for the hydrodynamic boundary conditions of the lagoon and inlets is very limited. Observations of river discharges and water levels are available at only some gauging stations upstream of the rivers. Observations of tidal levels at the inlets are available at some short periods. To use that data for model boundary conditions, model

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schematisation is extended to include the stations. The model schematization of the system is shown in Figure 1. The upstream boundary conditions of the model are the flow discharges at Duong Hoa (Ta Trach River), Binh Dien (Huu Trach River), Co Bi (Bo River), O Lau River. The down stream boundary conditions of the model are the tidal water levels in the sea at the locations of the inlets of Thuan An, Tu Hien. The water levels at the inlets are tidal predictions using the tidal constants determined from tidal analysis of observations. In cases when the inlet at Hoa Duan is open, the boundary condition at this location is taken the same as those for the Thuan An inlet, otherwise, it is assigned to a zero flow discharge boundary condition. Flow discharges of small rivers such as the Truoi River, Cau Hai River and other sub-basins are simulated in the model as discharge points. Water levels at the stations of Kim Long and Phu Oc are used for model calibration and verification.

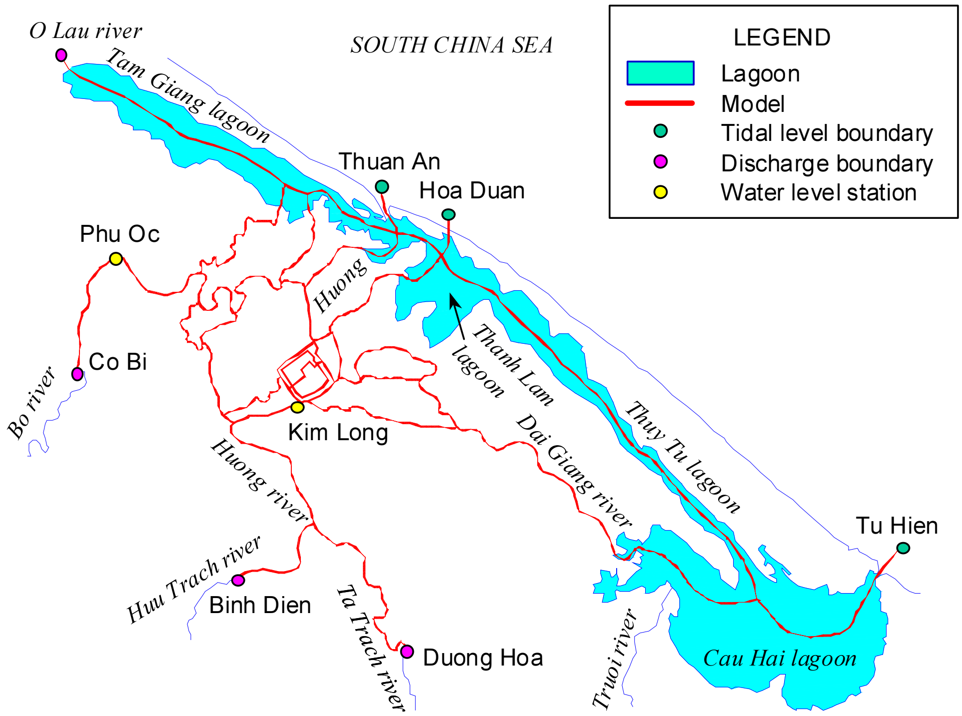

Figure 1. Model of the lagoon and inlet system

2.2. Model calibration and verification

The model is calibrated using available data of the flood October 1983. The available data during the flood November 1999 and in the dry season of 2000 are used for model validation. In model calibration and verification, effects of model parameters such as time step, bottom roughness and uncertainties in boundary conditions such as tidal constants, storm surges, and inlet openings are considered using sensitivity analysis. See Lam (2002) for details.

2.3. Model results

The computational scenarios are built with alternatives of inlet opening and configuration and different boundary conditions. Some scenarios of inlet opening are in Table 1. These scenarios are setup to investigate the effects of the Hoa Duan inlet in case of the inlet is present.

Table 2 lists the model results of maximum flood and ebb velocities at the inlets corresponding to the scenarios. We can realize that the flow velocities in the Tu Hien inlet are quite independent with changes in the Thuan An and Hoa Duan inlets. This is also confirmed by the consideration in the model the propagation of tidal waves from the inlets. Tidal waves which enter through the Thuan An and Hoa Duan inlets propagate along the Thuy Tu lagoon and meet the tidal waves propagating in the Cau Hai lagoon from the Tu Hien inlet at an old ebb tidal delta south of the Thuy Tu lagoon. This ebb delta is acting as an obstruction and relatively separates the Cau Hai lagoon from others. Therefore, the Thuan An inlet and the Tu Hien inlet can be considered as two independent single inlet-bay systems when the Hoa Duan inlet is closed. This is an important premise for the analytical analysis of the system.

Run No.	Thuan An		Hoa Duan	
	B(m)	A(m^2)	B(m)	A(m^2)
R01	535	4200	420	1900
R02	535	4200	close	
R03	close		420	1900
R05	344	1500	close	
R06	close		217	600
R18	500	3800	close	

Table 1. Scenarios of inlet openings

Run No.	Thuan An		Hoa Duan		Tu Hien	
	Flood	Ebb	Flood	Ebb	Flood	Ebb
R01	-0.6	0.6	-0.6	0.6	-0.8	1.1
R02	-0.8	0.8	—	—	-0.8	1.1
R03	—	—	-1.2	1.2	-0.8	1.1
R05	-1.4	1.5	—	—	-0.8	1.1
R06	—	—	-1.6	1.6	-0.8	1.0
R18	-1.0	1.0	—	—	-0.9	1.1

Table 2. Effect of inlet openings on inlet maximum flow velocities

Model results listed in Table 2 indicate that the opening of the Hoa Duan inlet reduces the flow velocity in the Thuan An inlet. The existence of the Hoa Duan inlet causes the maximum mean velocity (V_{max}) in the two inlets falling far below the order of 1 m/s. According to the “cross sectional stability” criterion suggested by Bruun et al. (1974), this is resulting in sedimentation and declination of both inlets. Therefore, the closure one of these two inlets is necessary for maintenance of another. The closure of the Hoa Duan inlet is the right selection for both flood evacuation, navigation and transportation. Based on the model simulation result for the flood of November 1999, the averaged distributions of flood discharges in the Thuan An, Hoa Duan and Tu Hien inlets are 60%, 25% and 15%, respectively.

Numerical modelling exercises can also help to select a suitable opening for the Thuan An inlet according to the cross sectional stability criterion as R18 in Table 2.

Based on the numerical model, inlet parameters such as bottom roughness, maximum flow discharge, tidal prism, C_K, etc, are obtained. The tidal prisms of the inlets have a strong relationship with the maximum flow discharges with C_K = 0.9 for Thuan An and C_K = 0.8 for Tu Hien as in the following formula

$$P = \frac{2A_C V_{\max}}{\omega C_K} \qquad (3)$$

These parameters are required for stability analysis of the system.

2.4. Inlet stability analysis according to P/M_{tot} criterion

Stability of a tidal inlet on sandy coast is determined by the balance of longshore sediment transport and flushing ability of tides in inlet channel. Based on that balance the ratio between the tidal prism (P, m^3/tidal cycle) and the total annual littoral drift (M_{tot}, m^3/year) were introduced by Bruun and Gerritsen (1960) and elaborated by Bruun (1968, 1978, 1986) as the P/M_{tot} criteria for inlet overall stability. The stability of an inlet is rated as good, fair, or poor according to the value of P/M_{tot} (Bruun, 1978).

For the inlets of Hue, the tidal prisms and maximum discharges are computed using the numerical model. Some of these are calculated using observations. Values of total littoral drift into the inlets are taken from various sources and having ranges like in Table 3, Table 4 and Table 5. Ranges of P/M_{tot} are determined accordingly to the ranges of M_{tot} in these tables.

From Table 3, the stability of the Thuan An inlet is in a "fair to poor" situation. The entrance shoals causing difficulties for navigation and flood evacuation. If the opening of the Thuan An inlet is small and the Hoa Duan inlet is opened, the stability situation of the Thuan An inlet will become "poor". It indicates that the tidal prism is not enough and flow is not able to push out the sediment that enters into the inlet from sides. Most of the cases like in Table 4, the Hoa Duan inlet have a "poor" stability situation. From Table 5, the stability situation of the Tu Hien inlet is always "poor" and does not depend on the openings of the Thuan An inlet and the Hoa Duan inlet.

Inlet opening scenario	P ($10^6 m^3$)	Q_{max} (m^3/s)	M_{tot} ($10^6 m^3/yr$)	$\frac{P}{M_{tot}}$	Stability situation
According to Lee, 1970	47	2900	1.6	30	poor, entrance shoals
Observed in May 2000	36	2660	0.64 – 3.42	11 – 56	fair to poor
R01:	32 – 40	2400	0.64 – 3.42	9 – 63	fair to poor
R02:	46 – 55	3330	0.64 – 3.42	13 – 86	fair to poor
R04:	26 – 31	1800	0.64 – 3.42	8 – 48	poor
R05:	30 – 36	2080	0.64 – 3.42	9 – 56	fair to poor

Table 3. Overall stability situation of the Thuan An inlet

Inlet opening scenario	P ($10^6 m^3$)	Q_{max} (m^3/s)	M_{tot} ($10^6 m^3/yr$)	$\frac{P}{M_{tot}}$	Stability situation
Observed in May 2000	21	1670	0.64 – 3.42	6 – 33	poor
R01	16 – 18	1172	0.64 – 3.42	5 – 28	poor
R03	34 – 41	2352	0.64 – 3.42	10 – 64	fair to poor
R04	11 – 13	747	0.64 – 3.42	3 – 20	poor
R06	16 – 18	1009	0.64 – 3.42	5 – 28	poor

Table 4. Overall stability situation of the Hoa Duan inlet

Inlet opening scenario	P ($10^6 m^3$)	Q_{max} (m^3/s)	M_{tot} ($10^6 m^3/yr$)	$\frac{P}{M_{tot}}$	Stability situation
R01	12 – 14	860	0.67 – 1.21	10 – 21	poor
R02	12 – 14	866	0.67 – 1.21	10 – 21	poor
R03	12 – 14	855	0.67 – 1.21	10 – 21	poor
R04	12 – 14	858	0.67 – 1.21	10 – 21	poor
R05	12 – 14	850	0.67 – 1.21	10 – 21	poor
R06	12 – 14	818	0.67 – 1.21	10 – 21	poor

Table 5. Overall stability situation of the Tu Hien inlet

3. ANALYSIS ON INLET HYDRODYNAMICS AND STABLIBITY

3.1. Analytic solutions with tributary inflow

Analytic solutions of (1) and (2) have been provided, e.g. by researchers such as Brown (1928); Escoffier (1940, 1975); Keulegan (1951, 1967); Baines (1958); van de Kreeke (1967); Mota Oliveira (1970); Shemdin and Forney (1970); Dean (1971); Huval and Wintergerst (1973); King (1974); Goodwin (1974); Freeman, Hamblin and Murty (1974); King and Shemdin (1975); Mehta and Ozsoy (1978); Escoffier and Walton (1979), Walton and Escoffier (1981). Where only the study of Escoffier and Walton (1979) give the solutions with tributary inflow by solving simultaneously a system of two non-linear equations using trial and error method.

For obtaining analytic solutions of (1) and (2) taking into account the contribution of tributary inflows, some simplified assumptions should be applied. The assumptions include neglecting bay and ocean current velocities, neglecting spatial variations of water surface in bay, flow area in the channel is constant, vertical ocean tide and flow velocity in the channel are sinusoidal. The simplified form of the system of equations (1) and (2) with tributary inflow can be obtained as

$$A_b \frac{d\eta_b}{dt} - Q_f - A_c u = 0 \tag{4}$$

$$\eta_b = \eta_o - \frac{L_c}{g}\frac{du}{dt} - F\frac{|u|u}{2g} \tag{5}$$

where subscripts o, b and c denote qualities in the ocean, bay and channel, respectively. Q_f is the rate of inflow discharging into the bay. Parameter F is referred as the overall impedance of the inlet by O'Brien and Clark (1974).

Equation (5) indicates that quadratic friction causes the tide in the bay to depart from sinusoidal as recognised by Keulegan (1967). To get the analytical solutions for the systems of equation (4) and (5), the non-linear friction term of (5) should be linearised. For example, Mehta and Ozsoy (1978) used Fourier expansion neglecting higher harmonics while Walton and Escoffier (1981) linearised the friction term using the method introduced by Lorentz (1926) on the equivalence of tidal work.

To obtain the solutions of (4) and (5) analytically, the following linearization of the quadratic friction term with tributary flow is used

$$|u|u \approx \frac{8(\hat{u}+u_f)}{3\pi}u \tag{6}$$

By assuming ocean water level and flow velocity in the channel are sinusoidal

$$\eta_o = a_o \cos(\omega t - \phi) \tag{7}$$

$$u = \hat{u}\cos(\omega t) + u_f \tag{8}$$

Phase lead ϕ is used to represent the phase difference between current in the channel and vertical tide in the ocean.

By using approximation (6), assumptions (7) and (8), the following equation can be derived from (4) and (5)

$$\left[\frac{A_b}{A_c}\omega a_o \sin\phi - (1-\alpha^2)\hat{u}\right]\cos(\omega t) + \left[\frac{A_b}{A_c}\left(\beta\hat{u} - a_o\cos\phi\right)\omega\right]\sin(\omega t) + \left[-\frac{Q_f}{A_c} - u_f\right] = 0 \tag{9}$$

with

$$\alpha = \omega\sqrt{\frac{A_b}{A_c}\frac{L_c}{g}} \tag{10}$$

is the inertia coefficient (van de Kreeke, 1988)

and

$$\beta = \gamma(\hat{u}+u_f) \tag{11}$$

where $$\gamma = \frac{4F}{3\pi g} \tag{12}$$

Because (9) holds for any t so we have

$$\sin\phi = \frac{\delta}{a_o}\hat{u} \tag{13}$$

$$\cos\phi = \frac{\beta}{a_o}\hat{u} \tag{14}$$

and $$u_f = -\frac{Q_f}{A_c} \tag{15}$$

where $$\delta = \frac{1-\alpha^2}{\omega}\frac{A_c}{A_b} \tag{16}$$

The phase lead ϕ and $\hat{u}$ can be obtained from (13) and (14) as follows

$$\phi = \arctan\frac{\delta}{\beta} \tag{17}$$

and

$$\frac{\delta^2}{a_o^{\,2}}\hat{u}^2 + \frac{\beta^2}{a_o^{\,2}}\hat{u}^2 = 1 \tag{18}$$

Notice that β is depended on $\hat{u}$ as in (11) so we have a quaternary equation of only $\hat{u}$

or $$\hat{u}^4 + 2u_f\hat{u}^3 + \mu\hat{u}^2 - \nu = 0 \tag{19}$$

with $$\nu = \left(\frac{3\pi g a_o}{4F}\right)^2 = \frac{a_o^{\,2}}{\gamma^2} \tag{20}$$

and $$\mu = \nu\left(\frac{\delta}{a_o}\right)^2 + u_f^{\,2} = \frac{\delta^2}{\gamma^2} + u_f^{\,2} \tag{21}$$

Value of $\hat{u}$ can be solved by iterations, for example, from (18) by

$$\hat{u} = \frac{a_o}{\sqrt{\delta^2 + \beta^2}} \tag{22}$$

or by using Newton-Raphson iteration technique using following expressions:

$$\hat{u}_{(k+1)} = \hat{u}_{(k)} + \Delta\hat{u}_{(k)} \tag{23}$$

with $$\Delta\hat{u}_{(k)} = -\frac{\hat{u}_{(k)}^4 + 2u_f\hat{u}_{(k)}^3 + \mu\hat{u}_{(k)}^2 - \nu}{4\hat{u}_{(k)}^3 + 6u_f\hat{u}_{(k)}^2 + 2\mu\hat{u}_{(k)}} \tag{24}$$

with

The iteration can stop when $\left|\Delta\hat{u}_{(k)}\right|$ is very small. Normally, it needs 4 or 5 iterations to converge with a high accuracy.

When $\hat{u}$ is determined, the phase lead ϕ can be calculated using (17). It is can be seen that both phase lag and amplitude of the flow velocity in the inlet are depending on the rate of inflow.

The equation for calculating bay surface level η_b is derived from (5) as

$$\eta_b = a_b \sin(\omega t) - \beta u_f \tag{25}$$

with

$$a_b = \frac{A_c}{A_b}\frac{\hat{u}}{\omega} \tag{26}$$

Amplitude and phase lag of water level in bay depends also on the inflow to the bay. For a small and deep bay, the difference in phase of water level in the bay and flow velocity in the inlet is ½π as shown in (8) and (25). The phase difference of water levels in the bay and the ocean is ½π+ϕ as shown in (7) and (25). The phase lead ϕ depends on the rate of inflow, tidal frequency, area of the bay, cross section, inertia and friction of the channel as in formulae from (11) to (17).

3.2. Analytic solutions without tributary inflow

In case of no fresh discharge to the bay, $u_f = 0$, the solution for $\hat{u}$ from (19) becomes

$$\hat{u} = \left[\left(\frac{\mu^2}{4} + \nu\right)^{\frac{1}{2}} - \frac{\mu}{2}\right]^{\frac{1}{2}} \tag{27}$$

where

$$\mu = \frac{\delta^2}{\gamma^2} \tag{28}$$

The tidal water level amplitude in bay derived from (26) and (27) is

$$a_b = \frac{1}{\omega}\frac{A_c}{A_b}\left[\left(\frac{\mu^2}{4} + \nu\right)^{\frac{1}{2}} - \frac{\mu}{2}\right]^{\frac{1}{2}} \tag{29}$$

with

$$K = \frac{1}{a_o \omega}\frac{A_c}{A_b}\sqrt{\frac{2ga_o}{F}} \tag{30}$$

is the repletion coefficient (Keulegan, 1967).

Equation (29) can be rewritten as

$$a_b = a_o \left\{ \frac{\left[\left(1-\alpha^2\right)^4 + 4\left(\frac{8}{3\pi}\right)^2 \frac{1}{K^4}\right]^{\frac{1}{2}} - \left(1-\alpha^2\right)^2}{2\left(\frac{8}{3\pi}\right)^2 \frac{1}{K^4}} \right\}^{\frac{1}{2}} \tag{31}$$

This expression is identical to the solutions of Mehta and Ozsoy (1978) and Walton and Escoffier (1981) including inertia. Walton and Escoffier (1981) presented the solution respecting to the damping coefficient D:

$$D = \frac{1}{\alpha^2 K^2} = \frac{F}{L_c}\frac{A_c}{A_b}\frac{a_o}{2} \tag{32}$$

3.3. Stability analysis for tidal inlets of Hue

Morphological changes of a tidal inlet are the result of the interaction between sediment transport entering the inlet and sediment transport capacity of inlet currents. The balance of this interaction defines the stability of the inlet. The transport capacity of the inlet currents depends on the flow velocity in the inlet, therefore, depends on the inlet cross sectional area. Escoffier (1940) introduced a hydraulic stability curve, referred as the Escoffier diagram, on which maximum flow velocity is plotted against cross sectional flow area. According to this diagram, an inlet is hydraulically stable if its cross sectional area is larger than a critical flow area. An inlet having a cross sectional area smaller than this value is termed hydraulically unstable. According to van de Kreeke (1985), the transport capacity of the inlet currents can be best characterised by the maximum bottom shear stress during a tidal cycle, $\hat{\tau}$. Based on Escoffier diagram, van de Kreeke (1985) used maximum bottom shear stress instead of maximum flow velocity for stability analysis. Later this approach was extended to multiple inlet systems (van de Kreeke, 1990[a], 1990[b]). For equilibrium conditions, the value of actual shear stress $\hat{\tau}$ equals the equilibrium shear stress $\hat{\tau}_{eq}$. The value of the actual shear stress is obtained from

$$\hat{\tau} = \rho f V_{\max}{}^2 \qquad (33)$$

The value of maximum flow velocity V_{max} can be determined by solving the system of equations (1) and (2). For analysis purpose, V_{max} is calculated based on the analytical solution (19) or (23) taking into account contribution of tributary inflow. The parameters of the inlets for analysis taken from observations and numerical model are listed in Table 6. Based on the observations and numerical model results, the relationship of tidal prism versus cross sectional area of the inlets rather coincide with those from van de Kreeke (1990[b]) as can be seen in Figure 2. As introduced by van de Kreeke (1990[b]), the equilibrium shear stress can be calculated from tidal prism and inlet cross sectional area

$$\hat{\tau}_{eq} = \rho f V_{\max}^2 = 466 f C_K^2 A_C^{0.062} \qquad (34)$$

Parameter	Thuan An inlet	Tu Hien inlet
Bay surface area, A_b (km^2)	104.2	112
Inlet cross-sectional area, A_c (m^2)	4000	600
Effective inlet channel length, L_c (m)	500	1000
Ocean tidal amplitude, a_o (m)	0.25	0.30
Tidal period, T (hours)	12.4	12.4
Manning's roughness, n	0.025	0.025
Coefficient C_K	0.9	0.8
Friction coefficient, f	0.006	0.010
Inertia coefficient, α	0.16	1.06
Equilibrium stress, τ_{eq} (N/m^2)	3.69	4.34

Table 6. Parameters of the inlets

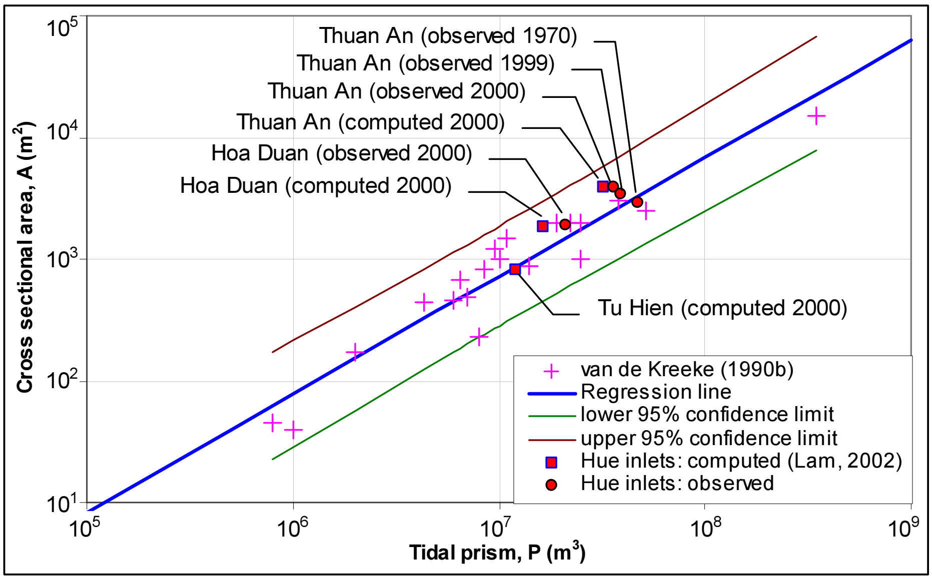

Figure 2. The relationship of tidal prism and cross sectional area

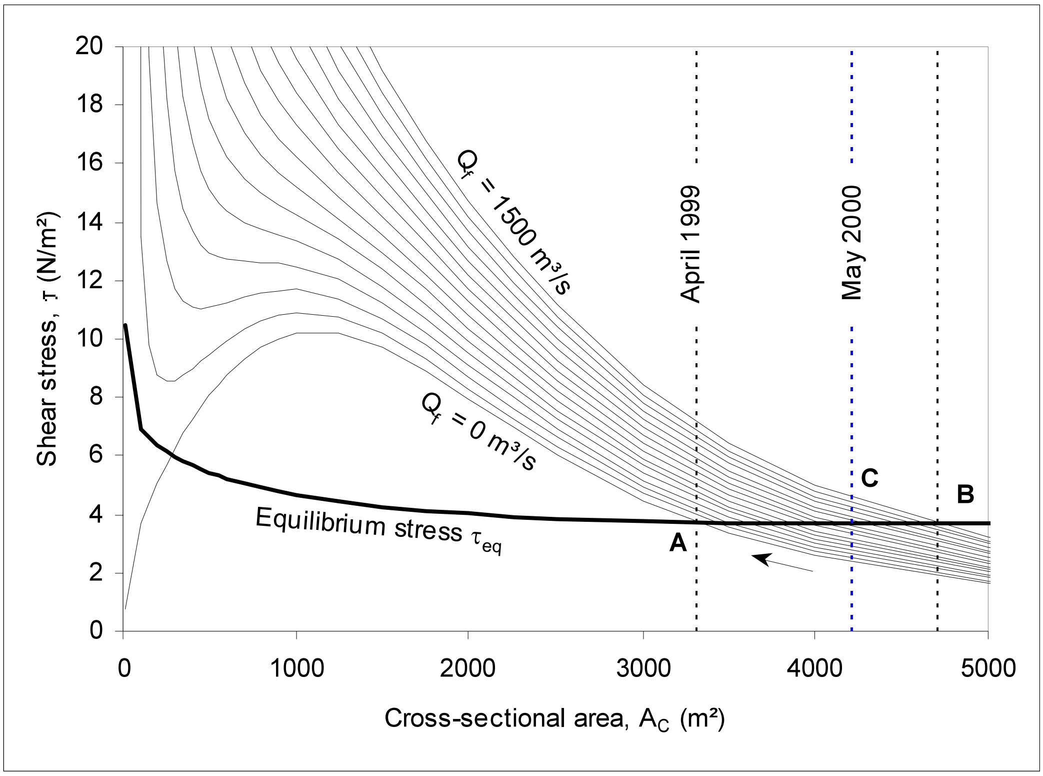

Figure 3. Closure curves and equilibrium stress curve for Thuan An inlet

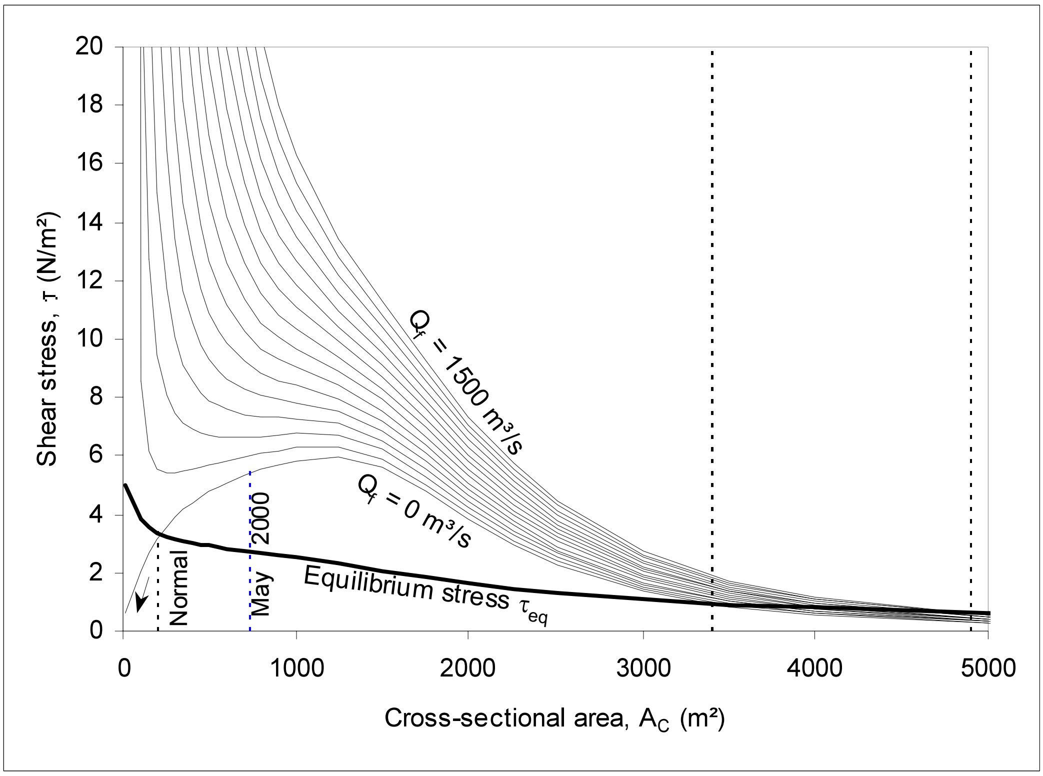

Figure 4. Closure curves and equilibrium stress curve for Tu Hien inlet

With different values of inlet cross sectional area and inflow discharge, the closure curves and equilibrium shear stress curves calculated for the two inlets are shown in Figure 3 and Figure 4. In Figure 3, we can see the range of stable cross sectional area of the Thuan An inlet is from 3300 m^2 to 4700 m^2 corresponding to the range of inflow from 0 to 1500 m^3/s indicated by the section from point A to point B. It is can be seen that the Thuan An inlet is normally at the stable equilibrium condition, even with small inflow discharges (point A – situation of April 1999). After the historical flood of November 1999, the inlet was widened and deepened (point C – situation of May 2000). The inlet tends to return to the stable equilibrium position in the direction of A if the inflow is smaller than the order of 1000 m^3/s.

In contrast, the Tu Hien inlet is normally at the unstable equilibrium condition as in Figure 4. Because inflow discharge of this inlet is small, according to Escoffier (1940) diagram, the inlet will easily to be closed if there is any deviation from this position to reduce its cross sectional area. After the flood of November 1999, the inlet was widened as can be seen in Figure 4 to the position of May 2000. But this position is very far away from the stable equilibrium compared with the unstable equilibrium point.

CONCLUSIONS

Numerical models can be successfully applied to get a better understanding on hydrodynamic characteristics of a complex tidal inlets system as well as the effects of the governing factors. The models can help to investigate different alternatives and to determine the design parameters in the planning process concerning to navigation and flood evacuation. Empirically, tidal inlet stability can be evaluated based on Bruun's criteria using values computed by numerical models or from observations. It is can be done using the approach of van de Kreeke (1990[a], 1990[b]) with the analytical solutions for tidal inlet hydraulics have been derived taking into account both inertia term and tributary inflow. The analytical solutions provide a quantitative estimation on the inlet hydraulics for analysis. Based on that, the consideration of inlet stability using closure curves with tributary inflows can be accomplished.

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NOTATION

The following symbols are used in this paper:

A_b = water surface area of bay;
A_c = cross-sectional area of flow in inlet channel;
a_b = bay tide amplitude;
a_o = ocean tide amplitude;
B = cross-sectional surface width;
B_b = surface width of bay;
C = Chezy roughness coefficient;
F = overall impedance of inlet;
f = Darcy-Weisbach friction coefficient;
g = acceleration of gravity;
h_f = head loss;
k_{en} = coefficient for entrance loss;
k_{ex} = coefficient for exit loss;
L_b = longitudinal length of bay;
L_c = effective length of inlet channel;
m = coefficient for combined entrance and exit losses;
Q = flow discharge;
Q_f = tributary inflow to bay;
R = hydraulic radius in inlet gorge;
V_{max} = maximum cross-sectional averaged flow velocity in inlet;
x = longitudinal co-ordinate;
t = time;
u = flow velocity in inlet channel;
u_f = flow velocity contributed by inflow;
$\hat{u}$ = amplitude of tidal induced flow velocity in inlet;
ϕ = phase lead between tides in inlet and in sea;
η = elevation of water surface respects to datum;
η_b = elevation of water surface in bay;
η_o = elevation of water surface in ocean;
π = Pi number;
ω = tidal frequency.

Subscripts

b = bay;
c = inlet channel;
f = river inflow;
o = ocean.