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Modeling Sedimentation of Fine-grained Sediments in a Rectangular Basin
長方形 海盆內의 細粒 堆積物 堆積模型

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Abstract□A simple box model was applied to the sedimentation of fine-grained sediments in a rectangular basin. Using the model explanation of the net depositional process of fine-grained sediments in a small tide-dominated rocky embayment was possible by a careful evaluation of coefficients for erosion and deposition. For a basin with an inlet through which the exchange of suspended sediments occurs between open sea, the model shows that the time-averaged concentration of suspended sediments for a tidal cycle reaches a steady state initial abrupt change in concentration. During a tidal cycle deposition of sediments seems to occur when the magnitude of tidal currents is substantially low near the slack waters. Resuspension and erosion of bottom sediments take place near the peak of tidal currents. For a depositional basin. Gamagyang Bay, the duration and the maximum rate of deposition appear to be longer and higher than those of erosion, which accounts for the net deposition of fine-grained sediments. The time-averaged concentration of suspended sediment in the basin is slightly lower than that of the open water due to the net deposition. The instantaneous concentration of suspended sediments showed the maximum value about an hour before high water and the minimum about an hour after low water.

要 旨: 간단한 box 模型이 長方形 海盆에서의 細粒 堆積物의 堆積現像을 설명하기 위하여 이용되었으며, 이 模型에 필요한 浸蝕 및 堆積率의 係數를 조사하여 南海岸 가막양만에 적용하여 보았다. 해분이 외해와 연결되어 있고 외해의 부유퇴적물 농도가 일정하면 해분내에서 한 조석 주기 동안의 평균 부유퇴적물 농도는 일정한 값을 유지하게 되고, 조류의 憩流時 부근에는 퇴적이 일어나고 최대유속시 부근에는 바닥 퇴적물의 재부유 및 침식이 일어나는 것을 보여주고 있다. 가막양만 처럼 퇴적이 우세한 해분에서는 조석 주기 중 퇴적이 일어나는 시간과 최대 퇴적률이 침식에 비하여 크게 나타나고 있으며, 이러한 퇴적 우세 해분의 부유퇴적물 평균농도는 외해의 부유퇴적물 농도보다 낮은 값을 보이고 있다. 또한, 조류의 유속변화에 따른 해분내의 부유퇴적물 농도변화는 고조의 약 한 시간 전에 최대값을 나타내고 低潮의 약 한 시간 후에 최소값을 나타낸다.

1. INTRODUCTION

Sedimentation of fine-grained sediments in a basin such as harbours or bays sometimes causes a serious problem in the mariculture of benthic animals or the maintenance of waterways for transportation. Usually basins are connected to the open sea through tidal inlets. Tidal currents through the inlet play an important role in the exchange of sea water and suspended sediments between the basin and the open sea.

For a basin which receives little sediment from the land via rivers and streams, the source of fine sediments within the basin is the open sea. During the flood current suspended sediments are carried into the basin from the open sea. Deposition of the sediments takes place as the speed of the current becomes weaker. During the ebb current resuspension of the bottom sediment takes place as the speed of the current becomes stronger

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*韓國海洋大學 海洋工學科(Department of Ocean Engineering, Korea Maritime University, Pusan 606-791, Korea) and the resuspended sediments are carried out of the basin to the open sea. The surplus or the deficit of sediments to the bottom during the exchange of sediments determines the net depositional or erosional environment of the basin.

These processes of transport, erosion, and deposition of sediments may not be a discrete process but a continuous and simultaneous process (McCave and Swift, 1976; Dyer, 1986). However the net effect of erosion or deposition can be examined in terms of the rate of erosion or deposition (Odd and Owen, 1972; McCave and Swift, 1976; Owen, 1977). The present study implements a simple box model to explain the sedimentary process of fine-grained sediments considering the rate of erosion and deposition and the horizontal flux of suspended sediments by the tidal currents. The model is also applied to a small rocky embayment, Gamagyang Bay, by evaluating the model parameters in the bay.

2. TRANSPORT, DEPOSITION AND EROSION

Water mass within a bay is continuously mixed and exchanged with the open water by tidal currents. Thus the concentration of suspended sediment in the water column within the bay varies with tidal currents mainly due to erosion, deposition, and advection during the tidal cycle.

Neglecting the horizontal diffusion the mean concentration of suspended sediments within a semi-enclosed rectangular basin, the axis of which is parallel to the direction of tidal currents can be written as

$$\frac{\partial (h\,C)}{\partial t} = \left(\frac{\partial m}{\partial t}\right)_e - \left(\frac{\partial m}{\partial t}\right)_d + \frac{\partial F}{\partial X} \qquad (1)$$

where, h : water depth

C : mean concentration of suspended sediments within the basin

$\left(\frac{\partial m}{\partial t}\right)_e$: rate of erosion

$\left(\frac{\partial m}{\partial t}\right)_d$: rate of depositon

$\frac{\partial F}{\partial X}$: advection by tidal currents

Near the viscous sublayer on a hydraulically smooth bed sediments continuously settle down into the sublayer and are deposited on the bed. At the same time the sediments above the sublayer are continuously replenished by the ejection of sediments from the sublayer. Thus the net rate of erosion or deposition can be given by the difference between the settlement and the ejection through the sublayer(McCave and Swift, 1976).

The rate of erosion or deposition is dependent upon the acting shear stress near the bed, and it can be represented in terms of overall probability of erosion or deposition (Einstein and Krone, 1962; McCave and Swift, 1976; Owen, 1977). When the acting shear stress near the bed exceeds a certain limit for erosion, sediment on the bed is eroded and suspended into the water column. On the other hand if the near-bottom shear stress is lower than the limit for deposition, suspended sediment within the water column is deposited on the bed. The probability of depostion and erosion can be given as the ratio of excessive or deficit shear stress to the limiting shear stress for deposition or erosion, respectively, and the rate of erosion and depositon is given by several workers (Ariathurai and Krone, 1976; Odd and Owen, 1972; Owen, 1977) as

$$\begin{aligned} \left(\frac{\partial m}{\partial t}\right)_e &= M\left(\frac{\tau}{\tau_e}-1\right) \quad \text{for } \tau > \tau_e \\ &= 0 \qquad\qquad\qquad \text{otherwise} \end{aligned} \qquad (2)$$

$$\begin{aligned} \left(\frac{\partial m}{\partial t}\right)_d &= V \cdot C\left(1-\frac{\tau}{\tau_d}\right) \text{for } \tau < \tau_d \\ &= 0 \qquad\qquad\qquad \text{otherwise} \end{aligned} \qquad (3)$$

where M : coefficient for erosion (mass/area/time)

τ : acting near-bottom shear stress

τ_e : limiting shear stress for erosion

V : settling velocity of sediment particles

τ_d : limiting shear stress for deposition

For cohesive sediments the limiting shear stress for erosion (τ_e) is substantially larger than the limiting shear stress for deposition (τ_d)(McCave, 1972), sediments are only transported in suspension without any net erosion or deposition when the shear stress is between τ_e and τ_d. The acting shear stress by turbulent flow near the bed over a hydraulically smooth bottom can be estimated by the Prandtl-Von Karman logarithmic velocity profile (Sleath, 1984).

$$\frac{U}{U_*}=5.75\log\left(\frac{U_* h}{\nu}\right)+3.0 \tag{4}$$

where, U : depth-average velocity

U_* : near-bottom friction velocity

v : kinematic viscosity of the fluid

The friction velocity in the equation (4) is related to the bottom shear stress as

$$\tau=U_*^2\cdot\rho \tag{5}$$

where, ρ : density of the fluid. Horizontal flux of suspended sediment by tidal advection between the semi-enclosed basin and the open sea through the inlet can be given as

$$\frac{\partial F}{\partial X}=\frac{U\cdot h\cdot C_i}{L} \tag{6}$$

where, C_i : concentration of suspended sediment in the water passing through the cross-sectional area of the inlet

L : length of the basin

For a semi-diurnal tide whose elevation changes sinusoidally with the period of 12 hours the water depth changes with time as

$$h=h_o+A\sin(\sigma t) \tag{7}$$

where, h_o : mean water depth of the basin

A : tidal amplitude

σ : angular frequency of the tide (=2 π/12 hrs)

Then the depth-averaged current velocity within the bay is

$$U=\frac{L}{h}\frac{\partial h}{\partial t}=\frac{L}{h}A\sigma\cos(\sigma t) \tag{8}$$

3. MODEL APPLICATION IN THE GAMAGYANG BAY

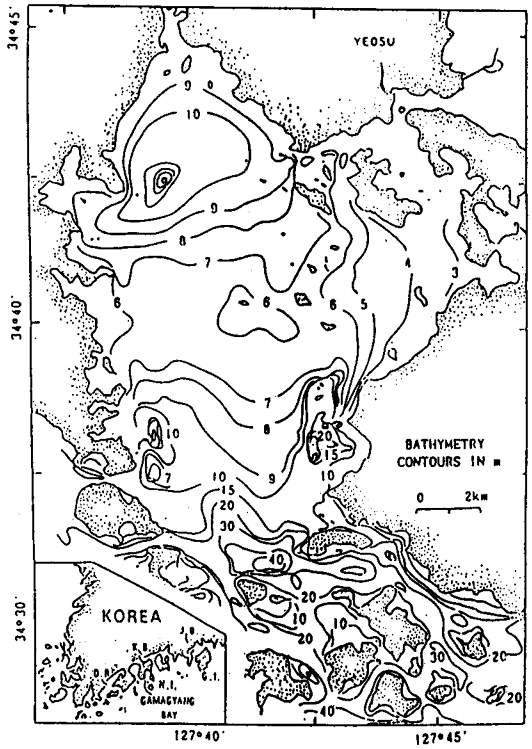

Fig. 1. Index map and the bathymetry of the Gamagyang Bay : D.B=Deukryang Bay, K.B.=Kwangyang Bay, G.I.=Geoje Island, N.I.=Namhae Island. Bathymetry was corrected to mean sea level.

The Gamagyang Bay in the southern coast of Korea, is a post-glacially submerged embayment, characterized by a thick accumulation of fine-grained sediments up to 30 m above the acoustic basement (Kang and Chough, 1982). Main portion of the bay is shallow and featureless except for the moats and depressions around the small islands and headlands (Fig. 1). The seafloor is covered with silty clay and clayey silt (Kang and Chough, 1982). To the south the bay is connected to the open sea (South Sea) through numerous inlets; a small inlet connects the bay to the Kwangyang Bay to the northeast through which exchange of the water mass is minimal (Chough *et al.*, 1982). Mean tidal range in the bay is 195 cm up to 380 cm during spring tide, 80 cm during neap tide (National Hydrographic Office of Korea, 1990, Chough *et al.*, 1982). Tidal currents are semi-diurnal, and reversing, and attain up to 25 to 35 cm/sec (Chough *et al.*, 1982). The bay is

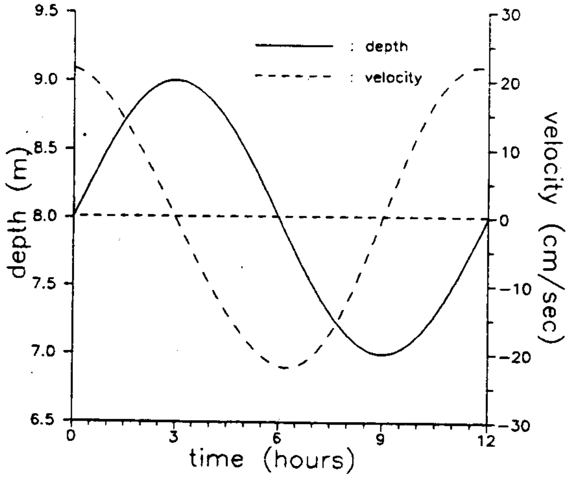

Fig. 2. Simulated tidal current and water level change in the Gamagyang Bay. Tidal current is slightly distorted from the pure cosine curve.

bounded by rocky mountains with limited drainage area. The source of recent sediments on the bottom was thought to be the open sea mainly transported into the bay by tidal currents through the southern inlets (Kang and Chough, 1982).

Main portion of the basin consisting of the thick accumulation of sediments was assumed to be a semi-enclosed rectangular basin. It was also assumed that the basin was only affected by the tidal currents through the southern inlets and the water level changes sinusoidally with the tidal period of 12 hours. Fig. 2 shows the calculated water depth and speed of tidal currents in the bay.

Parameters to apply the model to the Gamag yang Bay are given in the Table 1. Exact values for the parameters are quite controversial and need a careful evaluation (ASCE, 1975; Owen, 1977; Dyer, 1986; Metha, 1989). Ariathurai and Arulanandan (1978) found that the erosion constant (M) showed as steep change with the water temperature. Many workers used the value inthe range between 10^{-6}-2×10^{-5} g/cm^2/sec (Lang *et al.*, 1989; Perillo and Sequeira, 1989; Uncles and Stephens, 1989). However, Delo (1988) recommends to use the M to be 0.002 τ_e in SI unit system, which yields $M=1\times10^{-5}$ g/cm^2/sec for the present study.

The limiting shear stress for erosion (τ_e) depends on the nature of sediment (consolidation, clay mineral contents, organic content etc.). Migniot (1977) gives a way of determining the τ_e by the yield strength of soil. However the dependence of τ_e on the yield strength is also controversial (Partheniades, 1965; Sleath, 1984). For the present study τ_e was taken to be 0.5 dynes/cm^2 since the experiment by Sheng and Lick (1979) shows that no erosion takes place below 0.5 dynes/cm^2 when the acting bottom shear stress is less than 2 N/m^2. McCave (1972) also cites that shear stress of approximately 0.57 dynes/cm^2 could erode muds after a few hours of consolidation. Thus the 0.5 dynes/cm^2 seems to be a reasonable value for the muds being eroded immediately after deposition.

Table 1. Parameters applied to the Gamagyang Bay

M	10^{-5}	g/cm^2/sec	L	12.0	km
τ_e	0.5	dynes/cm^2	C_o	4.0	mg/*l*
τ_d	0.116	dynes/cm^2	ρ	1.026	g/cm^3
h_o	800	cm	ν	0.012	cm^2/sec
A	100	cm	V	2.726×10^{-3}	cm/sec

In the nature most suspended particles settling in the water are composite particles of minerals and organic matters (McCave, 1975; West *et al.*, 1990). McCave (1975) reviewed the data on the bulk density of suspended particles, and gives the average density of 1.228 g/cm^3 for the 7-8 ϕ particles assuming the mineral/organic ratio of 60/40 and the densities of 2.5 g/cm^3 and 1.03 g/cm^3 for the mineral and the organic matter respectively. Settling velocity of the particles was calculated by using the Stokes law assuming the mean grain size of the bay was 7.5 ϕ ($\rho=1.228$ g/cm^3).

McCave and Swift (1976) extrapolated the critical shear stress for the fine non-cohesive sediments to be the limiting shear stress for deposition (τ_d) for the cohesive sediments. τ_d for the present study was interpolated using the calculated settling velocity and the data of McCave and Swift (1976).

Sediment concentration in the open ocean (C_o) was assumed to be a constant of 4 mg/*l* which can be an approximate value of the suspended sediment concentration in the near-coastal waters of the South Sea (Cho, 1990).

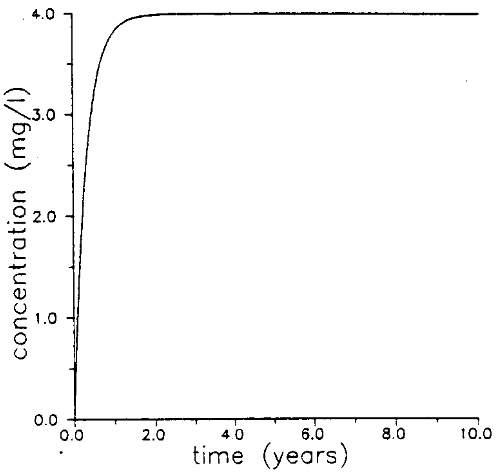

Fig. 3. Change of average concentration for each tidal cycle in the bay of initially no sediments in the water.

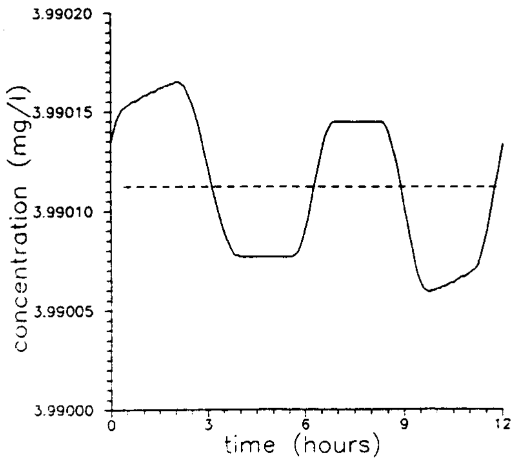

Fig. 4. Change of concentration in the bay during a tidal cycle. Dashed line indicates the mean.

4. RESULTS AND DISCUSSIONS

Equation 1 was solved numerically using the 4th-order Runge-Kutta method. Fig. 3 shows that the time-averaged concentration for each tidal cycle increases abruptly due to the tidal mixing and reaches a steady state even though the initial concentration within the bay was much lower than the concentration of suspended sediments in the open water. The bay maintains a constant time-average concentration, which is slightly (approximately 0.25 %) lower than the concentration in the open water.

However the instantaneous concentration during the tidal cycle in the bay changes with time due to the erosion, deposition, and advection (Fig. 4). Even though the amount of variation is extremely small, it shows that the mean concentration in the bay increases during the periods of erosion and decreases during the periods of deposition. Furthermore, due to the influx of open water, with higher concentration, the concentration still in creases in the periods of no erosion or deposition during the flood. On the other hand no change in concentration occurs during the ebb when the sediment is only transported without any erosion or deposition (Figs. 4 and 5). The concentration reaches its maximum about an hour before high water and minimum about an hour after low water (Fig. 4).

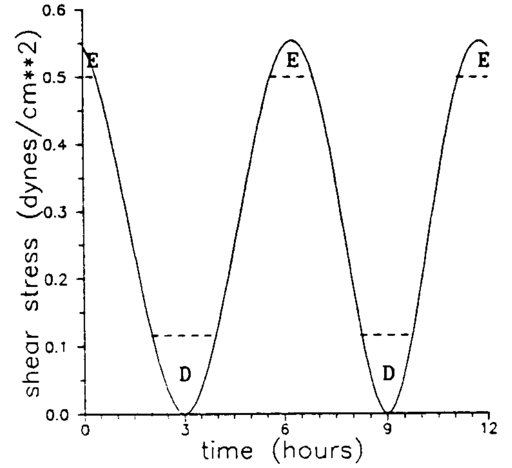

Fig. 5. Change of bottom shear stress in the bay during a tidal cycle. E and D denotes when the shear stress exceeds the τ_e and τ_d respectively.

Shear stress which is responsible for the erosion and deposition of the sediment reaches the maximum value at the time of peak current velocities between the two successive slack waters. The shear stress is minimum at the high and low waters (Fig. 5). Fig. 5 also shows that the τ_e is exceeded by a smaller amount of acting shear stress for a shorter duration compared to the amount and duration for the acting shear stress below the τ_d.

Due to the difference in magnitude and dura-

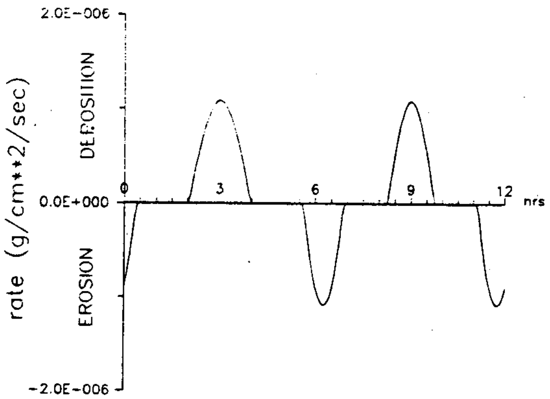

Fig. 6. Rates of deposition and erosion within a tidal cycle.

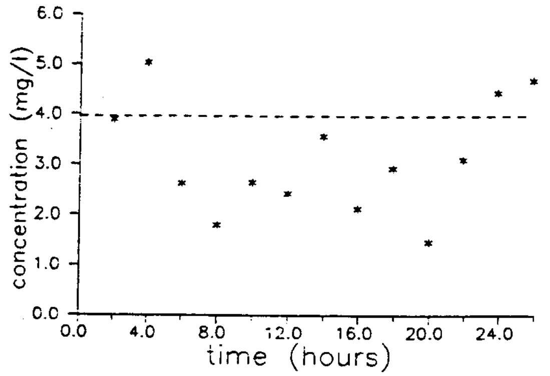

Fig. 7. Depth-averaged concentration measured at a station near the eastern margin of the bay. Dashed line is the calculated mean concentration in the bay (appr. 3.99 mg/*l*).

tion of deposition and erosion. Deposition occurs longer at higher rate than the erosion (Fig. 6). Consequently the longer and higher rate of deposition makes the Gamagyang Bay a net-depositional environment. Net rate of deposition for each tidal cycle was calculated to be approximately 2.08 $\times 10^{-3}$ g/cm^2/12 hrs, which is equivalent to 1518.4 g/cm^2/1000 years.

The organic carbon content in the core samples of the bay was about 0.5 % on the whole (Chough *et al.*, 1982). Cho (1990) also reports that the organic carbon content of less than 1 % in the sediment samples taken in the South Sea, which suggests that the organic matter in the bottom sediment is almost consumed at all during and after deposition. Then the net deposition rate gives 911 g/cm^2/1000 years for mineral deposition. Bulk density of the sediments in the seas adjacent to the bay ranges from 1.5 to 1.9 g/cm^3 within the top 1 m of the core samples (ADD, 1988). Assuming the bulk density of the thick sediment beneath the seafloor is about 2.0 g/cm^3 the rate of net deposition can produce the accumulation of the bottom sediment at a rate of about 455 cm/1000 years in the bay. The approximately 20 m thick sediments in the middle of the bay was thought to be deposited during the last 4500 years (Kang and Chough, 1982), which gives an accumulation rate of about 444 cm/1000 years. The calculated value of 455 cm/1000 years shows a reasonable agreement with the rate estimated from the bottom profiles.

Even though the exact value for the parameters may be variable, the model shows that the maximum deposition occurs near the slack waters and maximum erosion occurs near the peak current speeds, and there may be a period of no net-deposition or-erosion between the maximum deposition and the maximum erosion. The sediment concentration within the water column is directly related to the processes of transport, erosion, and deposition. It shows that the maximum concentration occurs about an hour before the high water and the minimum concentration about an hour after the low water.

In a depositional basin like the Gamagyang Bay the maximum rate for deposition is higher and the duration for deposition is longer than those for erosion. This asymmetrical process keeps the basin in a net-depositional environment, which results in a slightly lower concentration of suspended sediments in the basin than that of the open sea. Local variation of mean concentration in the basin may be expected. Actual measurement of suspended sediment concentration in the Gamagyang Bay in front of an island where the mean water depth was approximately 9 m shows a wide variation (Fig. 7). The average value of the measurement is about 3.4 mg/*l*. which is lower than the calculated mean concentration in the bay.

5. CONCLUSION

Sedimentation of fine-grained sediments in a semi-enclosed rectangular basin which is connected to the open sea by an inlet can be investigated by using a simple box model. For the application of the model to a real basin careful evaluation of the parameters is essential.

Deposition of suspended sediments from the water column is most likely to occur near the slack waters, and the erosion of the bottom seems to occur near the maximum tidal currents. However, the net deposition and erosion during a tidal cycle is not symmetrical. For a depositional basin deposition is dominant over erosion in maximum rate and duration in the basin. The mean concentration of suspended sediment in the basin is kept constant which is slightly lower than the concentration in the open water due to the net-depositional environment. The instantaneous depth-averaged concentration within a tidal cycle shows its maximum about an hour before high water and the minimum about an hour after low water due to the change in the rates of erosion, deposition, and horizontal flux.

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