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Tidal asymmetry and flood/ebb dominance around the Yeomha channel in the Han River Estuary, South Korea

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ABSTRACT

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Several field measurements were conducted to study the characteristic of tidal asymmetry and flood /ebb dominance in the Han River Estuary (HRE), Gyeonggi Bay (GGB) on the western coast of Korea. Tidal currents at this area were simultaneously measured at four stations during the winter season, and previously observed tidal data were analyzed. The HRE is macro-tidal coastal zone with a mean depth less than 12m and a tidal range varying 3.5 (neap) to 8.0m (spring). The tidal amplitude to depth ratio is large enough to generate non-linearity in the tidal wave. The relative phases ($2M_2$-M_4) are represented flood dominant using harmonic constants from previously observed tidal data. However, there exists a limitation to apply this kind of method for tidal asymmetry to an area in which freshwater discharge is assumed to be relatively small. Statistical analysis of tidal current data in HRE indicated that ebb current is stronger than flood. Analysis of slack time of tidal current showed that ebb duration time is longer than flood. To find the mechanisms for the features of ebb dominance, a tidal curve was reconstructed the major component (M_2), in combination with the shallow water component (M_4). This tidal curve presented domination of flood current. However, these curves showed ebb dominance after incorporating the non-harmonic components that included ebb-directional flow, calculated from tidally-averaged current. The results show that the flood current is overcome by enhanced ebb directional effect, which occurs around the Yeomha channel in the HRE owing to the seaward effect of averaged flow. These ebb directional current could be produced by freshwater and nonlinear effects of long-term variation of sea surface slope due to estuary non-linearity.

ADDITIONAL INDEX WORDS: *Tidal asymmetry, Flood and Ebb dominance, Non-linear effect, Freshwater, Han River Estuary.*

INTRODUCTION

The nonlinear effects on tide and tidal current that occur near estuaries and coastal areas are due to the comprehensive effect of bottom friction, fresh water, depth, topology, and a variety of other causes. Such nonlinear effects transform the tides and currents of estuaries and coastal areas to an asymmetrical form (Ippen and Harleman, 1966; Pugh, 1987; Aubrey and Speer, 1985; Blanton *et al*., 2002; Kang and Jun, 2003). The asymmetry of tides and currents is caused by the relative duration of flood and ebb phases, as well as differences between the maximum and average flow; such imbalance determines the volume and travel distance of sediments and suspended materials (Aubrey, 1986; Dronker, 1986). It also has an effect on the spatial and temporal movement of the estuarine turbidity maximum zone, which controls the biomass and productivity of plankton in the area (Cloern, 1987). Understanding tidal asymmetry is critical to identifying the erosion and accumulation characteristics at tidal flat resulting from the seawater circulation and sediment movement mechanism caused by the tidal current variations near estuaries.

Much research has been conducted on the flood- and ebb dominance (based on the depth and channel of tidal flat), and the movement of sediments (Aubrey and Speer, 1985; Speer and Aubrey, 1985; Friedrichs and Aubrey, 1988). Friedrichs and Aubrey (1988) decomposed the water level data of 26 estuary areas using the least-squares method, to obtain the amplitudes and phases of the M_2 and M_4 tide components. Using the obtained amplitudes and phase values, Friedrichs and Aubrey (1998) proposed that, as the M_4/M_2 amplitude ratio increases, the tidal asymmetry increases owing to shallow-water constituents. In addition, it was found that the relative phase difference $2M_2$-M_4 can indicate a flood-dominant environment if the relative phase difference is 0°~180°, and ebb-dominant if 180°~360°.

Because the traditional method, mentioned above, is based on water level data rather than velocity, it is inappropriate for the analysis of sediment movement (Robin and Davies, 2010). Also, because the research area is not greatly influenced by freshwater, there are limits to the application of this method in areas where freshwater inflow is strong (Seim *et al.*, 2006). Thus, in areas where freshwater effects are abundant and continuous, such as estuaries or even estuary areas with tidal dominance, the traditional method may not accurately determine whether the ebb or flood is dominant. Additionally, while the dominance of the ebb/flood of tide and currents are related, the tide and tidal current dominance may not always be consistent, because currents are influenced more by tidal flat, depth, and topological characteristics than are tides. Therefore, it is important to compare and check

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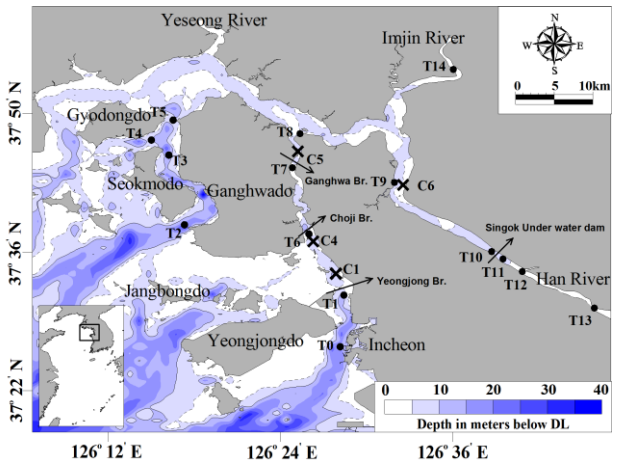


Figure 1. Topographic map of the study area, showing 5m (dotted line) and 10m (solid line) isobaths. The circle (●) and (x) symbols denote the tide and tidal current stations, respectively. Arrows (→) indicate the location of bridge and underwater dam.

results using analysis based on tidal harmonic constants, and observed current data.

This work uses M_2 and M_4 tidal constituents collected near the HRE and GGB to analyze tidal transformation properties and the flood/ebb dominance. The ebb dominance phenomenon and mechanism were proposed using the analysis of tidal phase differences and observed tidal current data around the Yeomha channel in the HRE, GGB.

STUDY SITE

The HRE has an average spring range of 8.0m and an average neap range of 3.5m at the Incheon tidal gauge. It has a complex coastal landform in which channels and islands are connected. The widely developed tidal flats, formed because of the large tidal range and gradually topographical gradients, causes complex seawater circulation (Park *et al*., 2002). The tidal wave characteristics of each channel are unique (Woo and Yoon, 2011). Kim *et al*. (2010) suggested there was ebb in depths owing to the influence of freshwater. Song and Woo (2011) presented the spring–neap variability of long-term tide components by analyzing tidal current observations near the Yeomha channel. Tide and tidal current changes are unique for each channel, and inflowing fresh water has different seasonal effects. Therefore, further research is required using not only the traditional methods, such as relative phase, for tidal asymmetry but also on the flood/ebb dominance using tidal current data.

METHODS

Figure 1 shows the location of the tidal station of HRE and GGB, and the location for water level observations from KHOA (Korea Hydrographic and Oceanographic Administration, 2002). Using the Tidal Analysis Software Kit (TASK; Proudman Oceanographic Laboratory, UK), we extracted the harmonic constant of the tidal station data provided by the KHOA and water level data from the HRFCO (Han River Flood Control Office). From November to December 2005, RCM series equipment was moored on surface buoys at four fixed points of HRE (Figure 1; C1 and C4~C6) to record the water velocity every 10 minutes at 1.0~1.5m below sea surface level. The U (east–west direction) and V (south–north direction) components of the raw observed velocity data were linearly transformed into a new coordinate system of major and minor directions. The dominant current component was extracted using PCA (Principal component analysis), as proposed by Preisendorfer and Mobley (1988), and was used in statistical analysis and calculation of 'slack water' time. The major component of the current was harmonically analyzed, and the amplitude ratio, phase difference, and current asymmetric rate were computed using the harmonic constant value of the main constituent.

The observation periods differ between each tidal current site, but there are 16 days during which the observations overlapped (December 2 to 17). The method has the advantage that the influence of fresh water, and weather influences such as wind, can be considered simultaneously because the current data were observed during the same period. The spatial change during the same time period at four of the stations from C6, located at the lower Singok underwater dam, and following the Yeomha channel up to C1 (near Yeongjong Bridge), can also be considered. Although the observed data is limited to the surface layer and the concurrent time series is less than 30 days, it is sufficient to understand the characteristics of tidal change and the flood/ebb dominance considering the simultaneity and focus of tidal observation.

RESULTS

Maximum and Mean Velocity

As seen in the current vector diagram (stick diagram) shown in Figure 2, a semidiurnal tide predominates at all stations. The positive and negative velocities refer to the directions of flood and ebb currents, respectively, and velocity value at station C6 is expressed in the opposite direction to other stations. Based on the tidal period, the spring tide velocity is markedly stronger than the neap tide.

Figure 3 compares the maximum and averaged velocities of flood and ebb currents in the major axis directions for each observation station, calculated via PCA analysis. For maximum velocity, the ensemble average of the top 5% velocity values was used because observational error can occur when using an instantaneous maximum value. The values of the same observation periods were arithmetically averaged to derive average velocity. At all stations, the ebb current showed a maximum velocity of more than 1.2m/s, while flood current shows a velocity of more than 1m/s. The average ebb current velocity is greatest at station C6 at approximately 0.9m/s, and smallest at station C5 at approximately 0.7m/s. However, the average flood

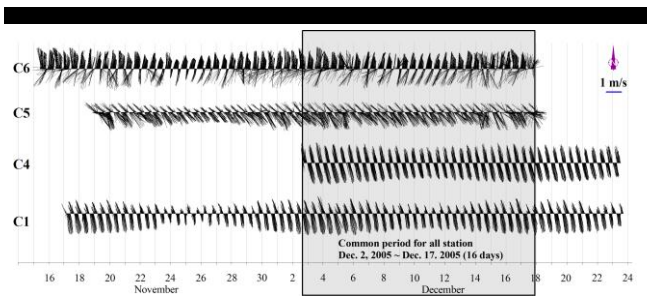


Figure 2. Stick diagram of tidal current. The gray box is the common period for all stations, from December 2 to 17, 2005. Positive and negative data refer to flood and ebb currents, respectively (except C6, opposite direction).

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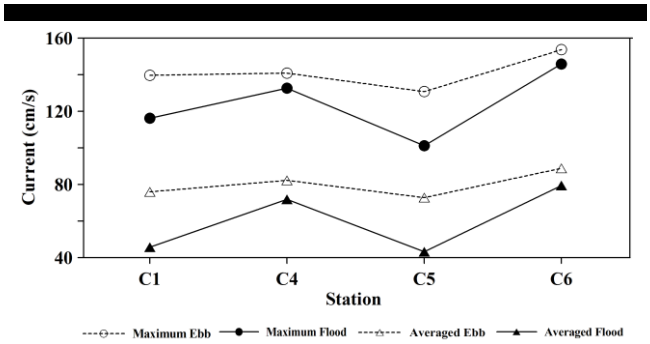


Figure 3. Statistical analysis of tidal current from all stations.

current velocity is approximately 0.8m/s at station C6, and approximately at 0.4m/s at station C5, showing a notable difference compared to the average ebb current velocity. In conclusion, the maximum and average fluid velocities were greater for ebb current than flood current at all stations, particularly at C1 and C5.

Flood and Ebb Current Duration

The durations of the flood and ebb currents from the tidal current at each station are shown in Figure 4. Slack time generally refers to a period (usually around high- and low tide at most locations) which tidal currents are smallest. The slack time according to tidal current is defined as the time when the velocity is 0~±0.05m/s. The variation in duration of flood and ebb currents at each station shows a 0.5 to 1 hour difference even during one day, owing to the influence of diurnal inequality (see Figure 4); in the case of station C4, the duration differed by more than an hour depending on spring or neap tide. The duration of flood current at stations C1 and C2 shows a 5.5~6.5 hour difference, compared with 6.5~7.5 hours difference for ebb current. The difference in duration increases further upstream, with flood current duration around 3~4 hours and ebb current duration 8~9 hours at stations C5 and C6. Moving upstream along the estuary, the increase in ebb current and decrease in flood current duration become more pronounced, and the ebb current duration exceeded that of the flood current at most stations.

Statistical analysis presented that the maximum and averaged velocities of ebb current are greater than those of flood. According to the slack time analysis, the characteristic of tidal current near the Yeomha channel within the HRE showed long ebb current durations. Therefore, the tidal characteristics of the Yeomha channel are unique in that it has strong ebb currents and a long ebb current duration.

Tide and Tidal Current Asymmetry

The amplitudes of the M_2 and M_4 constituents for each station were obtained by analyzing the harmonic constant of the tide within the study area, using tidal elevation and water level data (Figure 5). The amplitude of tide constituent M_2, which reaches its maximum value at Incheon harbor, decreases markedly as it passes through the southern entrance of the Yeomha channel, owing to friction effect (Woo and Yoon, 2011); and again at the northern entrance of the channel. Because of the influence of Singok underwater dam, located upstream of station T10, the amplitude of M_2 is less than 40cm upstream. Unlike the M_2 constituent, the change in the shallow-water M_4 constituent increases at the southern entrance of the Yeomha channel and reaches its maximum value at the northern entrance. Subsequently,

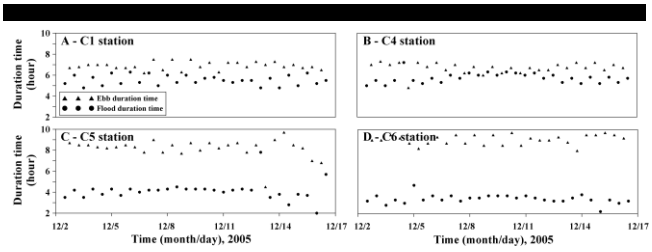


Figure 4. Comparison of ebb (triangle) and flood (circle) durations for C1(A), C4(B), C5(C) and C6(D).

because of the effect of the rapid decrease in the amplitude of M_2 constituent, the amplitude of M_4 constituent also decreases; although it decreases markedly after the Singok underwater dam, it has a larger value than M_2 constituent, which is a semidiurnal tide.

Figure 5B describes the amplitude of M_2 and M_4 constituents of the tidal current at each station, obtained through harmonically decomposing the dominant current component collected from the PCA analysis. Further upstream, the M_2 constituent decreases and M4 constituent increases, similar to the fluctuation in tidal amplitude. Nonetheless, the maximum amplitude of M_2 occurs at the southern entrance (station C4) of the Yeomha channel, whereas that of M_4 occurs at the northern entrance (station C6). The maximum value is exhibited as a result of the convergence of tidal waves in the southern entrance of Yeomha channel according to the degree of geographical convergence (Woo and Yoon, 2011). While there is very little decrease in the amplitude of M_2 at station C6, the M_4 constituent more than doubles, to a value greater than that of M_2.

Looking at the rate of change in amplitude ratio of the Satilla River studied by Seim *et al*. (2006), the value is low at 0.1 at the estuary mouth, but the amplitude ratio increases upstream; in particular, the increase in amplitude ratio of the current was greater than that of the tide. In the present study, the M_4/M_2 amplitude ratio at the estuary mouth is similar; however, moving upstream, the increase rate exceeds 0.35~0.5, which is more than double the largest current amplitude rate (0.16) reported by Seim *et al*. (2006). Blanton *et al*. (2002) suggested friction as the cause of the formation of shallow-water constituents in the Satilla River and the degree of convergence in channels. Compared to the

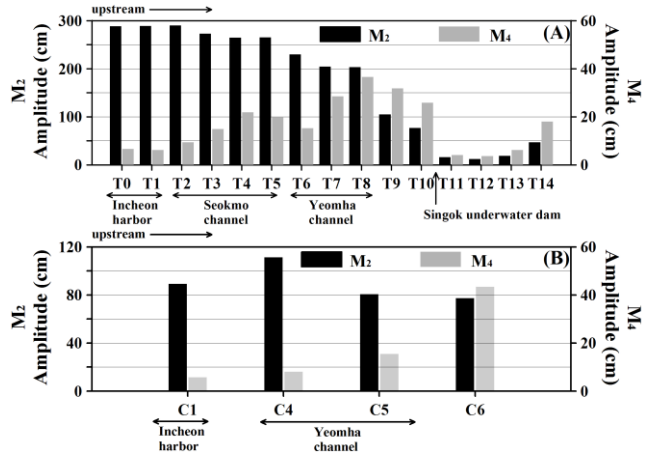


Figure 5. The amplitude of M2 (black) and M4 (gray) constituents for water level (A) and velocity (B).

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Satilla River, Yeomha channel is more affected by friction than the degree of geographical convergence in the transformation of tides and tidal currents. This result is consistent with the correlation between the geographical convergence degree and the bottom friction in the Yeomha channel, proposed by Woo and Yoon (2011). The decrease in energy due to bottom friction causes the increase in the amplitude of M_4 constituent, which affects tidal currents more than tides.

Dominance of Flood and Ebb

The relative phase difference between M_2 and M_4 constituents is mostly less than 180° from tide station (Figure 1; T1~T14 stations) ; according to the definition of Aubrey and Speer (1985), this can be explained as a flood dominant area. These results are consistent with the flood dominance phenomenon around GGB that was proposed by Kang and Jun (2003). Nevertheless, the velocity of the maximum and averaged flood and ebb mentioned above shows that the ebb is dominant at every station, and also that the duration of the ebb is longer than that of the flood at every station. Through tidal data, we can conclude that the HRE area is flood dominant and with stronger nonlinear effect closer to the upper stream of the estuary. However, this result conflicts with the ebb dominance from the statistical analysis of tidal currents described previously. To determine why the dominance of flood and ebb differs between the analysis of relative phase difference in tides and the velocity, we reconstructed the harmonic constant of tidal current and the non-tidal current constituents.

In order to consider the influence of fresh water, we need to understand the exact volume of inflowing fresh water to the Yeomha channel; however, as the fresh water contribution from the Han River and Imjin River to the Yeomha channel is unknown, the tidal residual flow is defined as the arithmetic mean value during the period of simultaneous tidal current observation. The defined residual flow includes all residual components associated with barotropic and baroclinic conditions, except for the tidal current components. The magnitude and direction of the residual flow of each station (see Table 1) shows an ebb flow of less than 180° (C6 has an ebb greater than 180°) at all stations. The magnitude of residual current changed 0.4 and 0.1m/s at C6 and C1, respectively.

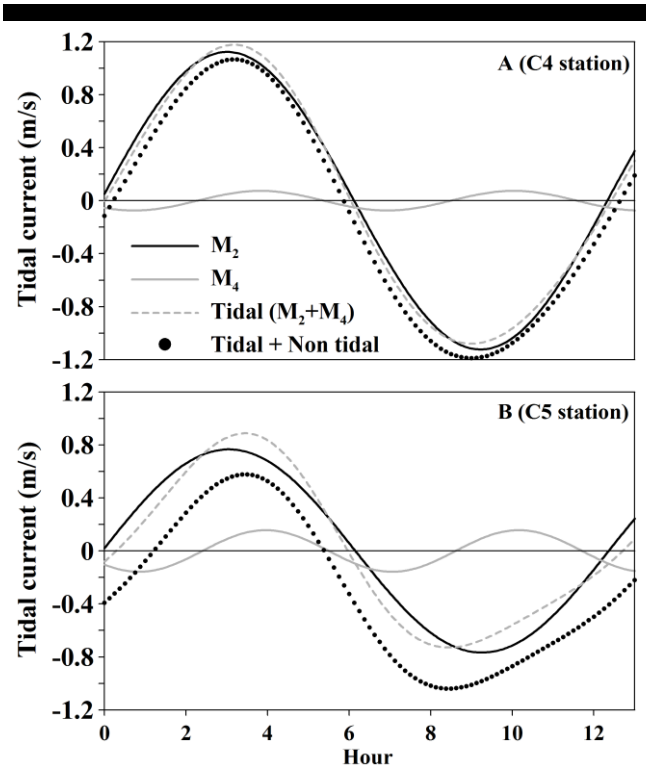


Figure 6. Schematic of the interaction of Tidal and Non-tidal components. Positive and negative current indicate the flood and ebb current, respectively. The black line represents tidal component (M_2 and M_4) for C4 and C5 station. The gray dashed line is the sum of tidal components (M_2+M_4) and the dotted line is the sum of Tidal and Non-tidal components.

Table 1. Phase difference in M_2 and M_4 at tidal current station. Magnitude and direction (0°=north) of residual current.

St	phase(°)			Residual current	
	M_2	M_4	$2M_2$-M4	Magnitude (m/s)	Direction
C1	71.6	269.9	233.3	0.11	151.2
C4	87.4	222.1	321.7	0.19	172.1
C5	88.4	229.2	307.6	0.31	133.6
C6	356.8	197.9	155.7	0.40	347.7

Table 2. Variation in tidal current and duration under Tidal and Non-tidal components at C4 and C5.

St	Component	Flood		Ebb	
		Vel (m/s)	Duration (hour)	Vel (m/s)	Duration (hour)
C4	Tidal	1.18	6.04	-1.08	6.38
	Tidal + Non	1.07	5.29	-1.19	7.13
C5	Tidal	0.89	5.67	-0.73	6.75
	Tidal + Non	0.58	2.71	-1.04	9.71

Figure 6 shows the tidal curve during the tidal period, which was reorganized using the amplitudes and phases of the M_2 and M_4 components from stations C4 and C5, showing the tidal curve formed by the composition of M_2 and M_4 tidal components and the composition of residual currents. When combining the two components, a typical flood dominant curve is formed, showing the slowing phase and increased amplitude associated with high tide and the quicker phase and decreased amplitude associated with low tide. If the residual current component is added, ebb current becomes dominant and the duration of the ebb current is increased like the dark dotted line. Looking at the detailed values provided in Table 2, the flood current velocity of station C4 is approximately 1.18m/s, the ebb current velocity is -1.08m/s. If the Non tidal component (provided in Table 1) is added, magnitude of flood and ebb current changes to1.07 and -1.19m/s, respectively and the ebb current duration becomes even longer. In the case of station C5, the ebb current duration, during which the ebb current intensifies, becomes longer because the residual current component (provided in Table 1) is larger than that at C4. The specific mechanism that causes the ebb current, the flow direction is considered to form and maintain long-duration ebb current as the ebb current of Yeomha channel

Various reasons which are generated residual current in ebb direction, such as continuous fresh water influence, were suggested by Kim *et al.* (2010), spring–neap tide variability of long period current component suggested by Song and Woo (2011), and the difference in pressure due to density change can affect residual currents. Considering that the magnitude of the residual current at station C6 is 0.4m/s, and that it decreases downstream, to 0.1m/s at station C1, it is speculated that the

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residual current due to fresh water has a smaller indirect downstream compared to that on the upstream.

CONCLUSION

To understand the seawater flow characteristics and mass transfer of the HRE and GGB, we analyzed tidal asymmetry and flood and ebb current dominance using tidal current observation data in winter 2005. The analysis used 16 days of simultaneous data from four tidal current stations. The harmonic constant was calculated from analysis of water level data from the KHOA and the HRFCO. The harmonic analysis of the tides and currents provided the amplitude change rate of the M_2 and M_4 components from Incheon harbor to upstream station, showing a 35% decrease in amplitude of M_2 component for tide, and 20% for currents. The M_4 component was increased by about 4 times for tides, and around 8 times in the case of currents. Therefore, the actual M_4/M_2 amplitude ratio is larger in the currents than tides.

Applying a traditional relative phase-difference ($2M_2$-M_4) analysis method, we find that the flood current is dominant in most parts of the HRE and GGB. However, statistical analysis of the current and duration shows that the ebb current is strongly dominant, which could be explained by the combined effect of relative phase difference in M_2 and M_4 components, influx of freshwater discharge, and the increase in non-tidal components in the ebb current direction due to the nonlinear tidal effect.

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