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Modeling of Sediment Transport and Sand Bank Formation in a Macrotidal Sea

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A two-dimensional numerical model was applied to investigate the sediment transport and sand bank formation in a macrotidal sea, the Kyunggi and Asan Bays. The tidal residual currents show quite complex pattern including counter-rotating eddies off the northwestern corner of the Dugjeok Island that reflect the promontory effect. Complex residual eddies are also present off the coast of the Taeanbando and in the Asan Bay. Net sediment transport pattern shows that sandy sediments in the Kyunggi and Asan Bays are generally transported landward from the outer sea suggesting sediment trapping inside the bays. This phenomenon may be related to the formation and maintenance of numerous sand banks in this macrotidal sea. Alternate occurrences of deposition and erosion predicted from the numerical model along the coast of the Taeanbando with strong deposition on the southwestern part of the 'Jangansatoe' (JSB), a large sand ridge off the coast of the Taeanbando appear to reflect the loose connection of JSB. The 'Joongangcheontoe', a central sand bank (CSB) with the main axis in the NW-SE direction in the Asan Bay may undergo a modification with strong deposition along the northeastern flank. These results indicate that the sand banks are actively modified and maintained by the strong tidal currents in this shallow macrotidal sea.

INTRODUCTION

The Kyunggi and Asan Bays cover the shallow coastal sea between Ongjin Peninsula and Taeanbando (Taean Peninsula), which is characterized by depths less than 50 m in general, numerous islands, complex bottom topography and irregular coastline. It is also a macrotidal sea with the tidal ranges over 8 m at spring tide and tidal currents over 1 m/s in channels. The tidal currents are also quite variable in speed and direction due to complex bottom topography, islands and irregular coastline. Ports of Inchon, Asan, Daesan, Pyongtack are all located in the Kyunggi Bay (Fig. 1) and vast amount of goods and raw materials are transported to or from many industrial complex as well as metropolitan cities of Seoul and Inchon. However, construction of many tidal barrier dams and land reclamation projects in the Kyunggi and Asan Bays in recent years resulted in changes of coastline, currents and sediment movement.

Numerous sand banks are well developed in the Kyunggi and Asan Bays. Among those two sand banks are notable. The 'Jangansatoe' or 'Jangan' Sand Bank (JSB) off the coast of the Taeanbando is developed along the coast from Hagampo to Daeranjido (Fig. 1) with the water depth less than 20 m (Fig. 2). The 'Joongangcheontoe' or Central Sand Bank (CSB) with depths shallow than 10 m is also found in the Asan Bay (Fig. 2). Deposition and erosion due to sand transport can lead to changes of water depth, which may hinder safe navigation of large vessels like oil tankers. It can also affect the efficiency of dredging of navigation channels.

Sand banks or sand ridges are commonly found in macrotidal coastal ocean and known to be related to tidal currents (e.g. Huthnance, 1973; Zimmerman, 1981). These sand banks have elongated shapes and seem to be parallel to the direction of the tidal currents. However, the major axis of sand bank is in fact located 8°—15° anticlockwise with respect to the tidal current direction (Zimmerman, 1981). This orientation reinforces the clockwise residual circulation (Zimmerman, 1981) and sand bank is well maintained (Huthnance, 1982a, 1982b). The length of sand bank is known to be same order of the tidal excursion length, which is the critical condition for the maximum response of the vorticity generation over a sand bank (Zimmerman, 1978; Robinson, 1981).

The sediments of sand banks in the Kyunggi Bay are mainly composed of sands and they are well sorted

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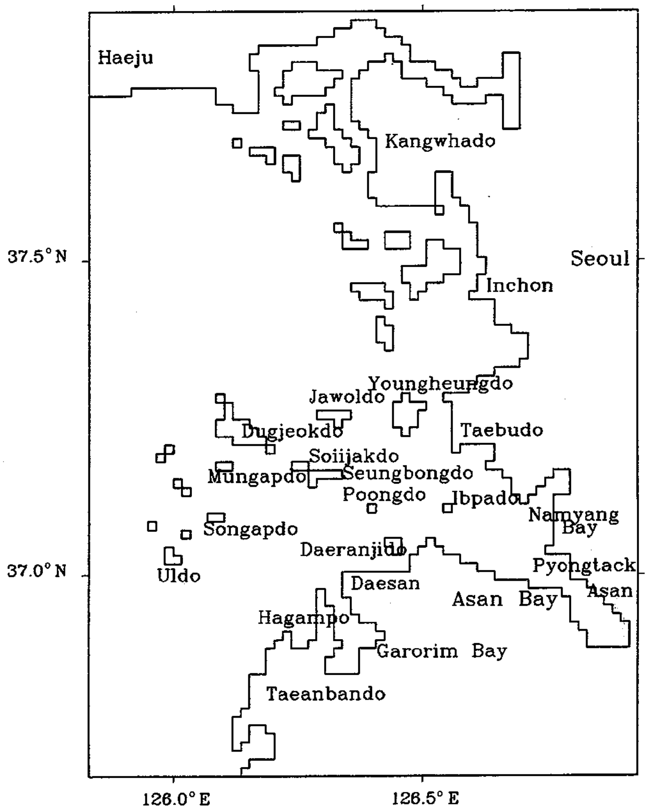

Fig. 1. The study area and the grid system of the model.

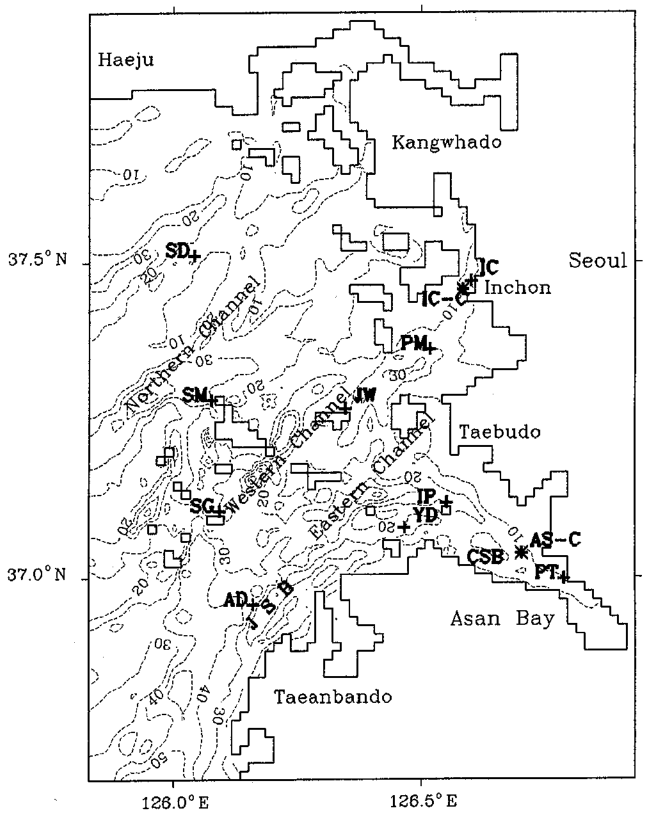

Fig. 2. Bathymetry of the study area. Depths are below mean sea level and the contour interval is 10 meters. Note that two notable sand banks are marked as 'JSB' for 'Jangan' Sand Bank off the Taeanbando and 'CSB' for Central Sand Bank in the Asan Bay. Also marked are locations where model results are compared with the observed data. SD; Sindo, PM; Palmido, IC; Inchon, SM; Sunmido, SG; Sungapdo, JW; Jawoldo, IP; Ibpado, YD; Yookdo, AD; Ando, PT; Pyongtack, IC-C and AS-C; Currrent Stations at Incheon and Asan Bay.

(Park *et al.*, 1994). The sand banks in the Kyunggi Bay are elongated and about 10–20 m high, 2–3 km wide and 10 km long with 15°–20° anticlockwise orientation to the tidal current (Bahng *et al.*, 1994). These characteristics of sand banks are similar to those found in other sand banks of macrotidal seas in the world, which suggests that the sand bank formation in the Kyunggi Bay is closely related to the tidal currents. Choi (1991), Choi and Park (1992) examined the boundary shear velocity over a sand bank in the Kyunggi Bay and showed that sandy sediments over the bank can be easily transported as bedload. Park and Lee (1994) also examined the sand waves on a sand bank in the bay and suggested that a sand bank can be maintained by the tidal currents. Accordingly, the change of sand bank of 10–20 m high due to the sand transport by tidal currents may result in significant change of water depths in the bay.

However, the general patterns of sediment transport by the tidal currents and resulting erosion and deposition which affect the sand bank formation and water depths in the Kyunggi Bay have not been studied so far. Hence, we intend to examine the formation and maintenance of sand banks due to sand transport in the Kyunggi and the Asan Bays with the emphasis on CSB and JSB and examine possible water depth changes using a numerical model.

TIDAL CURRENTS AROUND THE KYUNGGI AND ASAN BAYS

Hydrodynamic model

In order to understand the sand bank maintenance and water depth changes associated with sediment transport by tidal currents, we need to know the distribution of tidal currents in the study area. The observed data on tidal currents in this area are sparse, and moreover they are random in time and period. Thus, we need a numerical hydrodynamic model to represent the tidal currents in the Kyunggi and Asan Bays. The model used in this study is based on vertically averaged, two-dimensional equations of motion;

$$\frac{du}{dt} = -g\nabla\eta - f(\boldsymbol{k}\times\boldsymbol{u}) + C_d\frac{\rho_a}{\rho}\boldsymbol{W}|\boldsymbol{W}| - \frac{gu|u|}{C^2H} \quad (1)$$

$$\frac{\partial\eta}{\partial t} + \nabla\cdot(H\boldsymbol{u}) = 0 \quad (2)$$

where $\boldsymbol{u}$; depth-averaged current velocity, $\boldsymbol{W}$; horizontal wind velocity, $\boldsymbol{k}$; vertical unit vector, f; Coriolis parameter, g; gravity acceleration, C_d; surface friction factor, ρ_a; air density, ρ; density of sea water H; total water depth ($=h+\eta$), h; water depth below mean sea level, η; sea surface elevation with respect to mean sea level, C; Chezy coefficient ($=H^{1/6}/n$, n=0.03). The model domain includes the Asan and Kyunggi Bays and the model is comprised of 65×90 square grids with the resolution of 1.5 km (Fig. 1). There are many islands and sand banks in the study area, and the bottom topography is quite complex (Fig. 2).

For the open boundary conditions of the model, amplitudes and phases of M_2 tide from the observed data and results in Kang *et al.* (1998) were used. At the closed boundary, no normal flow and slip boundary condition were prescribed. Equations (1) and (2) were then solved numerically using a finite difference method (Leendertse, 1967) with a time step of 124.2 s and the model reached stable condition after a tidal cycle. The sea level and currents from the model at the 5th tidal cycle were then analysed for the verification of the model and subsequently used for the current distribution and the sediment transport study.

Verification of the model

The model results on sea level and currents were analyzed using Fourier analysis and the amplitude and phase of M_2 tide at 10 stations (See Fig. 2 for the location) were compared with the observed data (Table 1). The RMS error is found to be 5.3 cm in amplitude and 2.7° in phase. The computed tidal currents were also compared to the observed at two stations near Inchon and Pyongtack and also showed reasonable agreements in amplitude and phase (Table 2). The current observation station near Inchon was located in the narrow tidal channel near the coast and the model could not resolve well the current station with the 1.5 km resolution.

Nevertheless, overall distribution of the tidal currents at flood (Fig. 3) and at ebb (Fig. 4) compares quite well with the existing tidal current charts (NORI, 1997). Also, the residual current pattern around CSB in the Asan Bay (Figs. 5a and 5b) shows the southeastward current in the northern channel and the northwestward current in the southern channel as seen in the observed currents (Fig. 5c). Consequently, the model appears to reproduce the observed sea level and currents fairly well in the study area.

Tidal and residual currents in the Kyunggi and Asan Bays

The flood currents in the Kyunggi Bay generally flow northeastward from the Yellow Sea and they are especially strong along the three main channels; Eastern Channel off Taeanbando, Northern Channel northwest of the Dugjeokdo (Dugjeok Island) and midway channel between the Haeju coast and the Dugjeok Island (Fig. 3, See Figs. 1 and 2 for the location of channels). Also, the currents become strong between some islands due to the decreased cross-sectional area. The flood current in the Asan Bay flows south-

Table 1. Comparison of model results on sea level with the observed data

Location	Latitude	Longitude	Observed		Model		Difference	
			amp. (cm)	phase (°)	amp. (cm)	phase (°)	amp. (cm)	phase (°)
Inchon	37° 28' 08"	126° 35' 51"	290.6	138.4	284.8	140.4	−5.8	2.0
Sungapdo	37° 06' 17"	126° 05' 21"	222.4	121.7	221.8	123.5	−0.6	1.8
Jawoldo	37° 15' 40"	126° 20' 13"	250.5	129.3	258.6	132.4	8.1	3.1
Yookdo	37° 04' 51"	126° 28' 01"	250.6	125.6	259.2	128.2	8.6	2.6
Ando	36° 57' 15"	126° 10' 13"	220.3	115.8	219.0	115.4	−1.3	−0.4
Sunmido	37° 16' 38"	126° 05' 00"	232.9	127.7	230.1	126.3	−2.8	−1.4
Sindo	37° 30' 18"	126° 02' 43"	242.2	138.1	237.3	135.5	−4.9	−2.6
Ibpado	37° 06' 40"	126° 32' 27"	261.3	127.5	268.0	130.6	6.7	3.1
Palmido	37° 21' 32"	126° 30' 50"	272.8	133.6	275.6	135.5	2.8	1.9
Pyongtack	36° 59' 53"	126° 47' 14"	289.4	133.3	293.6	138.7	4.2	5.4

From Kang *et al.* (1998) and Korea Maritime and Port Adminstration (1991). The phase is referred to 135° E.

Table 2. Comparison of model results on tidal currents with the observed data

Location	Current	Observed		Model		(Model - Obs.)	
		amp. (cm/s)	phase (°)	amp. (cm/s)	phase (°)	amp. (cm/s)	phase (°)
Asan Bay (AS-C)*							
37°01' 40" N	North-component	32	239	38	242	6	3
126°41' 35" E	East-component	48	52	44	49	–4	–3
Inchon (IC-C)**							
37°28' 04" N	North-component	69	63	81	62	12	–1
126°34' 51" E	East-component	44	61	26	53	–17	–8

*From Korea Maritime and Port Adminstration (1991). The phase is referred to 135° E.
**From Office of Hydrographic Affairs (1993).

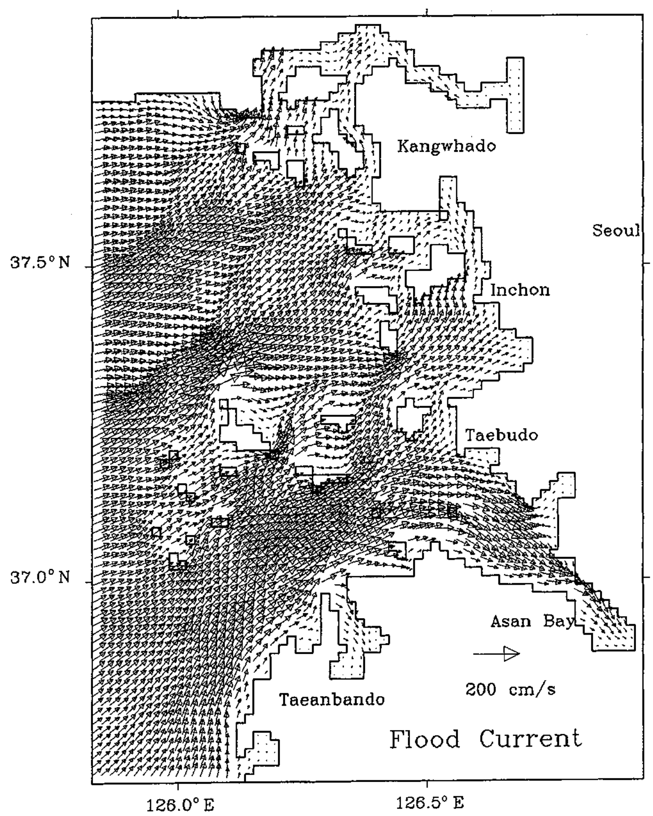

Fig. 3. Flood currents in the Kyunggi and Asan Bays. The time is 2.62 hours before highwater at Ando (See Fig. 2 for the location).

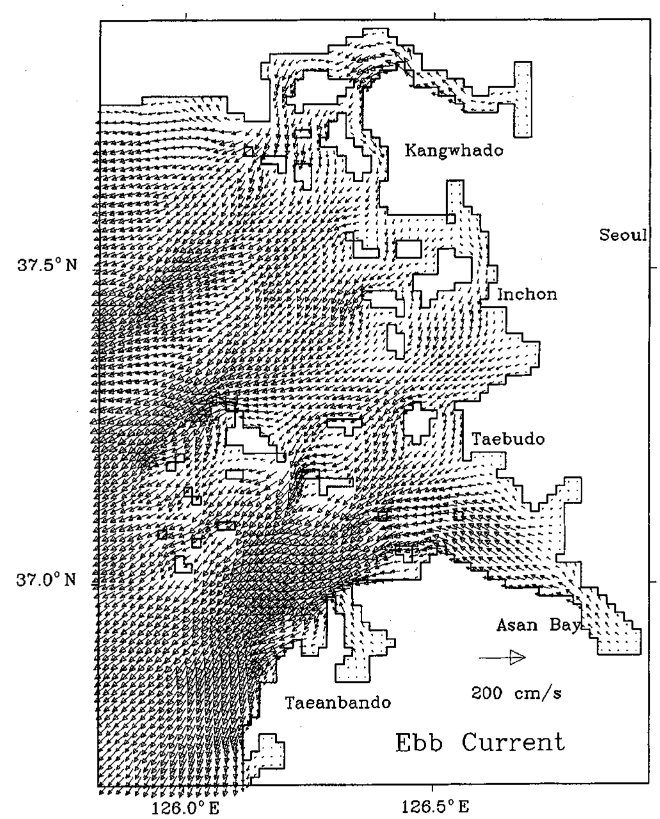

Fig. 4. Ebb currents in the Kyunggi and Asan Bays. The time is 3.59 hours after highwater at Ando.

eastward along the bay axis; however, it is stronger in the northern channel than in the southern channel. This may be related in part to the deeper water depths of the former. The currents off the northwest of the Dugjeok Island show the flow pattern around a coastal promontory; current speed increases due to advective acceleration caused by the island before passing the tip and decreases after that (e.g. Pingree and Maddock, 1979; Park and Wang, 2000). The currents are also strong off the coast of the Taeanbando where the convex shape of the curvature of the coastline appears to induce the acceleration of the currents as found around a coastal promontory. The ebb current flows southwestward in general while it flows northwestward in the Asan Bay, but the current strength is somewhat reduced (Fig. 4).

The tidal residual currents were obtained by averaging the instantanous currents over a tidal cycle and are shown in Fig. 5a. The pattern is quite complex due to numerous islands, irregular bottom topography

(a)

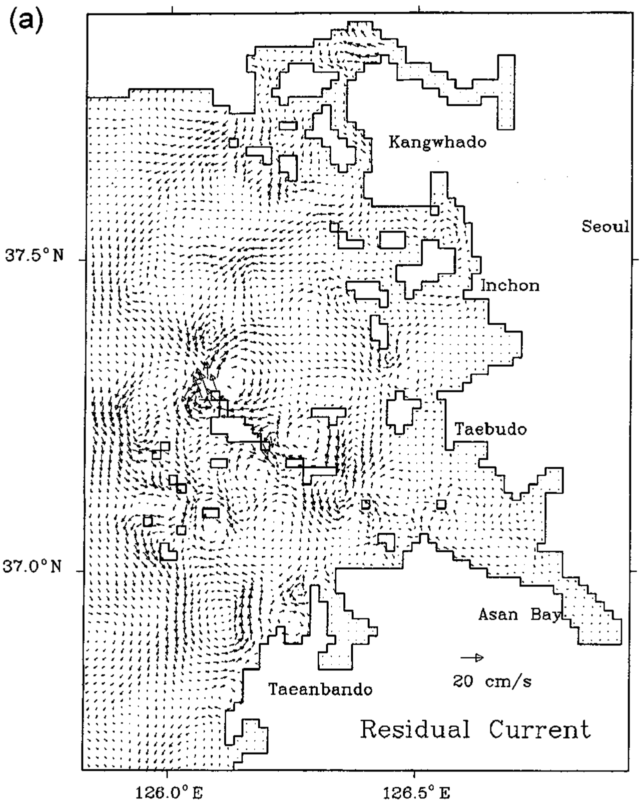

Fig. 5a. Tidal residual currents in the Kyunggi and Asan Bays.

(b)

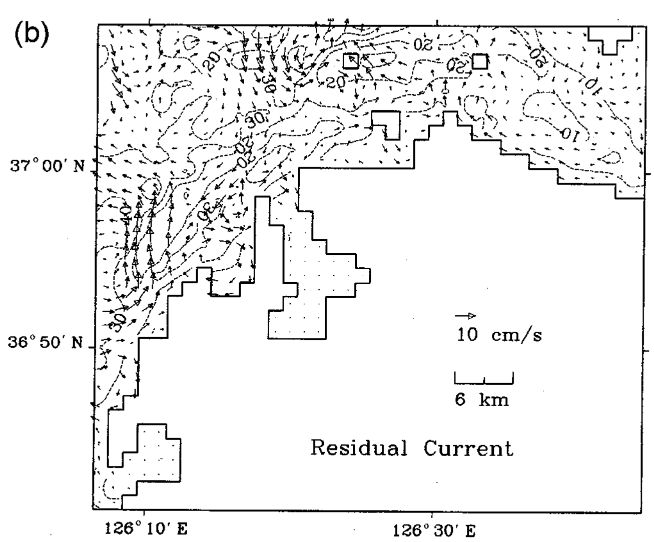

Fig. 5b. Tidal residual currents in the southern part of the Kyunggi Bay and the Asan Bay. The water depths below mean sea level are also shown.

(c)

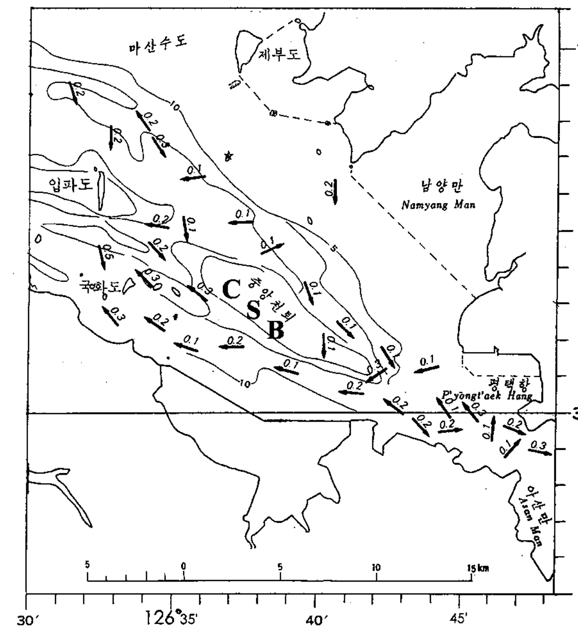

Fig. 5c. Observed tidal residual currents around the Central Sand Bank (CSB) in the Asan Bay (From Office of Hydrographic Affairs, 1996). The current speeds are in knots (0.1 knot ~5 cm/s).

and coastline and similar to those previously shown by Park (1995) and Lee and Choi (1997). The clockwise residual eddy around CSB in the Asan Bay (Fig. 5b) also appears to agree well with the observed one (Fig. 5c). The strong counter-rotating residual eddies with the maximum velocity of about 17 cm/s are found off the northwest of the Dugjeok Island, which seems to be induced by the promontory effect. The transient vorticity is produced by topographic vorticity tendency (column stretching) and frictional torque, and the advection of the transient vorticity leads to the residual vorticity resulting in counter-rotating residual eddies (e.g. Pingree and Maddock, 1979; Park and Wang, 2000). The residual eddies off the Taeanbando also seems to be caused also by the promontory effect where the Taeanbando itself probably acts as a coastal promontory. The clockwise residual eddy on the central bank (CSB) in the Asan Bay was previously speculated to be related to the formation of CSB in the Asan Bay (Park, 1995).

SEDIMENT TRANSPORT AND SAND BANK FORMATION IN THE KYUNGGI AND ASAN BAYS

Sediment transport model

There are many sand banks including 'Jangansatoe' (JSB) and 'Joongangcheontoe' (CSB) in the Kyunggi Bay (See Figs. 1 and 2 for the location). The JSB extends from Hagampo to Daeranjido with the length of about 30 km in convex shape. It was considered to be composed of three parts, southwestern, middle, and northeastern parts, based on the symmetry and the orientation (Park and Lee, 1994). It is 1–3 km wide and the water depths are shallower than 20 m. The CSB is located in the central part of the Asan Bay (Fig. 2) and water depths are shallower than 10 m over the sand bank. It is about 12 km long and 4 km wide at the northwestern part, but the width gradually decreases toward the southeastern part of the bank.

In tidal environment the topographic irregularities in sea floor or coastline can induce transient vorticity generation by the tidal currents through the topographic vorticity tendency and the frictional torque (Park and Wang, 1991, 1994, 2000). This leads to change of tidal currents, which in turn results in change of sediment transport, i.e., deposition and erosion. Sandy sediments are distributed widely over the Kyunggi Bay (Park *et al.*, 1994) and they can be easily transported as bedload by the tidal currents (Choi, 1991; Choi and Park, 1992). The existence of sand waves and megaripples on JSB and CSB were studied and it was suggested that both sand banks were moved significantly in recent years (Park and Lee, 1994; Park and Yoo, 1997).

Huthnance (1982a, 1982b) showed that a sand bank can be developed in tidal environment using a depth-averaged two-dimensional model. The cyclonic orientation of a sand bank to the tidal stream was found to be more favorable for the sand bank formation. Park and Wang (1991, 1994) also indicated that circular hollow and sand bank are unstable bedform configurations and tend to be elliptic with the cyclonic orientation to the tidal stream. Sand banks can also be developed around a coastal promontory induced by the promontory effect as described previously. The sand bank in the cyclonic residual eddy tends to be well developed than in the anticyclonic eddy due to the effect of the earth rotation (Pingree and Maddock, 1979; Park and Wang, 2000). In order to understand the sediment transport pattern and its effect on sand bank formation in the Kyunggi and Asan Bays, the approach of Huthnance (1982a, 1982b) was used as follows;

$$Q_b \sim |u|^2(u + \lambda|u|\nabla h) \quad (3)$$

where Q_b is bedload transport rate (volume/ unit width/ unit time) and λ is a coefficient. The first term in right hand side of Eq. (3) indicates that the bedload transport is related to u^3 and the second term represents the enhancement of the down-slope component of the transport. Further details on Eq.(3) can be found in Huthnance (1982a, 1982b).

Sediment transport in the Kyunggi and Asan Bays

Figures 6 and 7 show the sediment transport patterns at the time of maximum flood and ebb currents off Ando, respectively (See Fig. 1 for the location of Ando). The sediment transports at flood occur generally northeastward to the inner part of the Kyunggi Bay and they are especially large at the Eastern and Northern Channels where currents are strong. In the Asan bay the sediments are transported east and southeastward as expected from the current distribution at flood (Fig. 3). The sediment transports at ebb are significantly reduced and directed southwestward due to the reduced current strengths at ebb (Fig. 4). Averaging the instantaneous bedload transport over a tidal cycle, we obtain the residual (net) bedload transport distribution in the Kyunggi Bay (Fig. 8). It shows that the net sediment transports are generally directed toward the inner part of the Kyunggi Bay and toward the Asan Bay. This suggests that the sandy sediments

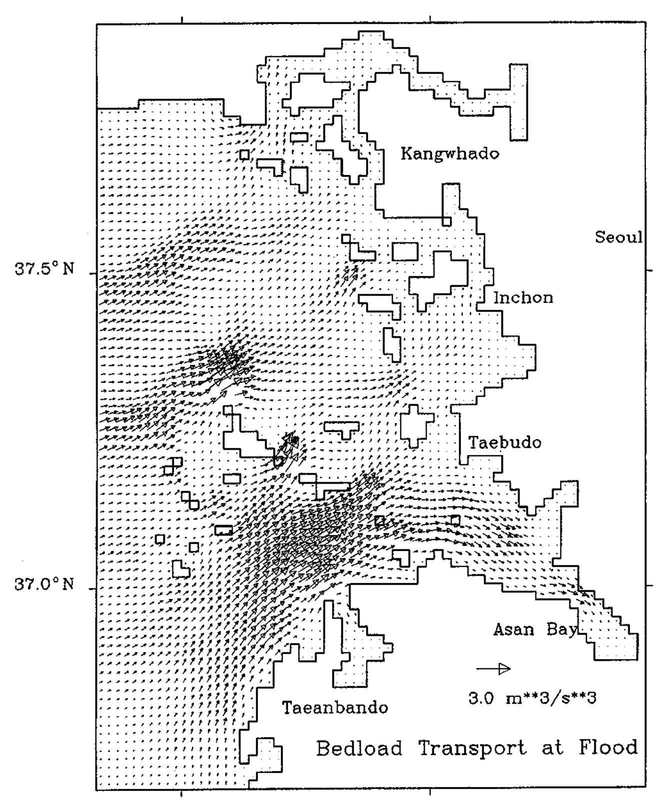

Fig. 6. Bedload transport at flood in the Kyunggi and Asan Bays. The time is 2.62 hours before high water at Ando.

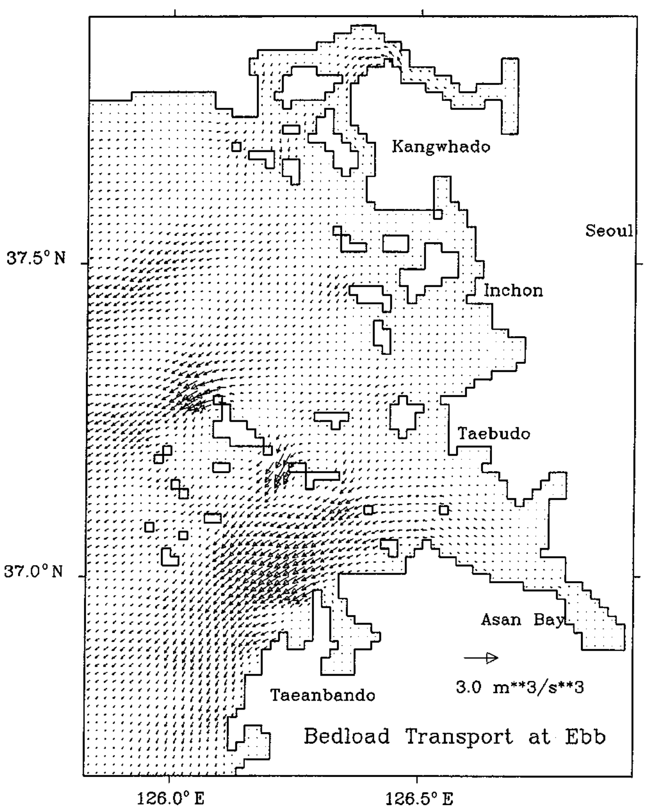

Fig. 7. Bedload transport at ebb in the Kyunggi and Asan Bays. The time is 3.59 hours after high water at Ando.

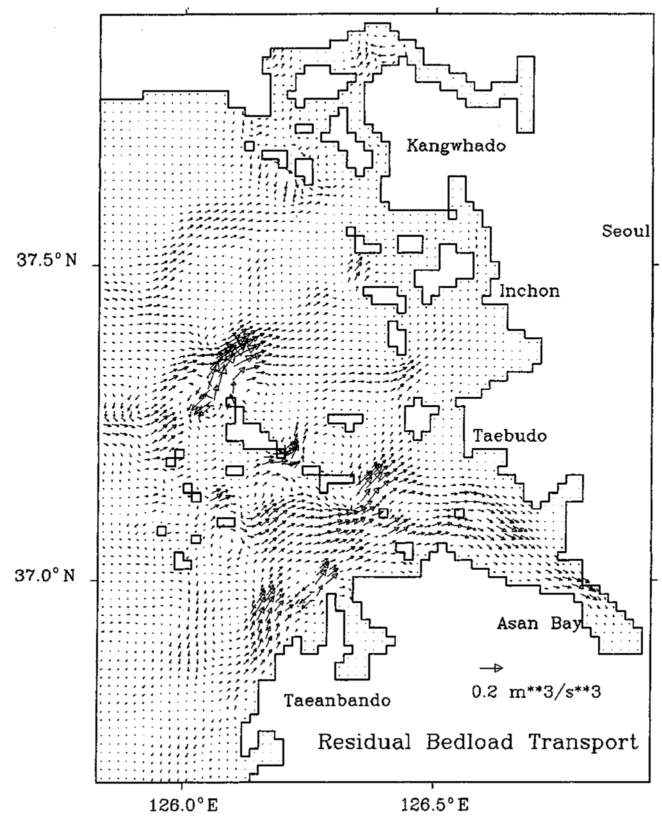

Fig. 8. Residual bedload transport in the Kyunggi and Asan Bays.

transported as bedload may be trapped inside the bay, which may be related to the maintenance and development of the numerous sand banks in this macrotidal sea. In fact, it was shown that the composition of sediments off the Taeanbando is similar to that found on the continental shelves of Yellow and East China Seas (Park *et al.*, 1994) suggesting offshore origin of sediments in this area.

Deposition, erosion and sand bank formation in the Kyunggi and Asan Bays

We first examine the instantaneous deposition/erosion pattern by taking divergence of the instantaneous sediment transport, i.e., $\nabla \cdot Q_b$. By the conservation of sand, the sediment erosion occurs in areas of bedload divergence (positive value) and deposition occurs in area of bedload convergence (negative value) (Park and Wang, 1991, 1994). The sediment transport at flood is generally along JSB and CSB, and increase (divergence) and decrease (convergence) of the sediment transport along the coast of the Taeanbando (Fig. 9a) result in erosion and deposition, respectively (Fig. 9b). Deposition occurs over large areas of the southwestern part of JSB off Hagampo and near the entrance of the Garorim Bay. This alternate fashion of erosion and depostion appear to be induced by the modification of currents due to the promontory effect.

Strong deposition occurs over the northeastern part of CSB due to the convergence of sediment transport along the path and erosion east of Ibpado due to the divergence (See Fig. 1 for the location). The deposition over CSB seems to have an axis normal to the NW-SE direction of the present sand bank. The sediment transport and depostion and erosion pattern at ebb (Figs. 10a and 10b) are reversed compared to those at flood, but the magnitudes are smaller than those at flood resulting in net landward transport of sediments (Fig. 8).

The residual bedload divergence in the southern part of the Kyunggi Bay and the Asan Bay was obtained by averaging the instantaneous divergence of bedload transport over a tidal cycle to examine the net deposition and erosion pattern and is shown in Fig. 11a. Erosion and deposition occur in an alternate fashion along the Taeanbando, which seems to correspond to the discontinuous pattern of sand banks of JSB as described previously. It also indicates a strong dep-

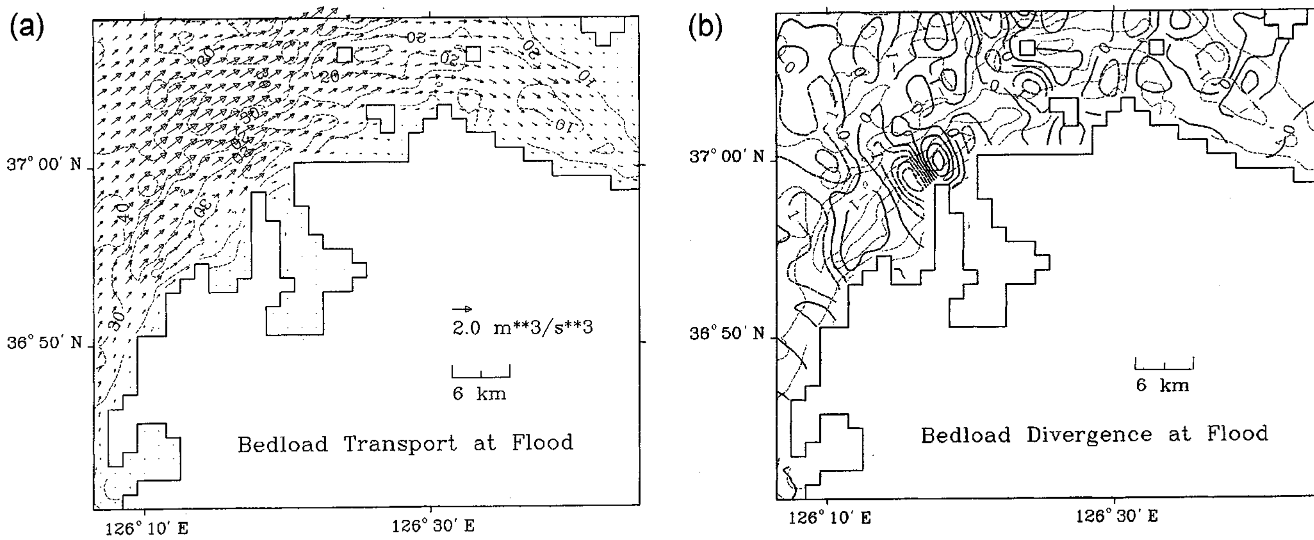

Fig. 9. (a) Bedload transport at flood in the southern part of the Kyunggi Bay and the Asan Bay. The dotted lines are contours of water depths below mean sea level. The time is 2.62 hours before high water at Ando. (b) Bedload divergence at flood in the southern part of the Kyunggi Bay and the Asan Bay. The solid lines are for bedload convergence (deposition) and the dashed lines are for bedload divergence (erosion). Also shown are depth contours. The time is 2.62 hours before high water at Ando. Contour interval is 1.0×10^{-4} m^2s^{-3}.

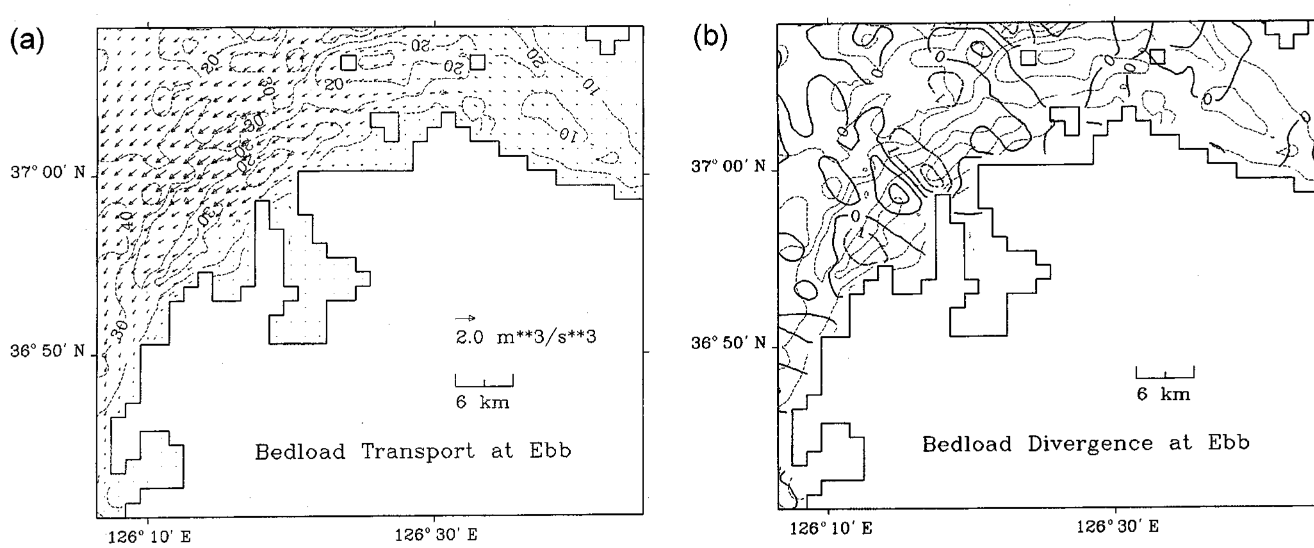

Fig. 10. (a) Bedload transport at ebb in the southern part of the Kyunggi Bay and the Asan Bay. The time is 3.59 hours after high water at Ando. (b) Bedload divergence at ebb in the southern part of the Kyunggi Bay and the Asan Bay. The solid lines are for bedload convergence (deposition) and dotted lines are for bedload divergence (erosion). The time is 3.59 hours after high water at Ando. Contour interval is 1.0×10^{-4} m^2s^{-3}.

osition on the southwestern part of JSB off the Taeanbando. In fact this is the area where extensive shoals are found and where the residual sediment transport converges (Fig. 11b).

However, the clockwise eddy usually found over a tidal sand ridge does not exist over JSB (Fig. 5b). Rather, the deposition is found where three residual eddies meet together. In addition, considering the fact that the sediment transport during flood is stronger than that during ebb, net erosion and deposition pattern seems to be controlled by the flood current (See Fig. 9b and Fig. 11a). This indicates that JSB is formed and maintained largely by the modification of the flood current due to the irregular coastline. Also, the deposition and erosion located slightly off JSB toward the coast suggests landward movement of JSB, which seems to agree with the previous results of Park and Lee (1994, Fig. 2D). Erosional

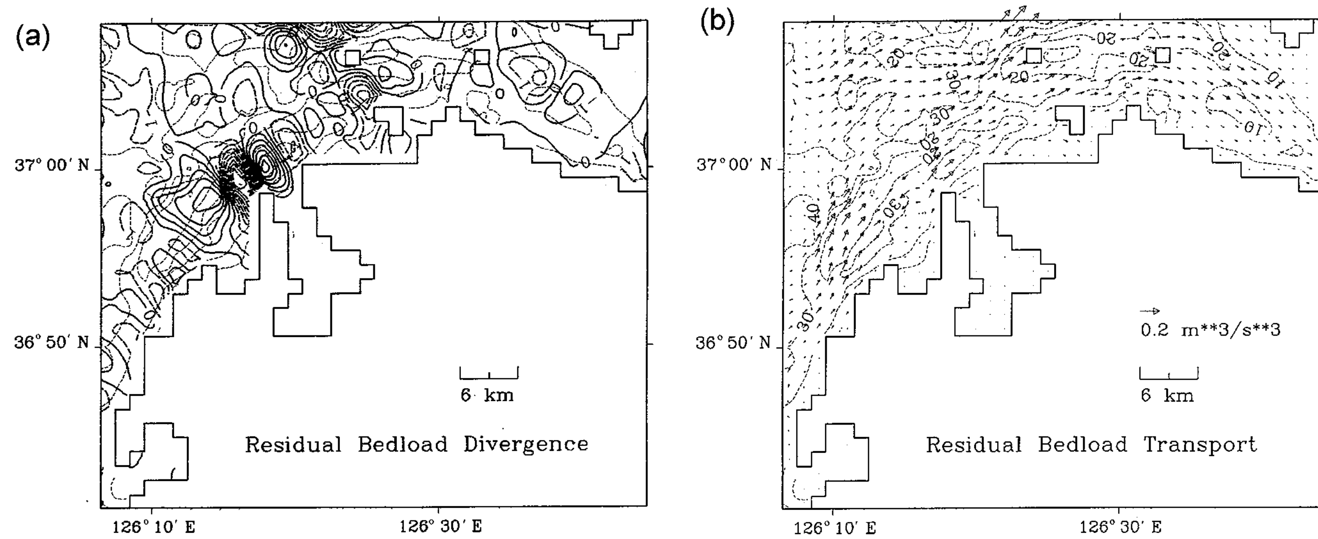

Fig. 11. (a) Residual bedload divergence in the southern part of the Kyunggi Bay and the Asan Bay. The solid lines are for bedload convergence (deposition) and dotted lines are for bedload divergence (erosion). Contour interval is 1.0×10^{-5} m^2s^{-3}. (b) Residual bedload transport in the southern part of the Kyunggi Bay and the Asan Bay.

area off the northwest corner of Daeranjido (See Fig. 1 for the location) and depositional area north of the island also tend to agree with the deeper and shallower water depths, respectively (Fig. 11a).

On the other hand, in the Asan Bay the net deposition is expected over CSB (Fig. 11a) where a clockwise residual eddy is found (Fig. 5b) as speculated previously by Park (1995) while erosion is likely east of Ibpado. The erosional area predicted by the model appear to coincide with the deeper water depths in that region.

The deposition ,however, is concentrated over the northeastern flank of the bank and is along the NE-SW direction, which is normal to the NW-SE direction of the current bank axis.

This deposition pattern agrees well with the previous results (Park and Yoo, 1997) that the sand bank have migrated toward northeastward. This migration may have been caused by the change of tidal flow due to the construction of the Seokmun tidal barrier and other topographic modifications nearby, and may also affect the northern channel which is now actively used as a navigation channel for large vessels in and out of the Asan Bay.

SUMMARY AND CONCLUSIONS

A two-dimensional hydrodynamic and sediment transport model was applied to investigate sediment transport and sand bank formation in a macrotidal sea, the Kyunggi and Asan Bays.

The tidal residual currents showed complex patterns including counter-rotating residual eddies with the maximum current of about 17 cm/s off the northwestern coast of the Dugjeok Island, which is probably caused by the promontory effect. There are also cyclonic and anticyclonic residual eddies with an offshore flow off the Taeanbando, which also may be caused by the promontory effect. An anticyclonic residual eddy is also found over the central bank (CSB) in the Asan Bay.

The sediments are mainly transported through three main channels in the northeast (flood) and southwest (ebb) directions. However, the magnitudes at ebb are significantly reduced compared to those at flood. Accordingly, the net sediment transports are northeastward in general in the Kyunggi Bay and southeastward in the Asan Bay indicating trapping of sandy sediments in the Kyunggi and Asan Bays. The sediment transport increases or decreases due to the modification of currents along the coast of the Taeanbando indicating the promontory effect on the deposition and the erosion of sediments. These may provide a part of major causes for the maintenance and formation of numerous sand banks such as JSB and CSB in this macrotidal coastal sea.

The net deposition and erosion pattern tends to correspond to areas of shoals and deeper water depths, respectively, suggesting the maintenance of shoals by the tidal currents. Strong deposition over the southwestern part of JSB and the alternate pattern of deposition and erosion along the coast of the Taeanbando also seem to reflect the discontinous pattern of JSB. However, the deposition pattern does not correspond to the clockwise or anticlockwise residual eddy suggesting complex modification of the tidal currents around JSB. The deposition/erosion pattern also suggests the landward movement of JSB. The deposition occur over CSB in the Asan Bay where a clockwise residual eddy is found. However, the deposition is centered over the northeastern part of CSB in the NE-SW direction and it suggests that the bank may undergo a modification from the present configuration. These changes may affect the safe navigation of large vessels along the Taeanbando and through the northern channel in the Asan Bay. These results indicate that the sand banks in the Kyunggi and Asan Bays are actively modified and maintained by the strong tidal currents in this macrotidal sea.

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