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The Classification of Estuary and Tidal Propagation Characteristics in the Gyeong-Gi Bay, South Korea

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ABSTRACT

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The barotropic tidal characteristics of Gyeong-Gi Bay (west coast of Korea) were studied with using observed tidal elevation data and numerical model. The estuary consists of 3 main tidal channels and freshwater discharges by three rivers through which major tidal flow and river discharge meet each other. It was found that the type of this estuary can be characterized by different tidal propagation pattern along those three main channels. Although three major channels show a hyper-synchronous type in general, the maximum tidal amplitude were observed at different channel. Numerical model study was performed to find out major physical factors that influence channel-dependent tidal propagation. Model results showed that the important factor for the change of tidal amplitude and phase along each channel were bottom friction, river discharge and tidal flat existences. On the other hand the river discharge modifies phase lag at high and low tide. Model experiment showed that the topographical characteristic was the most important factor for the generation of hyper-synchronous pattern in Gyeong-Gi Bay (GGB). The quantitative method shows that classification of the type. At Yeumha channel is more frictional than Seokmo channel.

ADDITIONAL INDEX WORDS: *Tidal wave propagation, Estuary classification, hyper-synchronous channel, Gyeong-Gi Bay, Yeumha channel, Seokmo channel*

INTRODUCTION

Description of Gyeong-Gi Bay

The study area, Gyeong-Gi Bay (Figure 1), located along the western coast of Korea is a tidally-dominated semi-enclosed bay. The bay is macro-tidal, with tidal range of 8m and 3.5m during periods of spring and neap tides, respectively. The predominant tidal constituent is semi-diurnal component in the GGB. It contains a complex coastal line and many islands. There are 3 major rivers and channels in the Gyeong-Gi Bay (Im, 1999; Kim, 1997; Park *et al*., 2002; Yoon, 2006).

The tidal wave propagates through the Yeumha (Y), Seokmo (S) and Kyodong (K) channel. Most of the freshwater input is the discharges from the Han River, Imjin and Yesung River. The averaged wet season discharge rate is 1,573 CMS and the normal season is 403 CMS, daily 527 CMS at Han River (Figure 2). (Im, 1999) and (Park *et al*., 2002) suggested river discharge rate is 1:2:6 considered width channel at each river.

Importance of channel study

Estuaries can be characterized by their geomorphology, their pattern of salinity stratification and mixing between freshwater and seawater (Hansen and Rattray, 1966). The interaction between tidal wave propagation and the geomorphology of the estuary is important factor for characterizing the type of estuary (Dyer, 1997).

The estuary type can be categorized by the balance of estuary convergence and frictional effect. Three types of estuaries are determined by the relative magnitude of the two influences. The influence was controlled by numerous physical factors including the river discharge, intensity of tide, tidal current, wind energy, the composition of the sediments, topography and geometric of channel (Dyer, 1997; Friedrichs and Aubrey, 1994).

The tides in the Gyeong-Gi Bay (GGB) mainly come (from tidal propagation) through the Y, S and K channel and also it is influenced by the river discharges. Moreover, the type of tidal wave propagation is affected by physical factors which are geometry, bottom topography and river discharge in the GGB. It is important that the interaction of river flow, tide, tidal current and basin morphology determine the type of tidal wave propagation.

The objective of this study was to characterize variation of tidal wave propagation at each channel and to find out the major physical factors based on the observation data and numerical modeling results.

DATA AND METHODS

Observation Data

The NORI (National Oceanographic Research Institute) had carried out field observations on tide in the GGB. The hourly measured tidal elevation data during 1 year, 2008 from NORI were used for harmonic analysis. The component amplitude and

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phase were obtained using the TIRA tidal analysis program for the data whose duration was around 1 month.

The main component was M_2 among 4 major constituent. The co-tidal and co-range lines of the 4 major constituents of previous research (Im, 1999; Kim, 1997; Park *et al.*, 2002; Yoon, 2006) showed that M_2 is usually the dominant tidal constituents in the GGB. Figure 2 shows the M_2 tidal harmonic along the Y and S channel. Plots revealed a change in the character of the tidal wave from the GGB mouth to the end of the channel.

The propagating in the estuary channels, M_2 tidal amplitude increased gradually from GBB mouth point but amplitude of M_2 decayed rapidly in the specified station of the channel. The station of decrease is different at each channel. The different points are channel mouth (SY, at Y channel) and channel end (CH, at S channel).

3 major channels show a hyper-synchronous type in general, according to (Dyer, 1997) diagrammatic representation (Figure 2). This classification shows the relative importance between geometric convergence and bottom friction for tidal elevation. However, there could be more important physical factors affecting the inflection of the tidal elevation curve other than bottom friction and geometric convergence. We tried to find out other physical factors that could affect the tidal propagation through numerical model results.

Model

The EFDC (Environmental Fluid Dynamics Computer code) used in this study has been widely applied to coastal ocean and estuary. Because EFDC uses orthogonal curvilinear coordinate in the horizontal, it is possible to make detail grid structure of model in the coastal channel and estuary. It is also possible to simulate the tidal flat using mass conservation method (Hamrick, 1992). The detailed model is presented in the (Hamrick, 1992).

An orthogonal curvilinear grid was designed to the model domain in 23,802 points, with variable resolution of 20 m by 20 m within the estuary and about 2 km by 2 km around offshore. Initial value of tidal forcing at the open boundary and river discharge rate of normal condition were obtained from freshwater discharge at Han River.

The calibration of model results was previously studied by (Yoon, 2006). In Figure 3, the comparison between measurement and model prediction is shown. The model results were reasonably well matched with the field measurement data in which amplitude and phase averaged error were lower than 10%.

To find out the relative importance of the many physical factors other than geometric convergence and bottom friction, so-called sensitive analysis was performed using different input parameters. By changing the value of topography, bottom friction coefficient and river discharge, it was tried to find the most sensitive factors that causes the inflection of tidal elevation curve. The list of the data sets is shown in Table 1.

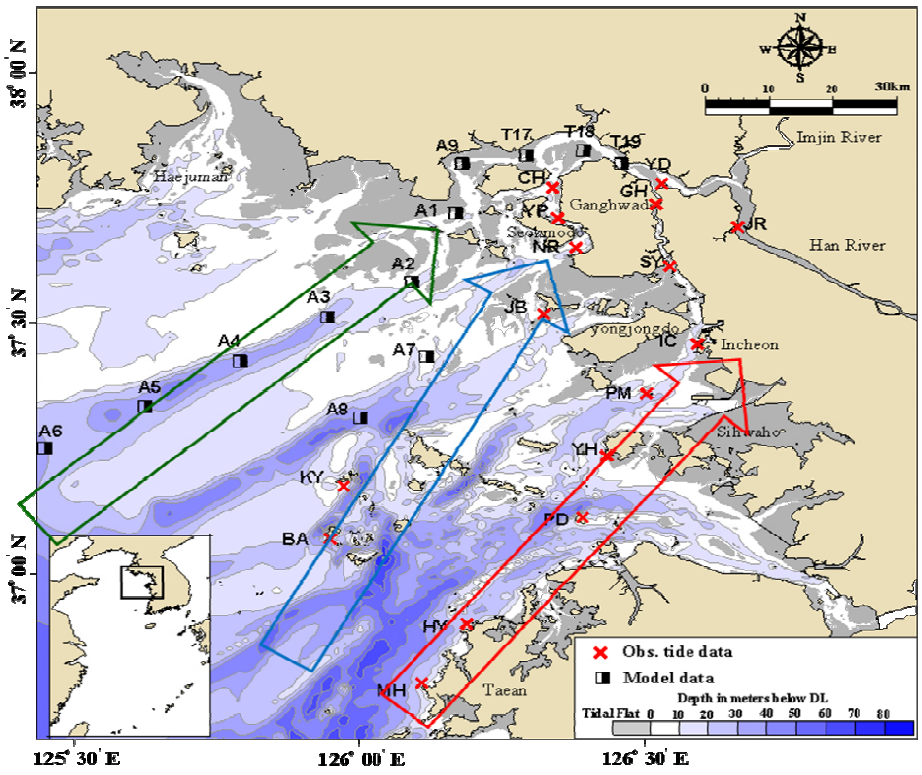


Figure. 1. Map of Gyeong-Gi Bay and Han River Estuary in the South Korea. Tide data stations of NORI (National Oceanographic Research Institute, x mark) and numerical results (◨ mark). The red, blue and green arrow indicated Yeumha (Y), Seokmo (S) and Kyodong (K) channel, respectively.

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Table 1: Numerical model simulation case

Experiment	Open boundary	Depth change	Bottom friction coefficient	River discharge
Base	M_2, S_2, K_1, O_1	Base	0.003	Normal condition
Case 1		Tidal flat +4(m)		
Case 2		Tidal flat -4(m)		
Case 3		Base	0.01	
Case 4		Base	0.001	
Case 5		Whole grid -1m		
Case 6		Whole grid +1m	0.003	Wet condition
Case 7		Base		Normal condition

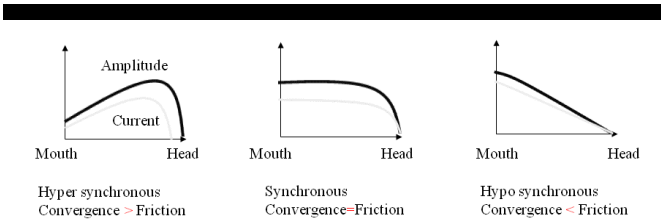


Figure 1. Diagrammatic representation of the modification of tidal range and current velocity amplitude in estuaries with varying geometries

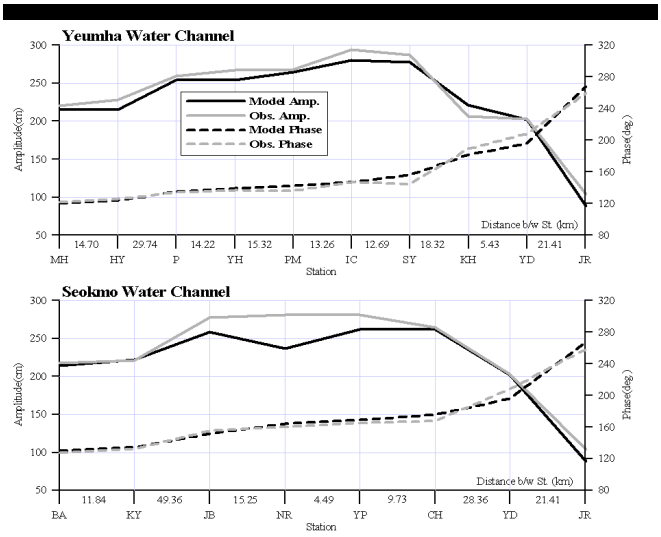


Figure 3. Tidal wave propagation of M2 amplitude and phase at channel YM and SM channel. Black line is model results and Gray line is observation data. The stations refer to Figure 1.

RESULTS

Change in Topography

The effects of increasing and decreasing the depth increased and reduced M_2 amplitude, respectively. The difference was caused by the fact that the increase/decrease in water depth allows the propagation of the tidal wave to be less/more hindered by the bed friction. These differences are greater in the upstream. Though the amplitudes were changed along the channel, however the type of propagation patterns were not changed much (Figure 4).

Change in Bottom Friction coefficient

In the EFDC, bottom friction term was used as bottom friction height coefficient. When the bed friction coefficient was set to one third of the base value (0.001), the amplitude of tidal constituent towards upstream tended to increase. Increasing the bed friction by factor of 3 (to 0.01) generally has the opposing effect of reducing the amplitude (Figure 5). At the southward station of IC (Y channel, look at the Figure 1), decay rate of amplitude is smaller than estuary stations (KH, YD and JR).

Change in Freshwater Discharge

Yearly averaged river flows of normal condition in the Han River are 403 CMS. Comparison value for river discharge of 5,000 CMS was used in the sensitivity test. In the upper estuary, mean sea level was slightly raised and tidal amplitude is slightly decreased with a small phase lag. When river discharge is 5,000 CMS, the change of amplitude with model results only appeared in the upper estuary.

The river discharges modified the tidal range and phase (Figure 6). As river discharge increasing, it was seen that the tidal range decrease. The time of low water has been significantly delayed, and high water occurs slightly earlier. At neap tide, change of tidal range and phase difference is smaller than spring tide (Figure 6).

Change in Area of Tidal Flat

Effect of tidal flat is limited to local ones. Amplitude of YH station (Y channel) and JB, NR station(S channel) is rapidly decayed. Tidal flat affects only in shallow water region.

Geometric Effects

Model resulted variation with difference of amplitudes at each case. However the type of tidal propagation pattern, hyper synchronous was not transformed. Even if the physical factors were important, channel geometric is more important for tidal propagation pattern, peak point and decay rate.

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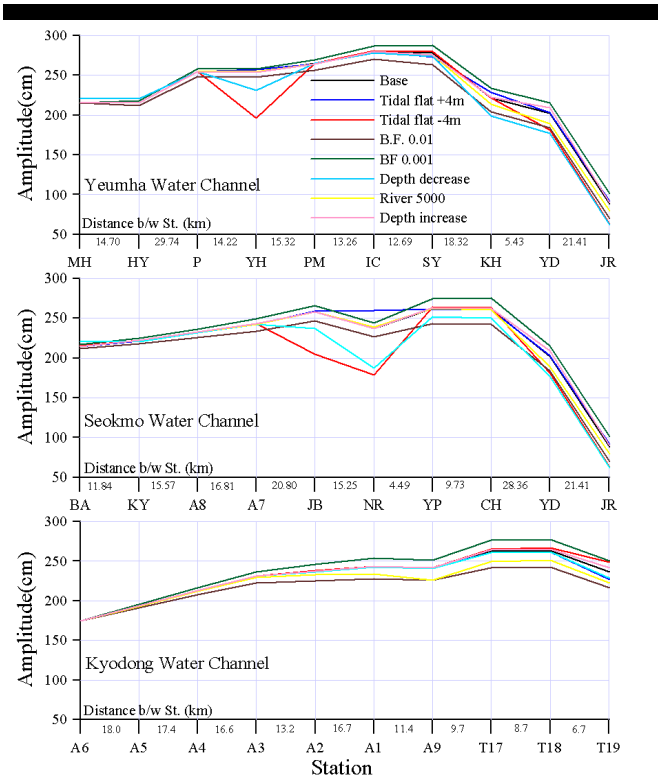


Figure 4. Tidal wave propagation according to model cases for the three channels. The model cases refer to Table 1.

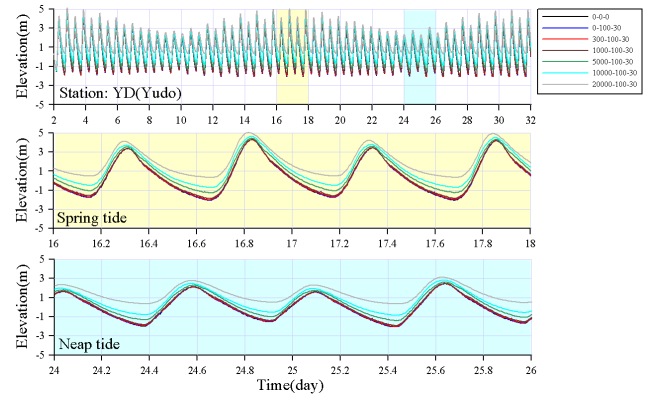


Figure 5. Numerical results according to river discharge condition at YD station. River discharge condition is Han, Imjin and Yesung River. Unit is CMS

The Quantitative Method

(Savenije, 2005) suggest that classification of estuaries should be based on two parameters, the estuary shape number and friction scale. He shall derive a relation for tidal amplification or damping, analytical solution of the St. Venant's equations yields:

$$\frac{h}{H}\frac{dH}{dx}\left(1+\frac{gH}{2cv\sin\varepsilon}\right)=\frac{h}{b}-f\frac{g}{C^2}\frac{v\sin\varepsilon}{c} \qquad (1)$$

where, h is the tidal-average estuary depth (m), H the tidal range (m), g the acceleration due to gravity (9.81 m/s^2), c the observed celerity of the tidal wave (m/s), v the amplitude of the tidal velocity (m/s), ε the phase lag in radians between high water (HW) and high water slack (HWS), b the length scale of the exponential width variation (m), C Chezy's roughness ($m^{0.5}/s$) and f a friction factor accounting for the difference in average water depth during ebb and flood flow.

From Equation 1, it can be seen that in an estuary where there is no tidal damping or amplifications:

$$\frac{1}{b}=f'\frac{v\sin\varepsilon}{\bar{h}c}=\frac{R'}{c} \qquad (2)$$

where, f is the adjusted friction factor, $sin(\varepsilon)$ is type of tidal wave (1 = progressive, 0 = standing wave), the parameter R' is a friction parameter, if convergence ($1/b$) is larger than friction (R'), the tidal wave is amplified; if it is smaller, then it is damped.

As a result of amplitude ratio, channel in the GGB can be adequately described as having a prismatic channel. Therefore, we use is made of a cross-sectional area that varies exponentially with distance. Since the positive x-direction is chosen in upstream direction, the formula reads (Savenije, 2005):

$$A=A_0\exp\left(-\frac{x}{a}\right) \qquad (3)$$

where, A_0 is the cross sectional area at x=0. The parameter a is defined as the cross-sectional convergence length. Similarly the assumption that the width varies exponentially yields the equation:

$$B=B_0\exp\left(-\frac{x}{b}\right) \qquad (4)$$

Combination of Equation 3 and 4 leads to an expression for the depth:

$$h=h_0\exp\left(-\frac{x(a-b)}{ab}\right) \qquad (5)$$

Figure 6 show the geometry of Y and S channel of which measurements of A, B, and h are available, plotted in a semi-log scale. The data of cross-sectional area are the result of the model. It can be clearly matched that the trends in cross-sectional area and the width conform very neatly with Equations 3 and 4. In table 3 provides values of a number of typical parameters. Comparison of two channels, Y channel is frictional channel and S channel is more convergence channel.

This results show that Y and S channel is amplified channel. Because Y channel is more frictional (or topography effect) channel, the maximum M_2 amplitude point is earlier appeared. Due to the short channel or/and the amplitude to depth ratio, at Y channel shows the phase lag of tidal current to elevation is nearly out of phase.

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Table 1: Characteristic values of Yeumha (Y) and Seokmo (S) channel.

Channel	A0	B0	h	a	b	1/b	R'/c	1/b : R'/c
Y	46954	3632	12.9	14.716	22.677	44.1	8.7	0.21
S	331288	7433	16.85	250.36	25.375	39.4	2.0	0.05

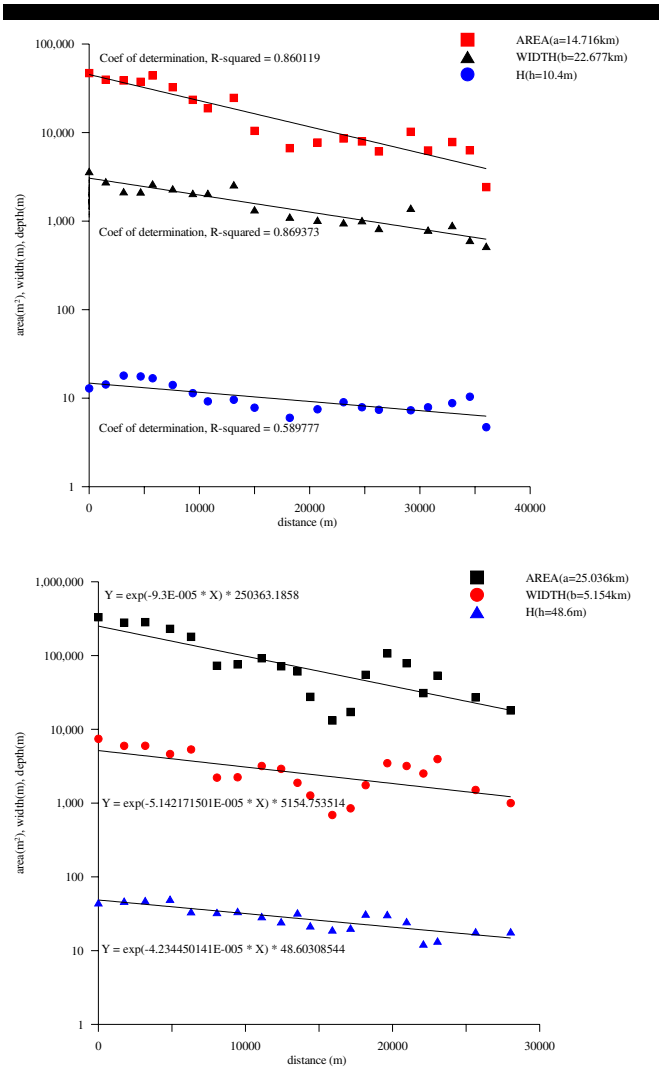


Figure 6. Semi-logarithmic plot of the geometry of the Han River Estuary, Yeumha channel (up), Seokmo channel (down): *A* is the cross-sectional area in m^2, *B* is the width in m, *h* is the cross-sectional average depth in m.

CONCLUSION

To understanding the barotopical tidal characteristic of Han-river estuary (HRE), we are studied with field measurement and numerical simulation. The Gyeong-Gi Bay (GGB) connected 3 major channels and 3 freshwater discharges. Analysis of M_2 amplitude is showed that the pattern of tidal wave propagation is showed hyper synchronous type but the location of maximum amplitude is different.

Numerical model study is performed to find out the major physical factors for the channel-dependent tidal propagation. Model results show that the important factor for the change of tidal amplitude and phase along each channel is bottom friction, compared with river discharge and tidal flat existence. Amplitude is changed along the channel however the type of propagation pattern is not transform at any model case. Model experiment shows the geometric characteristics of HRE is the most important factor for the generation of hyper-synchronous pattern

The quantitative method in this paper shows that classification of the estuary type in the GGB. Balancing between convergence and friction effect is an important parameter. Difference channels appear the trend of hyper-synchronous type. However maximum amplified location is different according to the rate of the balancing. The ratio of *1/b* (convergence term) over *R'/c* (friction term) is 1:0.21 and 1:0.05 at Yeumha (Y) channel and Seokmo (S) channel, respectively. At Y channel, more frictional channel, maximum position is located further upstream to the head.

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