Entrainment of Bottom Sediment in the Seto Inland Sea
in Summer*

Kichiichiro Kawana†, Terumi Tanimoto‡ and Takashi Ichiye†

Abstract: Time series of the vertical distribution of resuspended matter and bottom current were collected concurrently during summer at a few anchored stations in the Seto Inland Sea. The vertical distribution of resuspended matter was measured every hour for about one tidal cycle and the three components of current fluctuation were obtained at each sampling station. Current data at each sampling station show that the bottom is hydraulically smooth.

Assuming that the averaged vertical distribution of resuspended matter for one tidal cycle shows a steady state distribution, the settling velocity $W_s$ of resuspended matter is estimated to be in the range of $1.2 \times 10^{-7}$ to $5.7 \times 10^{-7}$ cm sec$^{-1}$ from analysis of the averaged distributions.

The relation between the erosion rate and the bottom shear stress for this study area is investigated and is compared with that for other areas. The results show that the erosion of sediment in the Seto Inland Sea during summer occurs even due to the low bottom shear stress which is considered as almost smooth hydraulically.

1. Introduction

The shear stress of the current near the sea bottom causes particles to be transported from the bottom into the overlying water. Erosion of cohesive sediment has been studied extensively from the point of view of hydraulics and bed load as well as in regard to the chemical and physical behavior of individual particles (Postma, 1967; Partheniades and Paaowell, 1970; Ariathurai and Arulanandan, 1978; Kelly and Gularte, 1981; Kamphuis and Hall, 1981). The process of transport of resuspended matter in the overlying water has been studied, using numerical models based on the mass conservation equation (Yalin, 1977). Sheng and Lick (1979) investigated the process of transport of resuspended matter in Lake Erie by means of numerical models. Onishi (1981) made a model of transport of the sediment and pollutants. In order to determine transport and dispersion of resuspended matter in the overlying water quantitatively using numerical models, comprehensive information on entrainment and deposition process at the sediment-water interface is needed. Raudkivi and Hutchison (1974) carried out an experiment in regard to erosion by use of a greatly simplified clay-water system. Fukuda and Lick (1980) measured experimentally the rate of erosion of fine-grained, cohesive sediment in freshwater with an annular flume. Lavelle et al. (1984) developed a method to determine the erosion rate from field data of near-bottom currents and total suspended matter concentration and applied it to evaluate an in situ erosion rate for the fine-grained sediment in the main basin of Puget Sound, Washington. The rate of erosion of cohesive sediment is dependent not only on shear stresses but also on particle size, the mineral composition of the sediment and probably many other factors. In situ determination of the rate of erosion is important in order to understand mechanism of resuspension of cohesive sediment.

In the Seto Inland Sea, a very turbid bottom water which is produced during summer by entrainment of the deposited particles at the

---

* Received 25 November 1985; in revised form 8 August 1986; Accepted 5 September 1986.
† Government Industrial Research Institute, Chugoku 15000 Hiromachi Kure Hiroshima 737-01, Japan.
‡ Department of Oceanography Texas A&M University College Station, Texas 77843 USA.
bottom has been observed in a wide area (Kawana and Tanimoto, 1984). Because this turbidity strongly influences water quality, knowledge of the entrainment process is important for solving water pollution problems. Measurement of temporal variations of the bottom current and the vertical distribution of resuspended matter has been carried out at a few anchored stations. We analyzed the vertical distribution of resuspended matter and will discuss the relation between the erosion rate and bottom shear stress.

2. Method

Figure 1 shows the sampling stations, at which a ship was anchored for about 12 hr. The turbid bottom water was observed at these stations. Each sampling date is also shown in Fig. 1.

The three components of the current fluctuation were measured for one tidal cycle at each station with an acoustic current meter mounted at a height of 70 cm from the bottom. A 12-hr continuous record of flow velocities was initially digitized at intervals of one second and divided into segments of 10 min duration (Sumi, 1985). The mean velocity of the horizontal current \( \bar{u} \) was calculated for each ten-minute record. The friction velocity \( u_* \) is taken as a scaling parameter in the benthic boundary layer. Assuming that the height of current measurement was in the constant stress layer, \( u_* \) was determined from the correlation of the vertical velocity fluctuation \( w' \) and longitudinal velocity fluctuation along the mean current direction \( u' \) by use of \( u_*^2 = -u'w' \). Details of the design of the current meter were described by Sumi (1983).

The vertical distribution of the beam attenuation coefficient was measured every hour during the period of continuous current measurement by lowering an \textit{in situ} beam attenuation meter from a ship (Kawana and Tanimoto, 1984). The beam attenuation coefficient is defined as the attenuation per unit length of a beam of light passing through the sea water and is used as indicator of the concentration of total suspended matter (TSM). Water samples were collected at intervals of about 5 m from the surface to the bottom and were filtered through 0.45-µm Millipore filters. TSM concentration was determined gravimetrically.
3. Results and discussion

3.1. Water movement near the bottom

The time series of $\bar{u}$ at 70 cm from the bottom and $u_*$ are shown in Fig. 2. The tide in the Seto Inland Sea is dominantly semi-diurnal. However, $\bar{u}$ at each sampling station changes with periods that differ from the semi-diurnal period, as indicated by the presence of higher harmonics. These higher harmonics may be mainly due to local eddies caused by topography.

Dynamics of the benthic boundary layer depends on $\bar{u}$ and the bottom condition or roughness (Monin and Yaglom, 1971). The flow in the benthic boundary layer can be classified into smooth, rough, and transitional hydrodynamic roughness regimes based on the value of the roughness Reynolds number $u_* D/\nu$ ($D$ is the grain diameter of the bottom sediment, $\nu$ the kinematic viscosity). The boundary layer in the hydraulically smooth flow has a low roughness Reynolds number $u_* D/\nu < 3.5$ (Soulsby, 1983). The bottom sediment in each sampling station is of mud with a median grain size of $10^{-3}$ cm (Tanimoto and Kawanami, 1984). Because $u_*$ shown in Fig. 2 is less than $1.0$ cm sec$^{-1}$, none of the roughness Reynolds number in this study exceed 3.5.

Figure 2 indicates that $\bar{u}$ ($z=70$ cm) and $u_*$ show similar trends of change with time. The friction coefficient $C_{70}$ is determined from $C_{70} = (u_*/\bar{u})^2$ by use of these data and the values of $C_{70}$ are plotted against $\bar{u}z/\nu$ (with $z=70$ cm) in Fig. 3. Although this figure shows large scatter, it is seen that the former decreases with increase of the latter. This can be explained from the logarithmic law for turbulent boundary layer which is expressed by $u = u_*/\kappa \ln(z/z_0)$, where $z_0$ is the roughness length and $\kappa$ is the von Karman's constant. Then $C_{70}$ is given by

$$C_{70} = \frac{\kappa}{\ln(z/z_0)}, \quad (z=70) \quad (1)$$

Thus, $C_{70}$ depends on $z_0$ as well as $z$. The roughness length $z_0$ for a hydraulically smooth flow decreases with the increasing mean speed as indicated by experiments by different authors quoted by Monin and Yaglom (1971). Therefore the above equation suggests that at a constant $z$ the friction coefficient decreases with increasing values of the mean velocity as shown in Fig. 3. On the other hand the friction coefficient for the hydraulically rough flow is distributed around a constant value (Komar, 1976). It is thought that the benthic boundary
layer at each sampling station is a hydraulically smooth flow.

3.2. Vertical distributions of resuspended matter

The vertical distributions of the beam attenuation coefficient and TSM concentration at Station 5 are shown in Fig. 4. The beam attenuation coefficient is almost uniform from the surface to about 8 m and reaches a minimum at about 8 to 10 m. The uniform attenuation value may be due to the summer stratification, because the water temperature in the surface layers is constant. The coefficient below 10 m increases exponentially with depth and reaches a maximum.
Entrainment of Bottom Sediment in the Seto Inland Sea

Fig. 5. Relation between beam attenuation coefficient and suspended matter concentration obtained at Station 5.

at the bottom. The high value near and at the bottom is due to resuspension of the suspended matter deposited on the bottom (Kawana and Tanimoto, 1984). The relation between the beam attenuation coefficient and TSM concentration at Station 5 is shown in Fig. 5. This figure suggests that the vertical distribution of TSM concentration is similar to that of the beam attenuation coefficient as shown in Fig. 4. The beam attenuation coefficient which is shown in units of meters increases almost linearly in proportion to TSM concentration for a range less than 15 mg L⁻¹. However, the linear proportionality is not observed in the range of high TSM concentration. This may be due to the following reason. When TSM concentration increases more than about 15 mg L⁻¹, the light path of the beam attenuation meter (50 cm) may be too long. The sensitivity of the meter falls gradually because of the effect of multiple scattering and overlapping of particles of suspended matter in the path of the light beam. Therefore the beam attenuation coefficient approaches an almost constant value after a critical value of TSM. We use the following equation for representing the relation between the beam attenuation coefficient (α) and TSM concentration (S) as shown in Fig. 5.

\[ e^{-\alpha} = b e^{-\alpha S} + c \]  \hspace{1cm} (2)

where \( a, b \) and \( c \) are positive constant. This equation has the features of Fig. 5, namely, \( \alpha \) increases linearly with \( S \) for smaller values of \( S \) and reaches a constant for larger values of \( S \). Using data in which the linear proportion is observed in Fig. 5, \( a \) and \( b \) are determined by the least squares method. Then \( c \) is determined from the residues of the difference between \( e^{-\alpha} \) and \( b e^{-\alpha S} \). The beam attenuation coefficient is converted into TSM concentration by using Eq. (2). From the vertical distribution of the converted TSM concentration, the net concentration due to the resuspended matter is obtained by subtracting the minimum concentration in the middle layer from each measured value. The vertical distribution of the net concentration due to the resuspended matter is shown in Fig. 6. The resuspended load \( Q(t) \) per unit area at a given time \( t \) is obtained by integrating the area under the curve in Fig. 6.

\[ Q(t) = \int_{z_m}^{z} S(t,z) \, dz \]  \hspace{1cm} (3)

Where \( z \) is the vertical coordinate (positive upward), \( z_m \) the height at the outer edge of the viscous sublayer, \( S(t,z) \) the concentration of resuspended matter. The height \( z_m \) corresponds to the depth of minimum values of \( S \). Chriess and Caldwell (1984) described that a viscous sublayer is always present over a bottom with a hydraulically smooth flow and its thickness varies from \( 8v/\nu \) to \( 20v/\nu \) for different data sets. Measurement of resuspended matter concentration in the viscous sublayer is difficult.

Fig. 6. Vertical distributions of net concentration due to resuspended matter at Station 5. 
Ordinate: Height from the bottom. The average distribution is obtained by averaging over one tidal cycle.
because this layer is thought to be very thin. We assume that the vertical distribution of resuspended matter in this study is obtained from above the viscous sublayer. The values of $Q(t)$ of other sampling stations are determined in the same way as Station 5 and are plotted in Fig. 2.

The resuspension of the bottom sediment is observed at all tidal cycles, although the value of $Q(t)$ is dependent on current velocity near the bottom. The change of $Q(t)$ may be influenced considerably by horizontal advection and the time-lag effect of the varying current. Complete evaluation of the effect of the horizontal advection or diffusion for the change of $Q(t)$ by use of the field data is difficult. However, in order to understand the resuspension mechanism, an accurate knowledge of the relation between the erosion rate $E$ into the water column and the bottom shear stress $\tau = p u^2$ is needed. So the vertical distributions of resuspended matter measured every hour for about one tidal cycle was averaged at each sampling station. Assuming that the average distribution is a steady state distribution, we estimate the mean erosion rate $\bar{E}$ of resuspended matter at each sampling station. $Q(t)$ at Station 2 increases suddenly at 15:15, when no corresponding increase of current velocity is observed. Because the flow system around this station is complicated due to tidal currents, residual flow and topography (Fujiwara et al., 1982), $Q(t)$ may change drastically due to the complicated flow system. And so the estimation of $\bar{E}$ is not carried out at Station 2.

The net resuspended matter flux $F_S$ (in grams per square centimeter seconds) at $z_r$ is the difference between $E$ and deposition rate $D_e$,

$$F_S = -A \frac{dS}{dz} \bigg|_{z_r} - W_S S_{se} = E - D_e = \frac{\delta Q}{\delta t} \tag{4}$$

where $W_S$ is settling velocity of resuspended matter, $A$ is the vertical eddy diffusivity. The simplest hypothesis is that deposition rate is proportional to the resuspended matter concentration $(S_{se})$ with the proportionality factor, $W_d$, having the unit of velocity (Fukuda and Lick, 1980; Lavelle et al., 1984).

$$D_e = W_d S_{se} \tag{5}$$

Fig. 7. Ratio of the vertical eddy diffusivity $A$ and settling velocity of resuspended matter $W_S$ versus height.

It is assumed that $W_d$ in the benthic boundary layer is equivalent to the settling velocity of resuspended matter, for particles of sufficient diameter and density that their settling dominates over Brownian diffusion near the sediment-water interface (Lavelle et al., 1984). It was clear from a photographic survey near the bottom that resuspended matter during summer in the Seto Inland Sea consisted of large aggregates of $10^{-2}$-$10^{-1}$ cm diameter (Kawana et al., 1984). The equivalence of $W_S$ and $W_d$ is hereafter presumed. Equation (4) shows that under steady state conditions $\bar{E}$ can be obtained easily from $W_S$ and $S_{se}$. $W_S$ in this study was determined as follows.

Assuming that the vertical water movement and the horizontal gradient of concentration are negligible, resuspended matter in the steady state are maintained by a balance between sinking with $W_S$ and vertical diffusion with $A$ and the ratio $A/W_S$ is obtained as follows;

$$\frac{A}{W_S} = \frac{1}{d((\ln S))} \frac{d}{dz} \tag{6}$$

$A/W_S$ is calculated from the average vertical distribution of resuspended matter. The relation between $A/W_S$ and height in each sampling station is shown in Fig. 7. $A/W_S$ increases gradually with height to about 1 m. The values of $A/W_S$ above 1 m remained constant.
Table 1. Settling velocity $W_s$ of resuspended matter. $A/W_s$ is the average of the ratios of vertical eddy diffusivity $A$ to $W_s$ 1 m above the bottom and $u_s$ the average for one tidal cycle.

<table>
<thead>
<tr>
<th>Station No</th>
<th>$A/W_s$ (cm)</th>
<th>$u_s$ (cm sec$^{-1}$)</th>
<th>$W_s$ (cm sec$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>726</td>
<td>0.4</td>
<td>0.022</td>
</tr>
<tr>
<td>3</td>
<td>657</td>
<td>0.2</td>
<td>0.012</td>
</tr>
<tr>
<td>4</td>
<td>740</td>
<td>0.3</td>
<td>0.016</td>
</tr>
<tr>
<td>5</td>
<td>348</td>
<td>0.5</td>
<td>0.057</td>
</tr>
</tbody>
</table>

Fig. 8. Mean erosion rate $E$ at each sampling station versus mean bottom shear stress $\tau$. Each $\tau$ is determined by averaging over one tidal cycle. The solid line indicates the erosion rate for Puget Sound, Washington estimated by Lavelle et al., (1984).

Within a small range. The relation between $A/W_s$ and height at each sampling station is assumed to be given by a solid line which is shown in Fig. 7. The solid line is obtained from the average value of $A/W_s$ above 1 m. If $W_s$ is independent of height, $A$ increase with height to 1 m and remains constant above that height. Lavelle and Mofjeld (1983) and Lavelle et al., (1984) showed that $A$ was given a broken-line profile.

$$A = \beta z$$

where $\beta$ is a maching height (Lavelle et al., 1984) and $\beta$ determined the rate of change of diffusivity in the boundary layer. In this study, $\beta$ is assumed to be 1 m from the result of Fig. 7. According to the mixing length hypothesis of Prandtl, we express $\beta = \kappa u_s$, where $\kappa$ is von Karman's constant which is approximate equal to 0.4 for marine environments in general (Soulby, 1983). $u_s$ at each sampling station is obtained by averaging over one tidal cycle and $W_s$ is estimated from the ratio of $A/W_s$. Values of $W_s$ at each sampling station are summarized in Table 1 and range from $1.2 \times 10^{-2}$ to $5.7 \times 10^{-2}$ cm sec$^{-1}$.

$E$ is estimated by using $W_s$ and $S_{se}$ and the relation between $E$ and the mean bottom shear stress $\tau (\tau = \rho u_s^2)$ is shown in Fig. 8. $E$ ranges from $7.9 \times 10^{-8}$ to $7.4 \times 10^{-9}$ g cm$^{-2}$ sec$^{-1}$ with $\tau$ varying from $4 \times 10^{-2}$ to $2.5 \times 10^{-1}$ dynes cm$^{-2}$. Sheng and Lick (1979) and Fukuda and Lick (1981) showed that no appreciable entrainment of Lake Erie sediment, of which the water content was 61-80%, occurred when the bottom shear stress was less than about 0.5 dynes cm$^{-2}$. Lavelle et al. (1984) estimated the relation between $E$ and $\tau$ for Puget Sound, Washington where water content of the sediment was 160-230%. The result for Puget Sound is also shown in Fig. 8. All $E$ estimated in this study are distributed in the range of the low bottom shear stress compared with the results for other areas. Thus entrainment in the Seto Inland Sea occurs during summer even though the bottom shear stress is low.

The resuspended matter in the Seto Inland Sea during summer is different in quality from the sediment collected with a standard sediment sampler and consists of matter newly deposited on the bottom surface, which is rich in organic matter (Kawana and Tanimoto, 1984). The newly deposited matter on the bottom surface consists of large aggregates with a density close to that of sea water and is very fragile (Tanimoto and Kawana, 1982). As the deposited matter is very light, a low bottom shear stress may easily entrain the deposited matter into suspension rather than the deposited matter being immediately incorporated into the sediment.

References


夏季における瀬戸内海海底質の再浮上

川名 吉一郎*, 谷本裕巳**, 市米 善**

要旨：瀬戸内海の数点の観測点で、再懸濁物質の鉛直分布と底層流の時間変動が同時に測定された。各観測点で、再懸濁物質の鉛直分布が1時間毎に1潮汐間測定され、底層流の3成分が得られた。底層流の資料は、各観

* 中国工業技術試験所 〒737-01 奈良市広町15,000
** テキサス農工大学

観点の海底面が滑面であることを示していた。
再懸濁物質の1潮汐間の平均鉛直分布は、定常状態の分布であることを仮定し、その分布を解析することから、再懸濁物質の沈降速度は1.2×10^{-3}から5.7×10^{-3} cm/secの範囲にあると推定された。
再浮上率と海底面の剪断応力の関係が調べられ、他の海域における関係と比較すると、瀬戸内海での夏季の再浮上は小さな剪断応力でも生じていることがわかった。