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Estimation of Boundary Shear Velocities from Tidal Current in the Gyeonggi Bay, Korea

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한국 경기만에서 조류자료에 의한 경계면 전단속도 산출

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From tidal current measurements on a tidal sand ridge in the Gyeonggi Bay from August 24 to September 28, 1987, tidal current velocities at 1.0 m above bottom (U_{100}) and boundary shear velocities (U_*) are calculated. The mean speeds of tidal current for flood and ebb over the entire period are 56.3 cm/sec and 63.7 cm/sec in mid-depth (9.0 m above bottom), and 43.9 cm/sec and 43.8 cm/sec in near-bottom (1.5 m above bottom). The exponent (P) in "power law", which is generally used for extrapolation from the mid-depth current velocity to that at the top of notionally logarithmic layer, is estimated to be 0.15 in the study area. Using logarithmic velocity profile assumption, mean values of U_{100} and U_* are calcuated to be 41.4 cm/sec and 2.39 cm/sec, respectively. The mean value of U_* (2.39 cm/sec) is much higher than the critical shear velicity (U_{*c}) of 1.40 cm/sec reported by Choi (1990), and thus, it can be suggested that the most of sands on the tidal sand ridge in the study area are easily eroded and transported for the greater part of tidal period.

1987년 8월 24일부터 9월 28일까지 경기만에 발달한 조류 기원 사퇴위에서 측정한 조류 자료를 분석하여 해저면 상부 1.0m에서의 조류 속도(U_{100}) 및 경계면에서의 전단 속도(U_*)를 구하였다. 전 조사기간 동안 평균 조류 속도는 중층(해저면 상부 9.0m)에서 창조시 56.3 cm/sec, 낙조시 63.7 cm/sec, 저층(해저면 상부 1.5m)에서 창조 때 43.9 cm/sec, 낙조 때 43.8 cm/sec로 계산되었다. 본 연구에서 "power law"의 지수 P는 0.15로 추정된다. 해저 경계층에서의 유속 구조가 대수적 속도 구조(logarithmic velocity profile)라는 가정을 이용하여 구한 U_{100}, U_*의 평균값은 각각 41.4 cm/sec, 2.39 cm/sec로 계산되었다. 본 연구에서 계산된 평균 U_*값은 (2.39 cm/sec) 동일 지역에서 최(1990)가 보고한 경계면에서의 임계전단 속도(U_{*c})보다 상당히 크며, 따라서 본 연구지역의 모래는 대부분의 조석 기간중 쉽게 침식 운반되는 것으로 보여진다.

INTRODUCTION

The Gyeonggi Bay is one of the many coastal embayments developed in the western coast of Korea. The Gyeonggi Bay has a very complex bottom topography which has numerous islands and ubiquitous tidal sand ridges trending oblique (NE-SW direction) to the coastline (Fig. 1). The water depth of the Bay is about 0~40 m. The tidal currents in the Bay are very strong and oscillatory. The flood tidal current flows mainly in NE direction and ebb tidal current flows in SW direction.

Geophysical, marine geological and geochemical studies of the Gyeonggi Bay, mainly composed of sandy sediments, have been carried out (Chang *et al.*, 1981; Chang *et al.*, 1982; Kim *et al.*, 1979; Kim *et al.*, 1988, 1989; Choi, 1990). Kim *et al.* (1979) have studied the internal structures (cross-bedding)

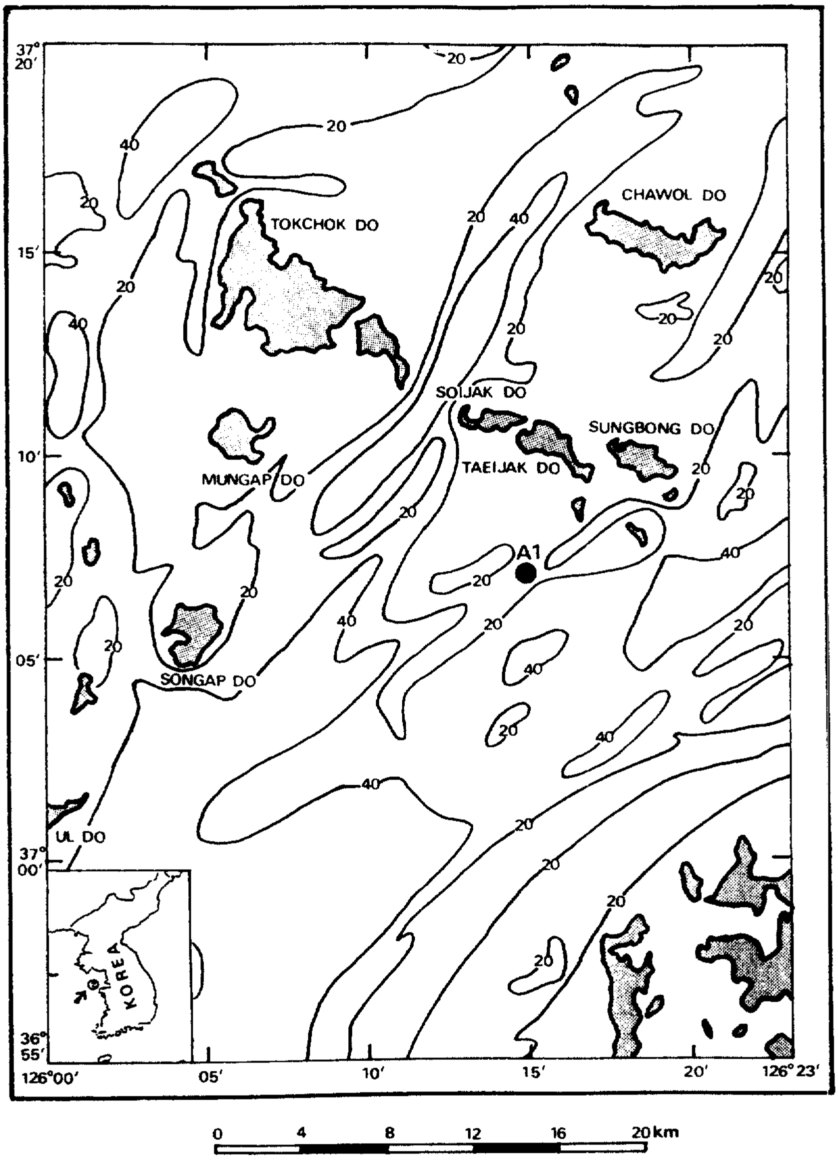

Fig. 1. Map showing the station (A1) of current measurements. The depth contours are in meter scale.

of the small sand bar located in the north of Chawol Do island by box coring method, and reported the path of sand transport to be SW direction. However, there were few in-situ field experimental studies for the estimation of sediment transport rate in the Gyeonggi Bay, especially on the tidal sand ridge.

For the estimation of sediment transport rate, it is important to reasonably estimate the necessary factors such as the boundary shear velocity (U_*), and density (ρ) and kinematic viscosity (ν) of fluid as well as the grain size and roughness of bed (y_0) (Yalin, 1977; Middleton and Southard, 1984; Dyer, 1986).

The present study was undertaken to estimate the U_*, ρ, ν, and y_0 values in the Gyeonggi Bay. For those purpose, the tidal currents were measured on a tidal sand ridge in the southern part of Soijak Do island and Taeijak Do island in the southern Gyeonggi Bay (Fig. 1). The tidal sand ridge is located between the East and West Waterways, and is approximately 15 km long and 2~4 km wide. The average water depth on the crest of the ridge is about 20 m.

Continuous current velocity, and the temperature· and salinity were measured simultaneoulsy. The density and viscosity of the sea water were calculated from the measured data. And the boundary shear velocities, and density and kinematic viscosity of the fluid are calculated. The exponent P in power law, which is generally used for extrapolation of velocity from the mid-depth to the top of notionally logarithmic boundary layer, is also estimated from the measured current data.

METHODS AND MATERIALS

Current Measurements

The direction and speed of tidal current in the study area were continously meaured at stations A1 from August 24 to September 28, 1987. The station A1 (37°07′00″ N, 126°15′00″ E) is located on the crest of the selected sand ridge in water depth of 19.0 m (Fig. 1). RCM-4 type current meters were moored in mid-depth (9.0 m above the seabed) and near bottom (1.5 m above the seabed) over the entire period.

The measured current data were analysed by a numerical low pass filter (Doodson-X_o Filter) to eliminate the short term components (anomalies), and then used to delineate the time variation of tidal current. The harmonic constants for the tidal current are calculated by harmonic analysis. Tidal current directions are separated into 16 directions, and the directional frequencies and average speed of the whole data in each direction are plotted on current rose diagrams.

The dynamic viscosity μ and fluid density ρ are variables which are important to determine the shear force exerted by the fluid at or near the surface of seabed. The dynamic viscosity and fluid density are dependent on the temperature and salinity of the fluid. So, to evaluate more accurately the dynamic viscosity and fluid density, temperature and salinity were simultaneously measured by RCM-4 current meters with optional conductivity sensors at the station A1.

In the bottom boundary layer, the velocity distribution is usually assumed to be a logarithmic (Sternberg, 1972; Middleton and Southard, 1984; Lees, 1983; Dyer, 1986). The logarithmic velocity profile in the turbulent boundary layer is

$$\frac{U}{U_*}=\frac{1}{\kappa}\ln\frac{y}{y_o} \tag{1}$$

where U is the mean current velocity at distance y above bottom; U_* is the boundary shear velocity; κ is von Karman constant (0.4); y_o is the value of y for which U=0, and is so-called "roughness length".

For the layer above the notional boundary layer, "power law" has been used to extrapolate from the mid-depth current velocity to that at the top of boundary layer (2.0 m above bottom) (Dyer, 1970; Lees, 1983; Dyer, 1986). The power law velocity profile(Dyer, 1970 and 1986) is given by

$$\frac{U_m}{U_{200}}=(\frac{y_m}{y_{200}})^P \tag{2}$$

where P is the empirically determined exponent; U_m is the velocity at the height (y_m) of current measurement above boundary layer; U_{200} is the velocity at the top of notional boundary layer (2.0 m above bottom). Dyer (1970) suggested that the value of exponent P is between 1/7 and 1/10. Based upon the velocity profile measurements from a Marconi current meter system and Braystoke direct reading current meter, Lees (1983) suggested that the value of P was able to be approximated as 0.1 within 90% significance level.

When the water depth is less than about 20 m and flow speed is less than 80 cm/sec, veering of the flow direction in the water column due to the bottom friction and earth's rotation is of the order of 2°~3°, and is within the error of the current measurements (Dyer, 1970; Lees, 1983; Dyer, 1986).

RESULTS AND DISCUSSIONS

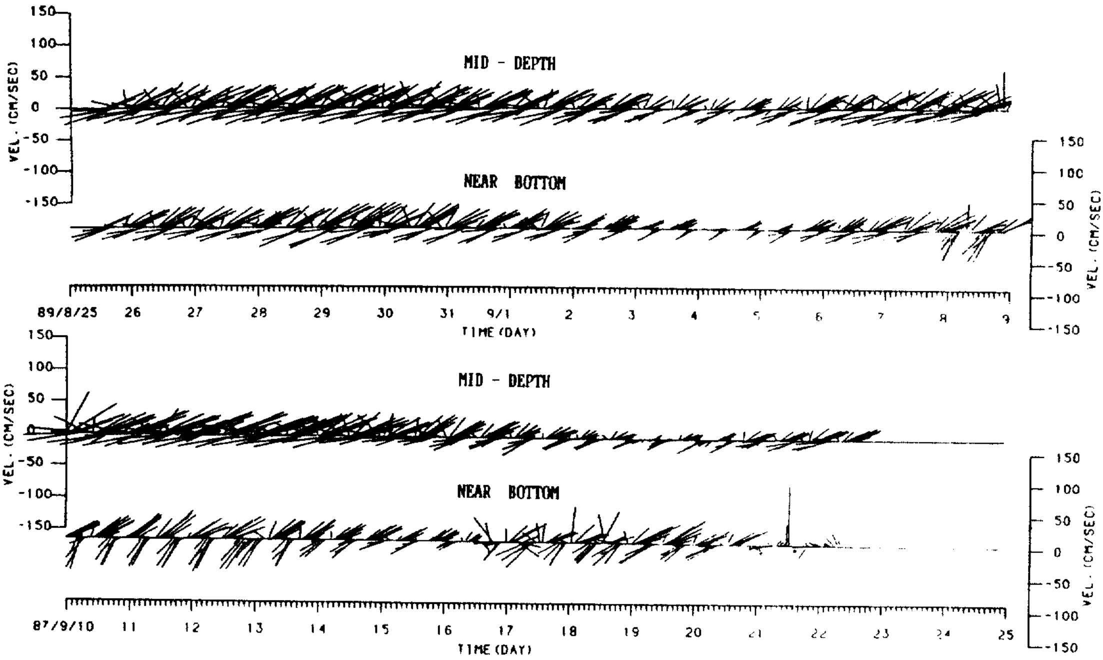

Fig. 2. Speeds and directions of tidal current in the mid-depth (9.0 m above bottom) and near bottom (1.5 m above bottom) at station A1.

Tidal Currents

The tidal current of the study area is semi-diurnal, and strong and stable. The tidal current flows largely in east-northeastward for flood and west-southwestward for ebb (Figs. 2 and 3). In mid-depth, the mean and maximum speed of tidal current for the entire period are 56.3 cm/sec and 101.2 cm/sec in flood tide, and 63.7 cm/sec and 134.5 cm/sec in ebb tide, respectively. On the other hand, the mean and maximum speed in near bottom are 43.9 cm/sec and 92.5 cm/sec in flood tide, and 43.8 cm/sec and 95.3 cm/sec in ebb tide, respectively.

Fig. 4 shows the means and standard deviations of tidal current speed of flood and ebb tide averaged over 33 tidal cycles (near bottom) and 53 tidal cycles (mid-depth). The duration of flood tide is a little longer than that of ebb tide in both depths. However, the peak tidal current velocities during the ebb tide are a little higher than those during the flood tide (esp. in mid-depth). The residual current by harmonic analysis is relatively weak (5-8 cm/sec) and northward in both depths.

Over the entire study period (August 24~ September 28, 1987) at the satation A1, the temperature ranges from 18.9℃ to 23.0℃ in mid-depth and from 18.2℃ to 22.8℃ in near bottom. On the other hand, the salinity ranges from 27.04‰ to 29.29‰ in mid-depth and from 26.1‰ to 29.90‰ in near bottom. The sigma-t of mid-depth and near bottom has the values of 18.3 g/cm^3~20.2 g/cm^3 and 17.5 g/cm^3~20.6 g/cm^3, respectively. The average values of the temperature, salinity, and sigma-t over the whole period are 21.6℃, 29.2‰, and 20.0 g/cm^3 in mid-depth, and 21.6℃, 28.6‰ and 19.5 g/cm^3 in near bottom, respectively.

Kinematic viscosity of each depth at the station A1 for the average temperature and salinity is 1.0076×10^{-2} cm^2/sec in mid-depth and 1.0067×10^{-2} cm^2/sec in near bottom. Thus, considering the significant figures of the data, the kinematic viscosity and density of the sea water in the study area can be reasonably approximated to be 1.01×10^{-2} cm^2/sec and 1.02 g/cm^3 in both depths, respectively.

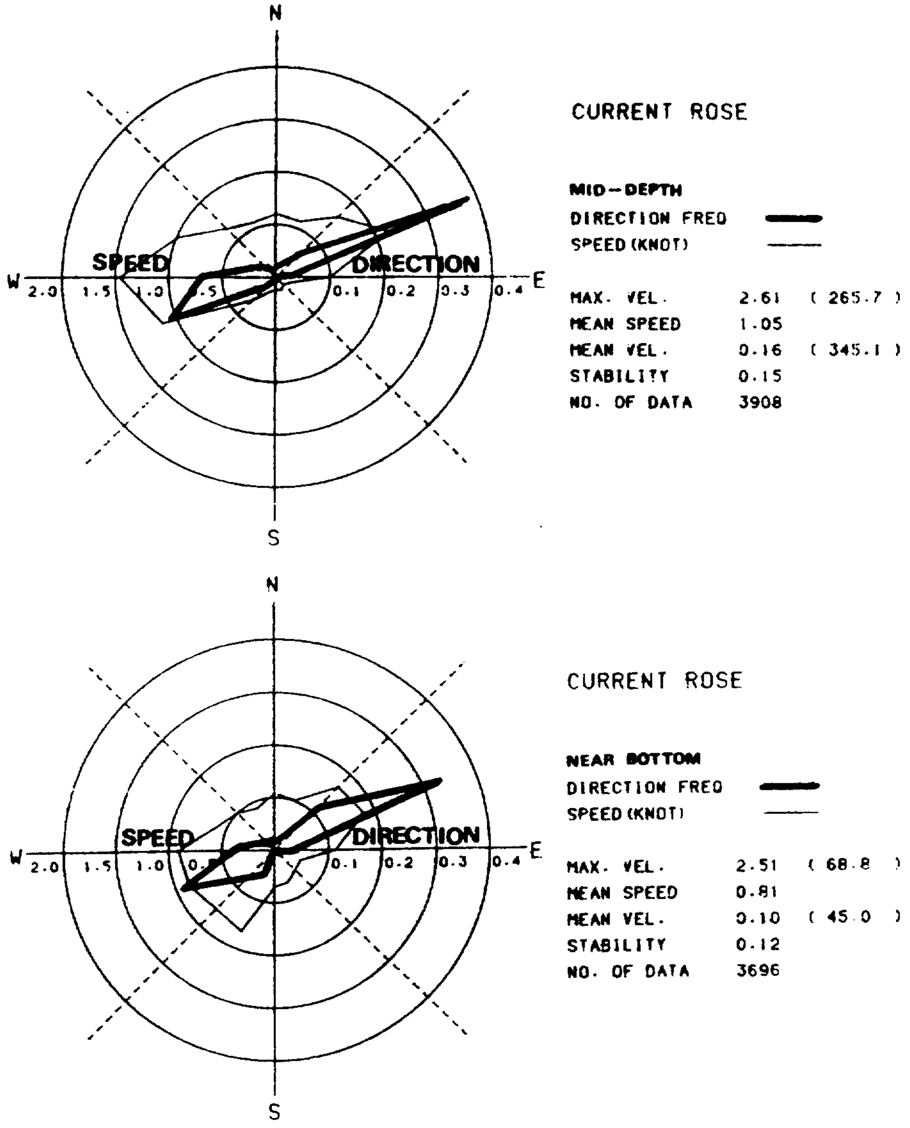

Fig. 3. Current rose diagrams showing the frequency and average speed of tidal current at station A1. Unit of speed is knots, and the number in parenthesis is the direction.

Roughness length (y_o)

For hydrodynamically smooth flow, laboratory investigations have revealed that roughness length (y_o) is a function of kinematic viscosity and shear velocity (Sternberg, 1968; Middleton and Southard, 1984; Dyer, 1986). In case of hydrodynamically rough flow, however, viscous effects become unimportant (Sternberg, 1968; Middleton and Southard, 1984). Ideally, the values of y_o have to be determined from velocity profile measurements in near bottom, whenever needed. However, direct measurement of near bottom velocity profile (in boundary layer) is extremely difficult even in the measurement at laboratory. Thus, y_o is used to be obtained by comparisons of the sediment characteristics in the study area with those of other areas for which estimation of y_o are available (Sternberg, 1968; Kachel and Sternberg, 1971; Ludwick, 1975; Gadd *et al.*, 1978; Heathershaw, 1981; Lees, 1983).

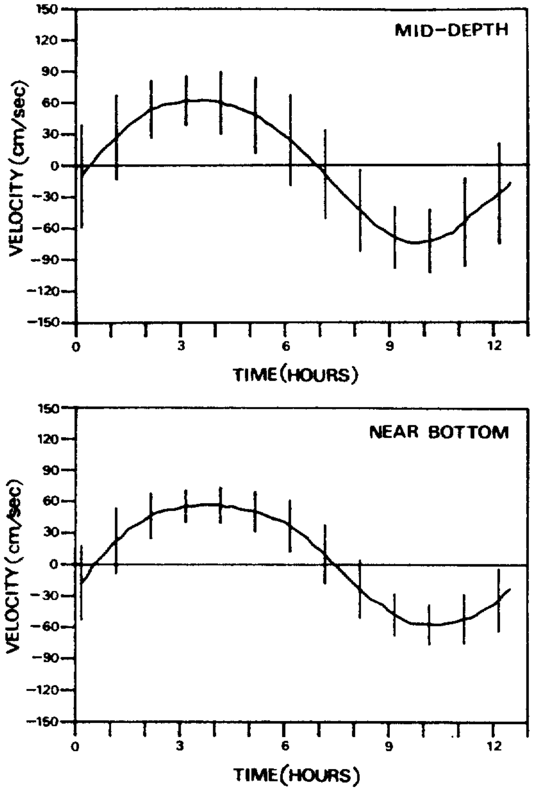

Fig. 4. Means and standard deviations of tidal current velocity during flood and ebb tide averaged over 33 tidal cycles (near bottom) and 53 tidal cycles (mid-depth) at station A1.

Table 1. Roughness length (y_o) and subsequent drag coefficient (C_{100}) used for calculation of bedload transport rate.

Sediment	Possible bedform	y_o(cm)	$C_{100}^{(1)}$
Mud$^{(2)}$	Planar	0.01	1.9×10^{-3}
Sand	Unrippled	0.04	2.6×10^{-3}
Muddy sand or sandy mud	Planar	0.05	2.8×10^{-3}
Sand and gravel	Irregular	0.1	3.4×10^{-3}
Find sand	Rippled	0.5	5.7×10^{-3}
Sand or gravel	Rippled or irregular	0.5	5.7×10^{-3}

(1): Drag coefficients (C_{100}) are calculated by the relation that $C_{100}=[\kappa/(\ln 100/y_o)]^{1/2}$ (Dyer, 1986)

(2): y_o for the mud bottom is included for completeness

Table 1 is made by compiling y_o values from various sources (Dyer, 1970; Ludwick, 1975; Vincent and Harvey, 1976; Heathershaw, 1979; Dyer, 1980; Lees, 1983; Dyer, 1986). The values in Table 1 can be regarded as mean values which are independent of any changes occurring over the tidal cycles.

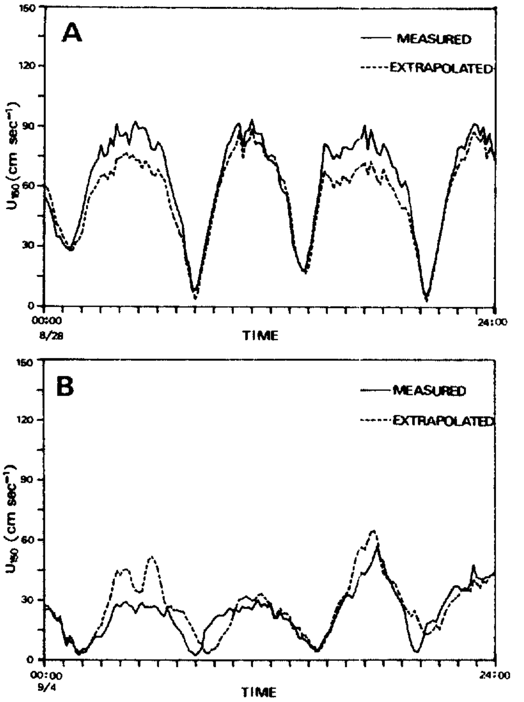

Fig. 5. The differences between U_{150} measured in near bed and U_{150} extrapolated from the velocity in mid-depth at station A1. A is the data at spring tide and B is the data at neap tide. Exponent P of power law (eq. 2) is assumed to be 0.1.

Choi (1990) reported that the sediment at the station A1 is medium sand (mean size of 0.035 cm) and unimodal with good modality. The sonographs obtained from side scan sonar survey near station A1 show the ripple bedforms superimposed on sand waves (Choi, 1990). Thus, it is reasonable to assume that the roughness length in the study area ranges between 0.1 cm and 0.5 cm. Drag coefficient (C_{100}) converted from the roughness length of 0.1 cm and 0.5 cm is 3.4×10^{-3} and 5.7×10^{-3}, respectively. From the field measurements conducted within six tidal channels in Puget Sound, Washington, Sternberg (1968, 1972) concluded that the value of C_{100} was not very sensitive to the bed configuration in case of hydrodynamically rough flows. He suggested the mean value of C_{100} as 3.1

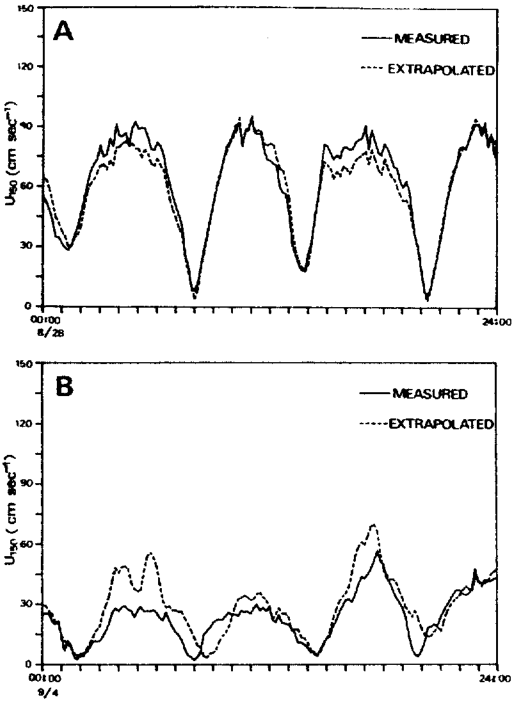

Fig. 6. The differences between the measured velocities and the extropolated velocities same as Fig. 5, except that the value of P is assumed to be 0.15.

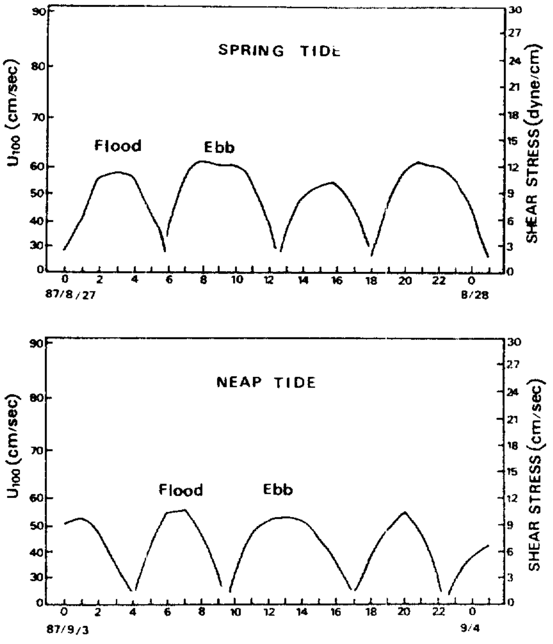

Fig. 7. Current velocity at 1.0 m above bottom (U_{100}) and shear stress (τ_o) at one hour interval at spring tide (August 28, 1987) and neap tide (September 4, 1987). Shear velocity (U_*) can be calculated from shear stress and sea water density (ρ) such as $U_* = (\tau_o/\rho)^{1/2}$.

$\times 10^{-3}$ for the complex bed composed of rocks, gravel, and ripple sand bottom. Thus, roughness length(y_o) of 0.1 cm seems to be proper in the present study area.

Boundary Shear Velocity

The tidal current data obtained in near bottom at the station A1 are reliable only in the first half period due to the malfunction of current meter. Thus, tidal current velocity in near bottom for the later half period are extrapolated from those measured at mid-depth (9.0 m above bottom) using empirical approach "power law" (eq. 2).

The mean, standard deviation, and the confidence level of the differences between the measured and the extrapolated velocities in near bottom at neap tide and spring tide are examined separately (Figs. 5 and 6). Assuming the exponent P has the value of 0.1 suggested by Dyer (1970) and Lees (1983), the differences between the measured and extrapolated values have the mean value of -5.76 ± 0.32 cm/sec with 95% confidence level (Fig. 5). However, assuming the P has the highest value of 0.15 suggested by Dyer (1970), the differences have the mean value of -2.06 ± 0.36 cm/sec with 95% confidence level (Fig. 6). Therefore, the exponent P of power law (equation 2) is assumed to be 0.15 in the present study.

Equation (1) is, so called, Von Karman-Prandtl logarithmic velocity profile equation. Although this equation was derived from steady, uniform flow, the occurrence of a logarithmic velocity distribution in the lower two meters of marine tidal flow appears to be well established (Sternberg, 1967; Kachel and Sternberg, 1971; Ludwick, 1975; Heathershaw, 1981; Lees, 1983). And it has been reported by numerous researchers that equation (1) can fairly approximate the velocity distribution throughout the full depth in wide-open channels for both smooth and rough boundaries (Blatt *et al.*, 1980; Middleton and Southard, 1984; Dyer,

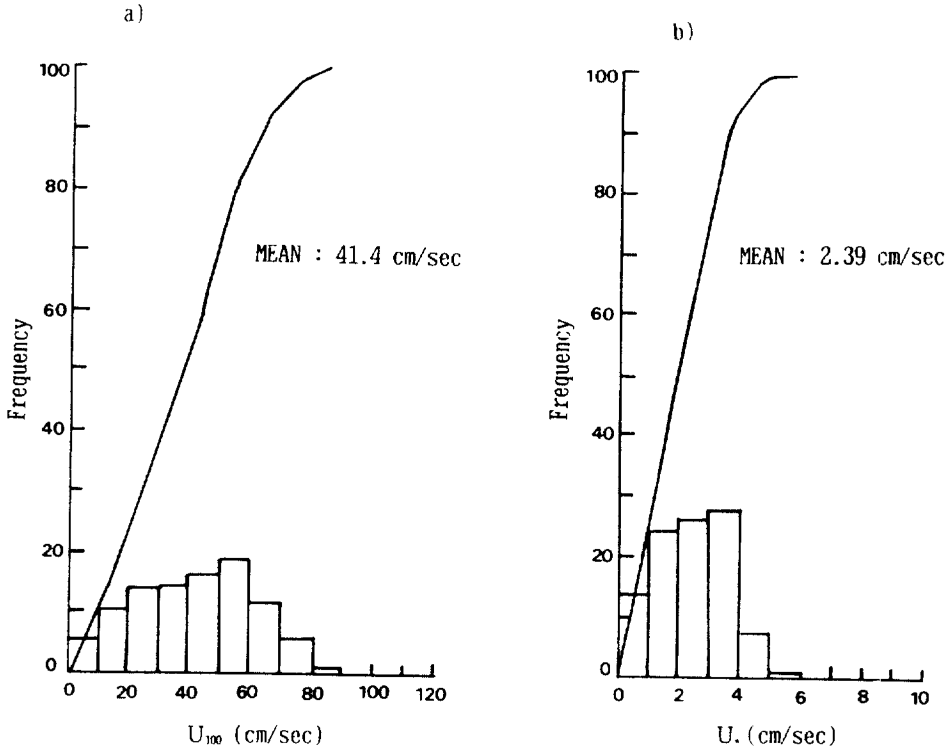

Fig. 8. Histograms and cumulative curves of velocity distribution at station A1 from August 25 to September 27, 1987. U_{100} and U_* are calculated using logarithmic velocity profile equation (1).

1986).

Choi (1990) proposed that the calculation of shear velocity by logarithmic velocity profile under the simplified assumption of steady flow can be applied to the real situation in the sea. From the measured and extrapolated current velocities in near bottom (U_{150}), the boundary shear velocities (U_*) over the entire period are calculated using logarithmic velocity profile (eq. 1) and assumed roughness length (y_o). The current velocities at one meter above bottom (U_{100}) are also needed for the estimation of sediment transport rate by Bagnold's bedload formula (Bagnold, 1963; Hardisty, 1983; Choi, 1990). Thus, U_{100} is calculated from the estimated U_* by logarithmic velocity profile equation (1).

Fig. 7 shows the U_{100} and U_* calculated from the average speed of the tidal current at station A1. It is shown that the U_{100} and U_* during flood tide is a little higher than those during ebb tide. Fig. 8 shows the histograms and cumulative curves of the velocities (U_{100} and U_*) distribution at station A1 from August 25 to September 27, 1987. The mean values of U_{100} and U_* are 41.4 cm/sec and 2.39 cm/sec, respectively (Fig. 8).

Using the modified Shields' diagram (Madsen and Grant, 1976), critical shear velocity (U_{*c}) for moving sands at the station A1 was reported to be 1.40 cm/sec from the mean grain size, kinematic viscosity, and density of the sea water and the sand grain (Choi, 1990). It can be shown from Fig. 8 that about 70% of the estimated U_* are higher than the critical shear velocity of 1.40 cm/sec reported by Choi (1990). Thus, it can be suggested that the most of sands in the study area are easily eroded and transported for the greater part of tidal period.

CONCLUSION

Tidal current data at station A1 in the study area show that the duration of flood tide is longer than that of ebb tide. However, the mean and maximum speed of the tidal current over the entire period are 56.3 cm/sec and 101.2 cm/sec for flood, and 63.7 cm/sec and 134.5 cm/sec for ebb in mid-depth (9.0 m above bottom). On the other hand, those in near bottom (1.5 m above bottom) are 43.9 cm/sec and 92.5 cm/sec for flood, and 43.8 cm/sec and 95.3 cm/sec for ebb, respectively. The average water temperature, salinity, and sigma-t of the sea water in near bottom at station A1 are 21.6℃, 29.2‰, and 20.0 gm/cm^3, respectively. The kinematic viscosity in near bottom is estimated to be 1.02×10^{-2} cm^2/sec.

Exponent P in power law, which is generally used for extrapolation from mid-depth current velocity to that at the top of a notionally logarithmic layer, is estimated to be 0.15 in the present study. U_{100} and U_*, which are necessary for estimation of sediment transport rate, are calculated using logarithmic velocity profile equation from the measured and extrapolated velocities in near bottom (U_{150}) at station A1. Assuming roughness length (y_o) is 0.1, the mean values of U_{100} and U_* are 41.4 cm/sec and 2.39 cm/sec, respectively. Comparing the mean U_* of the present study and U_{*c} of Choi (1990), it can be suggested that the most of sands in the study area are easily eroded and transported for the greater part of tidal period.

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