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On the Importance of Consolidation and Fluidization in Numerical Modelling of Muds and Pollutants Transports
니토 및 오염물질 이동의 수치모의에 미치는 퇴적층의 압밀과 유동화의 중요성에 관하여

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Abstract □ Existing theories and experimental results on mud bed consolidation, fluidization and erosion are briefly reviewed. The importance of the history of bed shear strength profile which experiences periodic and random consolidation and fluidization is qualitatively discussed by reanalyzing a field data set in Youngkwang area of Korea. According to the results of existing laboratory experiments and the reanalyzing, the numerical modelling of mud or pollutant transport without considering consolidation and fluidization may cause the time lag between the hydrodynamic forcing and the increment of sediment and bed-originated pollutant concentrations in water column. The time lag can derive serious error in the transport direction, consequently in the budget of a heavy-concentrated bottom-originated substance, especially in macrotidal environments with relatively high wave energy.

Keywords : cohesive sediment, consolidation, fluidization, shear strength, macrotidal regime

要　旨 : 니토층의 압밀과 침식 및 파랑에 의한 유동화에 대한 이론과 실험결과를 개략적으로 고찰하였으며, 영광 해역의 기존자료를 재분석하여 주기적 및 비주기적 압밀과 유동화를 겪는 해저 니토층의 전단강도 연직분포의 시간변화 이력의 중요성에 관하여 정성적으로 논하였다. 기존의 실내실험 결과 및 영광 해역의 현장자료에 따르면, 저면의 압밀과 유동화를 고려하지 않고 니토 혹은 오염물질을 수치모의할 경우, 유체역학적 작용력과 수주내 농도증가 사이에 시간차이를 유발할 수 있다. 이러한 시간차이는, 특히 파랑에너지가 비교적 큰 대조차 환경에서 저면으로부터 기인하는 고농도 물질의 이동방향 측면, 즉 물질수지 측면에서 심각한 오차를 발생시킬 수 있다.

핵심용어 : 점성퇴적물, 압밀, 유동화, 전단강도, 대조차 환경

1. INTRODUCTION

The behavior of fine-grained cohesive sediment plays key roles in coastal environmental assessing the various possible effects including depositions of harbours and their approaching channels, erosions of tidal flats and pollutant transport caused by many types of coastal developments in muddy environments.

The major behavior of mud consists of horizontal and vertical transport by advection and diffusion, settling, deposition, consolidation, fluidization, resuspension and erosion. These processes may be divided into three groups according to water-sediment system. The first is water column process including advection, diffusion and settling. The second is the interfacial process including deposition, resuspension and erosion. And the last is bed process of consolidation and fluidization. Additional point of view, settling, deposition and consolidation of

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the deposited muds are belong to sinking process, while fluidization, resuspension and erosion to sourcing process.

Many interdisciplinary parameters of cohesive sediment effect on these processes. Berlamont *et al.* (1993) presented 28 parameters characterizing mud and grouped them in physicochemical properties of overflowing fluid, physicochemical properties of the bed, characteristics of bed structure, and water-bed exchange processes.

However, only a few empirical physical parameters such as the settling velocity of mud floc, the critical shear stresses for deposition and erosion, and the erosion rate, have been incorporated in most numerical models (O'Connor and Nicholson, 1988; Teisson and Fritsch, 1988; Tsuruya *et al.*, 1990; Diserens *et al.*, 1993), even though Teisson *et al.* (1992) and Sheng *et al.* (1992) tried to simulate flow-particle interaction by a two-phase flow model and a Reynolds stress model. Addition to these simplifications of mud processes, another restriction is adoption of lumped parameters which do not account for the basic natures. For example, the bed shear strength is very important in estimating the erosion rate and is effected by many parameters. However, most researchers use a simple function relating bed shear strength with its dry density (Migniot, 1968; Thorn and Parsons, 1980; Ockenden and Delo; 1988) or bulk density (Villaret and Paulic, 1986), and assume the related coefficients account for other parameters. And in this engineering point of view, various instruments using acoustic probe, nuclear radiation probe, vibration transducer probe, and pressure transducer probe, have been developed for measuring bulk density (van Rijn, 1993). In order to confirm this assumption, the dry or bulk density plays always major role in the determination of the magnitude of the shear strength, but Parchure (1984) and Montague *et al.* (1993) found that microbial community at the water-bed interface considerably increases the critical erosion shear stress of the bed.

Consolidation and fluidization of mud beds are also the processes which have been scarcely incorporated in the numerical models though its neglecting may cause considerable errors. For example, a model without the routine for the processes may cause the time lag between hydrodynamic forcing and bed response in a macrotidal estuary (Le Hir and Karlikow, 1992). The time lag may also occur at non-estuarine muddy coasts regardless their tidal range, and will be highlighted in macrotidal muddy environments with relatively high wave energy. For example, when or if bottom-erodible waves attack to a macrotidal open coast for a few hours during flood and wave-driven fluidization routine is not incorporated in the applying model, the amount of transported sediment computed by the model during the flood period will be always much higher than that during subsequent ebb period because not only current-driven bed shear stress but also wave-induced stress act as applying forces for the bed erosion. However, if most wave-induced shear stresses are exhausted and dissipated in fluidizing the partially and fully consolidated mud beds, the amount of transported sediment during the subsequent ebb period with much less total shear stress may be considerably higher than that during the former flood period. This possible phase lag between temporal variations of applying bed shear stress and the amount of sediment transport should be due to neglecting the fluidization by waves. Especially, the difference between computed and real transport directions of high-concentrated suspension can cause serious problems.

However, there are few researchers to point out the above possible errors caused by neglecting the fluidization of mud bed, especially through field studies. This paper is concerned with qualitative discussion on the importance of the history of mud bed shear strength profile in the numerical modellings of muds and pollutants transports, based on the related theories, experimental results and a field data set in a part of southwestern coastal zone of Korea.

2. BASIC THEORIES AND EXPERIMENTAL RESULTS ON MUD PROCESSES

Turbulence-mean instantaneous profile of sediment concentration is well illustrated in Fig. 1 (a) as well as cohesive bed response to waves in Fig. 1 (b) (Mehta, 1989).

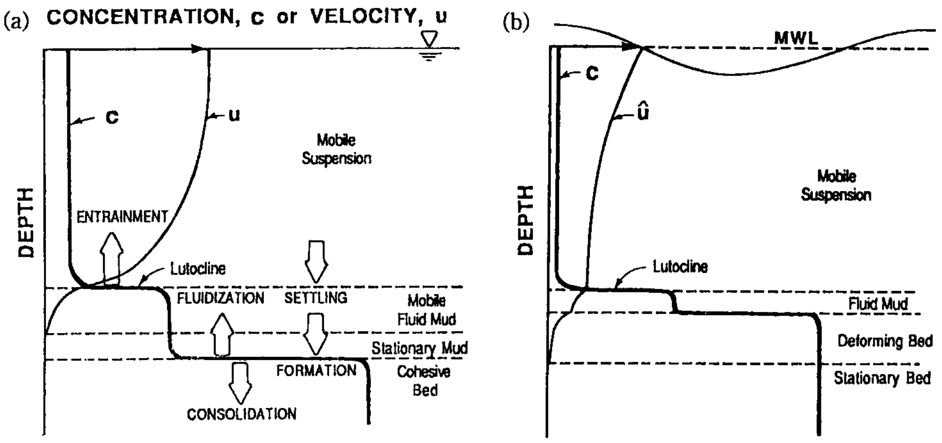

Fig. 1. Idealized profiles of instantaneous vertical concentration and velocity (a) and schematic diagram of cohesive bed response to waves (b) (after Mehta, 1989).

Deforming bed in Fig. 1 (b) represents elastic deformation and subsequent fluidization due to the penetration of horizontal orbital force into the bed. Current theories and experimental results on consolidation and fluidization shown in Fig. 1 are briefly reviewed here.

2.1 Sedimentation and Consolidation Theories

The well known *sedimentation theory* which has been used in various disciplines was derived from the continuity equation of volume concentration (C_v) under the assumption that particle settling velocity (w_s) is a function of only its concentration (Kynch, 1952):

$$\frac{\partial C_v}{\partial t} + \phi(C_v)\frac{\partial C_v}{\partial z} = 0 \tag{1}$$

Manipulating Eq. 1 of a simple kinematic wave equation yields the general solution of $C_v = f(z - \phi t)$ in which $\phi[= d(w_s C_v)/dC_v]$ is the propagation speed, z and t are vertical coordinate and time, respectively. The solution means that C_v is constant along the characteristic line, $z = \phi t +$ constant. The descending of the height (h) of water-mud interface in initially uniform-concentrated column with height of H_o is shown in Fig. 2. Zone ① is the constant settling rate zone : characteristic lines are parallel because they all correspond to the same initial concentration. When the particles reach the bottom, a layer of higher density is formed and grows linearly. Below the corresponding characteristic line, hindered settling continues. The density increases because of upward flux of the pore water by hindered settling, and thus the slope of characteristic line changes. At a certain density a soil structure is formed, and the corresponding characteristic line defines the bed surface, below which zone ③ exists where consolidation takes place(Toorman and Berlamont, 1993).

Gibson *et al.* (1967) formulated one dimensional non-linear *consolidation theory* by applying material coordinate system, and by assuming that the soil skeleton is homogeneous, pore water and the sediment are incompressible as follows:

$$\frac{\partial e}{\partial t} + \left(\frac{\gamma_s}{\gamma_f} - 1\right)\frac{d}{de}\frac{k}{1+e}\frac{\partial e}{\partial z} + \frac{\partial}{\partial z}\left\{\frac{k}{\gamma_f(1+e)}\frac{d\sigma'}{de}\frac{\partial e}{\partial z}\right\} = 0 \tag{2}$$

Equations for stress equilibrium, continuities of fluid and sediment in the control volume, and extended Darcy's law are implicated in Eq. 2 in which e, γ_s, γ_f, k and σ' are void ratio, unit weights of sediment and fluid, permeability, and effective stress ($= \sigma - p$), respectively, σ and p are total stress and pore water pressure.

Sedimentation and consolidation theories seem to have their own merits in the phases before and after the occurrence of consolidation, respectively. However, set-

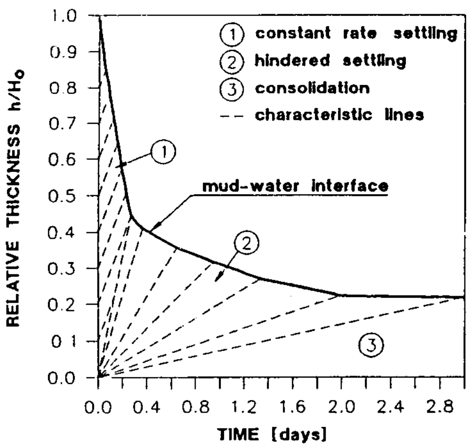

Fig. 2. Settling curve and characteristic lines (after Toorman and Berlamont, 1993).

tling, deposition and consolidation all belong to a series processes of continuous sinking, and thus a governing equation unifying the sinking processes had been required.

Two kinds of *unifying theories* were suggested. Toorman and Berlamont (1991, 1993) extended Kynch's theory to take into account of consolidation by introducing stress equilibrium and Darcy's law as follows:

$$\frac{\partial \Delta\rho_f}{\partial t}+\frac{\partial}{\partial z}\left(w_{so}\Delta\rho_f+\frac{w_{so}}{g}\frac{\partial\sigma'}{\partial\Delta\rho_f}\frac{\partial\Delta\rho_f}{\partial z}\right)=0 \qquad (3)$$

where $\Delta\rho_f$ $(=\rho-\rho_f)$ is excess density, $\rho[=n\rho_f+(1-n)\rho_s]$ is total density of control volume, n is porosity, ρ_f and ρ_s are densities of fluid and sediment, respectively, and $w_{so}=k\Delta\rho_f/\rho_f$.

On the other hand, Alexis *et al.* (1992) extended consolidation theory of Gibson *et al.* by considering the compressibility of fluid and sediments and non-Darcian flow as follows:

$$\frac{\partial}{\partial z}\left[\gamma_f v_m\left\{\frac{e}{1+e}\left(\gamma_s'-\frac{\partial\sigma'}{\partial z}\right)\right\}\right]=\gamma_s\frac{\partial}{\partial t}\left(e\frac{\gamma_f}{\gamma_s}\right) \qquad (4)$$

where v_m is the mean relative flow velocity depending on the void ratio(e) and excess pore pressure gradient, but not necessarily according to the Darcy's law. And parameter γ_s' is unit weight of submerged solid particles. Validities of these two unifying theories were confirmed by comparisons of the results of numerical modellings with those laboratory experiments.

2.2 Erosion Rates of Mud Beds

It may be necessary to review the formulae for estimating the erosion rate of mud bed in order to point out the importance of the shear strength profile in numerical modelling.

There are many kinds of formulae and this diversity is ultimately because of the fact that theoretical approach to erosion is actually impossible due to many parameters implicated in a mud bed. Therefore, most formulae have been derived from laboratory experiments in the direction that the erosion rate can be expressed by a functional form as

$$\varepsilon=\varepsilon(\tau_b-\tau_s, v_1, v_2, \cdots, v_i) \qquad (5)$$

where ε is erosion rate, τ_b is applying bed shear stress, τ_s is shear strength of mud bed against erosion, and v_1, $\cdots$,v_i are parameters specifying erosion resistance (Mehta *et al.*, 1989).

Two kinds of mud beds have been used for flume tests (Mehta *et al.*, 1982, Parchure and Mehta, 1985). The first is placed bed which is prepared either by pouring a thick slurry of sediment and fluid or by remolding previously formed beds. The second is deposited bed which is formed by allowing suspended sediment to deposit under low flow velocity or under quiescent condition.

The empirical erosion formulae derived from placed mud beds yield linearly increasing erosion with time because the shear strength in the beds are relatively uniform over the depth(Partheniades, 1962; Christensen, 1965; Kandiah, 1974; Arulanandan, 1975; Christensen and Das; 1973; Raudkivi and Hutchison, 1974; Gularte, 1978; Lambermont and Lebon, 1977; Mehta, 1981; Delo, 1988). The representative formulae are of Kandiah:

$$\varepsilon=\alpha_1\left(\frac{\tau_b-\tau_s}{\tau_s}\right) \qquad (6)$$

and of Delo:

$$\varepsilon = \alpha_2 \left(\tau_b - \tau_s \right) \tag{7}$$

where α_1 and α_2 are empirical coefficients determined from the experiments. Eq. 6 was adopted in the numerical models of O'Connor and Nicholson (1988), Teisson and Fritsch (1988) and Tsuruya *et al.* (1990), while Diserens *et al.* (1993) used Eq. 7.

Deposited beds, on the other hand, show stratification in the bulk density and the shear strength, and then the empirical formulae from the beds yield decreasing erosion rate with increasing bed depth (Krone, 1962; Yeh, 1979; Fukuda and Lick, 1980; Thorn and Parsons, 1980; Mehta *et al.*, 1982; Parchure, 1984). The representatives showing exponentially decreasing erosion rate with bed depth are of Mehta *et al.*:

$$\varepsilon = \varepsilon_1 \exp \left\{ \alpha_3 \frac{\tau_b - \tau_s(z)}{\tau_s(z)} \right\} \tag{8}$$

and of Parchure:

$$\varepsilon = \varepsilon_2 \exp \left[\alpha_4 \{ \tau_b - \tau_s(z) \}^{1/2} \right] \tag{9}$$

where ε_1, ε_2, α_3 and α_4 are empirical coefficients, and z is bed depth form water-bed interface, respectively. Sheng *et al.* (1992) used the formula of Parchure in their three dimensional sediment transport model. Kuijper *et al.* (1989) also adopted Parchure's formula to interprete their results of annular flume experiments. Hayter (1983) suggested a bed schematized model in which Eq. 8 was applied for the erosion of partially consolidated new deposits and Eq. 6 for the erosion of consolidated bed. Additionally, Hayter incoporated consolidation algorithm based on the experimental results of Thorn and Parsons (1980).

The formulae through deposited bed tests seem to be more reasonable to estimate the erosion rates of natural muds, in that most mud beds can be schematized into stationary suspension, consolidating and consolidated beds with increasing the depth (Mehta *et al.*, 1982).

Eqs. 8 and 9, however, mean the steady state profile of bed shear strength, which is caused by the purpose of erosion test. That is, the flume tests were designed to extract the critical shear stress for erosion, and then the flows in most experiments were increased stepwise. Consequently there were no periods for the beds to deform due to the differences of applying bed shear stresses. Considering this background of Eqs. 8, 9 and continuous natural flow condition, it may be more reasonable to regard the shear strength of a mud bed as a time dependent property

This time dependent property plays key role in consolidation and fluidization of mud beds, and existing studies on wave effects on the deformation of the profile are briefly reviewed in following section.

2.3 Wave-Driven Fluidization of Mud Beds

Mud bed response to wave forcing is quite different from that to current forcing in that wave effect is confined to a layer of relatively small height over the bed, and that the fluidized mud is not easily entrained in upper water column unless a shear-dependent current is present. Using the deposited kaolinite bed prepared to study current-driven erosion rate by Parchure (1984), Mehta (1989) regarded the 8-day consolidated shear strength profile as a settled pre-storm bed, and the 1-day profile as a post-storm profile weakened by waves (Fig. 3).

A noticeable results of laboratory experiment and numerical modelling on the mud bed response to wave forcing was firstly obtained by Maa (1986). Wave-induced vertical and horizontal orbital velocities, $\hat{w}$

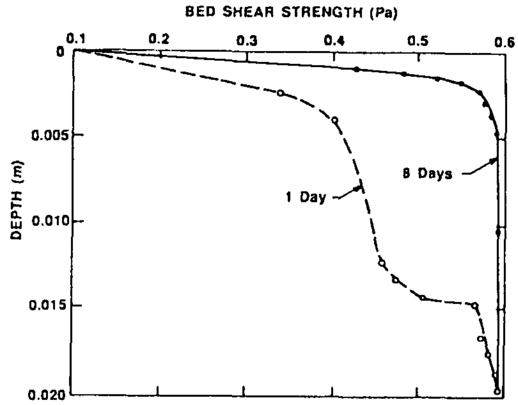

Fig. 3. Kaolinite bed shear strength profiles obtained in flume experiments (after Parchure, 1984).

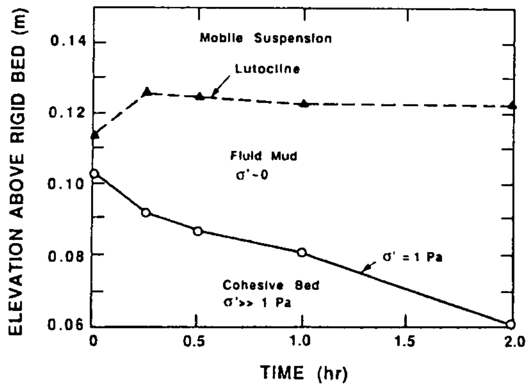

Fig. 4. Fluidization of Tampa Bay mud by waves in a flume (after Ross, 1988).

and $\hat{u}$ penetrate into a fluid mud. Considerable attenuation of wave height up to 50% was associated with relatively rapid fluidization.

Fig. 4 shows impressive fluidization obtained in a flume experiment with a natural mud by Ross (1988). The thickness of the fluid mud increased with wave loading time.

The confinement of wave loading effect to near bed was shown by Mehta and Maa (1986) in Fig. 5. Concentration profiles at 300 and 537 minutes after erosion initiation were very similar especially near lutocline because of the low vertical wave diffusion and low velocity gradient in the upper portion of the water column due to the absence of shearing current.

Using a layered Voigt model regarding mud as a viscoelastic material, Maa and Mehta (1990) calculated water-mud interfacial bed shear stresses which were, in general, larger than that calculated by assuming the mud to be rigid. The augmented shear stresses at the interface are due to out-of-phase motion between water and mud.

According to the laboratory experiment of du Wit and Kranenburg (1992), a layer of fluid mud was generated due to wave action. The threshold value of the wave height at which fluidization occurred increased as the consolidation period increased. Pore water pressure measurements showed a transient decrease possibly caused by the break down of the aggregate structure, succeeded by gradual build up of an excess pore pressure so as to compensate for the vanishing effective stress.

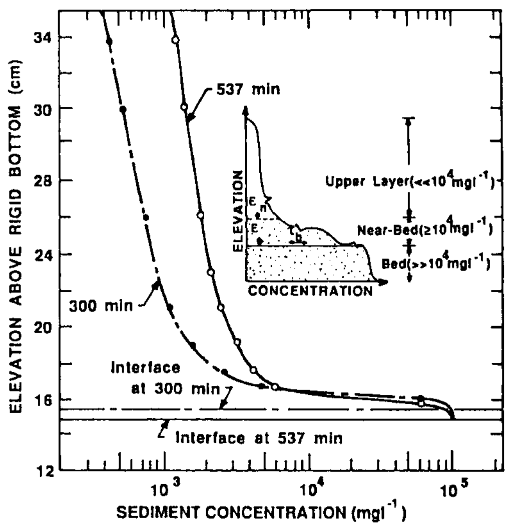

Fig. 5. Suspended sediment concentration profiles during erosion by waves. Elevations are measured above rigid flume bottom (after Mehta and Maa, 1986).

3. A CASE FIELD STUDY

A field data set is used as a material to discuss the importance of periodic bed processes due to tidal forcing or non-periodic processes due to storm forcing. The temporal variations of shear strength profile and fluid mud thickness were not included in the data set. Nevertheless, a characteristic variation pattern of near bed concentration which could not be explained without introducing fluidization, was observed.

The study area (Fig. 6) is a low-macrotidal regime (Hayes, 1979) with the mean tidal range of 3.8 m according to the results at sites T1 and T2 (KEPCO, 1994). Seasonal variation of incoming wave height is so large that suspended sediment concentration become higher in winter. According to wave measurement at site W by KEPCO (1994), the occurrence frequency of the significant wave heights (H_s) beyond 0.8 m was 31.3% in winter, while only 2% in summer.

Distribution of the bottom sediment in Fig. 7, although did not cover the whole study area, showed that the content of sand and mean diameter decrease with increasing water depth (KEPCO, 1994).

Representative time variations of suspended sediment concentration at 1m above the bottom in spring and summer seasons are shown in Fig. 8. The results at sites I and D were obtained by KORDI (1980), and those at S1, S2 and S3 by KEPCO (1994) using a pumping unit. The temporal variation at site S2 is very similar to Fig. 9 representing a typical variations of currents and sediment concentration in a tide-dominated environments.

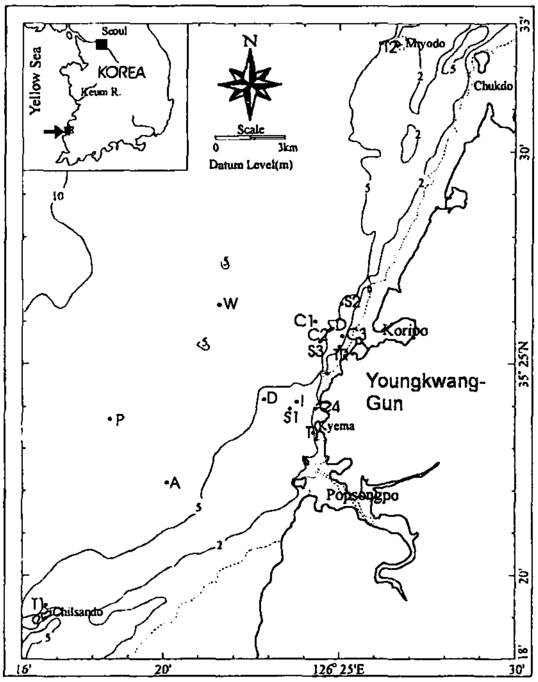

Fig. 6. Map showing the study area and field observation points.

Considerably higher winter concentrations obtained by KORDI (1992) at site A are shown in Fig. 10 with various hydraulic parameters. The concentration, water level and current velocity were all measured at 1.6 m above the bottom with a self-recording instrument, Aquasensor of Chelsea Instrument Inc. of UK. The wave heights were measured at site P about 3 km off in the direction of NW from site A.

The most noticeable feature in Fig. 10 is the time lag between the peaks of wave height and sediment concentration. That is, the concentration of only about 0.7 g/l was associated with the highest significant wave height of 3 m at P, while the peak concentration of about 3 g/l with a significant wave height of only 1.5 m occurred 40 hours later. This time lag is too long to be explained with only advection effect.

In order to investigate this time difference more quantitatively, the bed shear stresses driven by current and wave were computed. The bed shear stress driven by mean current can be expressed as

$$\tau_{bc} = 0.125\,\rho\, f_c\, U^2,$$
$$f_c = 0.24\left(\log\frac{12h}{k_s}\right)^{-2} \tag{10}$$

where τ_{bc} is current-driven bed shear stress, ρ is sea

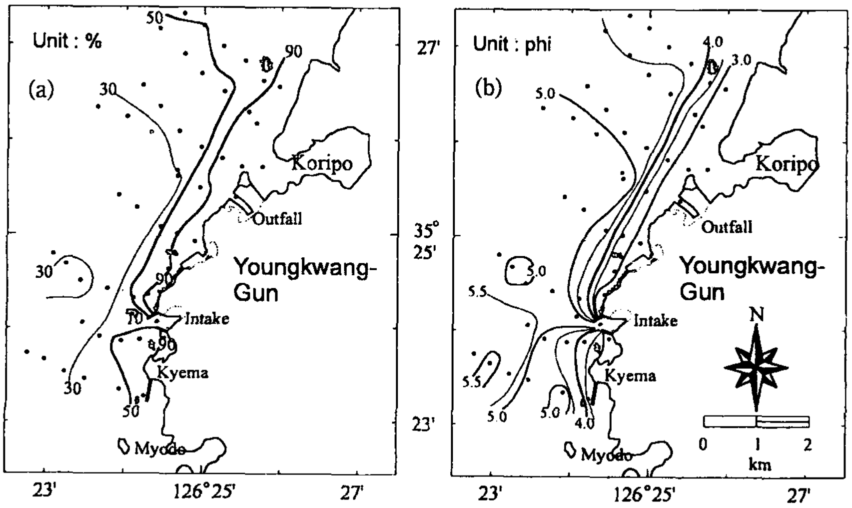

Fig. 7. Distributions of sand content (a) and mean diameter (b).

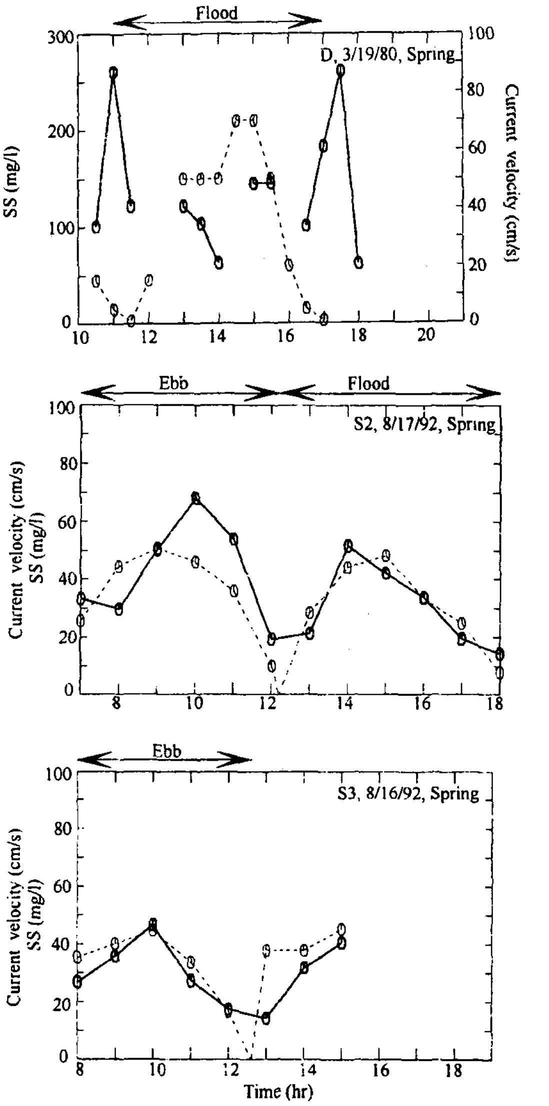

Fig. 8. Temporal variations of suspended sediment concentrations (solid lines) and current velocities (dotted lines) at 1 m above the bottoms in spring tide (after KORDI, 1980; KEPCO, 1994).

water density, f_c is current-driven bed friction coefficient, U is depth-averaged current velocity, h is total water depth, respectively. And k_s is roughness height ($=30\,z_0$) and z_0 is reference level at which velocity is zero (van Rijn, 1989).

Depth mean current velocity can be expressed as

$$U=\frac{u_*}{\kappa}\left\{\frac{z_o}{h}-1+\ln\left(\frac{h}{z_o}\right)\right\} \tag{11}$$

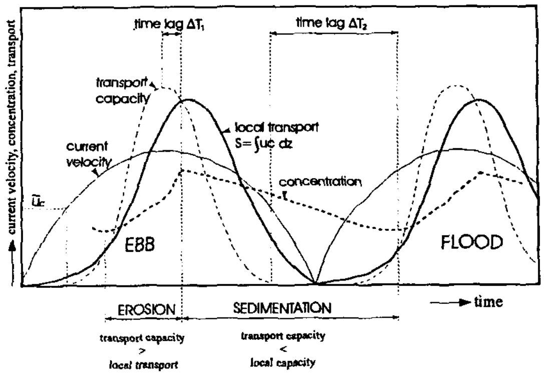

Fig. 9. Typical sedimentary processes in tide-dominated sedimentary environments (after van Rijn, 1989).

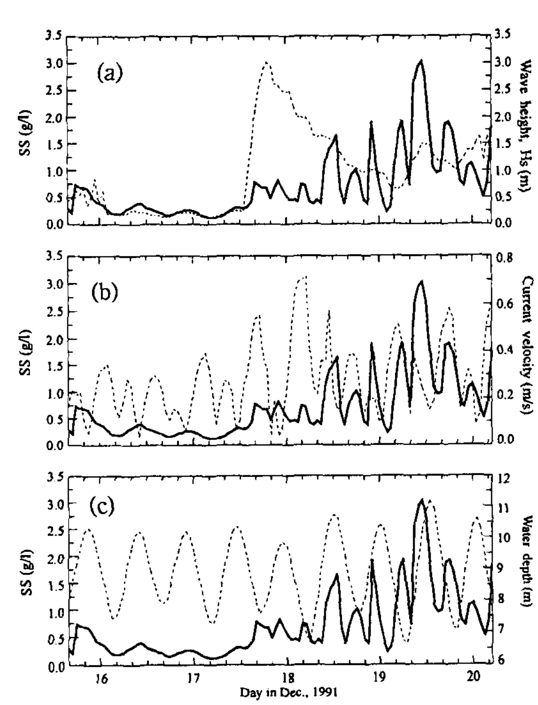

Fig. 10. Temporal variations of suspended sediment concentrations (soild lines) at 1.6 m above the bottom of site A in winter season with significant wave height (a), current velocity at the same height as SS (b), and water level (c) (after KORDI, 1992).

where u_* and κ are shear velocity and von Karman constant (=0.4), respectively (van Rijn, 1989). Current-driven shear velocity is computed by the equation of velocity distribution expressed as

$$u(z)=\frac{u_*}{k}\ln\left(\frac{z}{z_o}\right) \tag{12}$$

where z is the height from the bed, $u(z)$ is current velocity at z. As the value of $u(z)$, measured velocity at 160 cm above the bed at A was used. Reference level, z_0 varies according to bed type. Based on a hydrographic chart (No. 344) by Office of Hydrographic Affairs and the results of Heathershaw (1981), the value of 0.01 cm was taken as z_0.

And then, period-average of wave-driven bed shear stress (τ_{bw}) is

$$\tau_{bw} = 0.25\,\rho\, f_w \hat{u}^{\,2} \tag{13}$$

where $\hat{u}$ is the maximum orbital velocity and f_w is wave-driven bed friction coefficient calculated by Jonsson's (1966) formula:

$$f_w = \exp\left\{-6+5.2\left(\frac{\hat{a}}{k_s}\right)^{-0.19}\right\},\qquad f_{w,\max} = 0.3 \quad \text{for } \hat{a}/k_s \le 1.57 \tag{14}$$

where $\hat{a}$ is the peak value of orbital excursion length. By linear wave theory, $\hat{a}$ and $\hat{u}$ are computed as

$$\hat{a} = \frac{H}{2\sinh(kh)},\qquad \hat{u} = \omega\hat{a} \tag{15}$$

where H is wave height, ω is angular frequency ($=2\pi/T$), T is wave period, k is wave number ($=2\pi/L$), and L is wave length. An approximate solution of Hunt (1979) can solve kh directly without iterative calculation of dispersion relationship.

Computed maximum wave-driven, current-driven and total bed shear stresses are summarized in Table 1. The maximum τ_{bw} was about 6 times higher than the maximum τ_{bc}, and the maximum τ_{bw} and total stress ($\tau_{bw}+\tau_{bc}$) occurred at same time. Therefore, in storm periods, this area can be regarded as a wave dominated environment in the aspect of sedimentary processes.

Temporal variations of computed bed shear stress and SS concentration are shown in Fig. 11, and observed and computed hydraulic parameters at the occurring time of the concentration peaks are summarized in Table 2.

As shown in Fig. 10, from 13:00 on 17th December in 1991 when H_s was 0.2 m, wave grown up to 3.0 m

Table 1. Maximum shear stresses, their hydraulic parameters and SS at site A.

Max. Shear Stress (N/m^2)			Occurrence	Tidal	h	H_s	U	$\hat{u}$	SS
τ_{bw}	τ_{bc}	$\tau_{bw}+\tau_{bc}$	time	phase	(m)	(m)	(m/s)	(m/s)	(g/l)
5.38			19H 17D	Flood	8.18	3.01	0.35	1.32	0.67
	0.88		05H 18D	LW	6.85	2.00	0.75	0.93	0.72
		5.56	19H 17D	Flood	8.18	3.01	0.35	1.32	0.67

Table 2. Hydraulic parameters associated with observed SS peaks at site A.

Peak No.	Occurrence time	Tidal phase	h (m)	H_s (m)	u_{160} (m/sec)	U (m/sec)	$\hat{u}$ (m/sec)	τ_{bw} (N/m^2)	τ_{bc} (N/m^2)	SS (g/l)
1	18H 15D	Flood	9.12	0.64	0.22	0.23	0.17	0.24	0.08	0.74
2	10H 16D	HW	10.23	0.23	0.04	0.04	0.02	0.02	0.00	0.40
3	22H 16D	HW	10.22	0.22	0.06	0.07	0.02	0.01	0.01	0.27
4	16H 17D	Ebb	7.94	2.07	0.54	0.57	0.86	2.71	0.50	0.78
5	22H 17D	Flood	9.73	2.59	0.04	0.05	0.96	3.15	0.00	0.81
6	04H 18D	Ebb	7.42	1.99	0.70	0.74	0.87	2.77	0.84	0.74
7	13H 18D	Flood	10.64	1.45	0.16	0.18	0.51	1.18	0.05	1.66
8	18H 18D	Ebb	7.71	1.05	0.37	0.39	0.40	0.82	0.23	1.01
9	22H 18D	Flood	9.59	0.99	0.20	0.21	0.32	0.60	0.07	1.91
10	06H 19D	Ebb	6.73	0.69	0.43	0.45	0.31	0.58	0.32	1.93
11	11H 19D	Flood	10.23	1.49	0.24	0.26	0.53	1.28	0.10	3.02
12	18H 19D	Ebb	7.69	1.12	0.58	0.61	0.42	0.89	0.58	1.90
13	00H 20D	Flood	10.37	1.35	0.27	0.29	0.47	1.06	0.12	1.13
14	05H 20D	Ebb	7.62	1.11	0.62	0.66	0.41	0.88	0.67	1.81

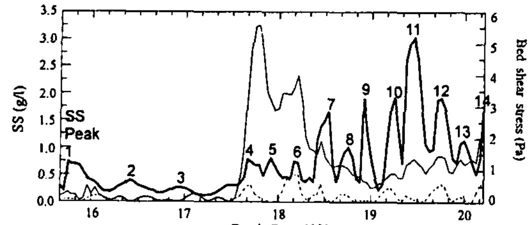

Fig. 11. Observed SS (bold line), computed $\tau_{bw} + \tau_{bc}$ (fine line) and τ_{bc} (dotted line).

of H_s at 19:00 on the day. And it stepwise decreased to about 0.6 m at 05:00 on 19th, then increased again to 1. 5 m at 11:00 on the day. From the peak 4 to 11 as shown in Figs. 10 and 11, the peak concentration during half tidal cycle stepwise increased. The maximum bed shear stress of 5.56 N/m^2 and the maximum concentration of about 3 g/l occurred at 19:00 on 17th and at 11:00 on 19th, respectively, and the time lag was 40 hours. This time lag may be interpreted into two aspects. The first is the saturation period required to increase sediment concentration of upper layer by shearing tidal currents. The other possible process may be bed fluidization due to wave forcing.

If we regard the 34 hours from 13:00 on 17th to 05: 00 on 19th as the first storm period, there are 6 peaks of concentration (peak numbers 4~9). As shown in Fig. 11 and Table 5, the concentrations of the former peaks 4, 5 and 6 were much lower than the peaks 7, 8 and 9 even though their total shear stresses were about doubled those at the latter three peaks. These time lags between the peak bed shear stresses and the peak concentrations seem to be caused by both effects due to the bed fluidization and the saturation of the water column with high-concentrated suspension. That is, the higher shear stresses of the former peaks were most exhausted in fluidizing the bed, by which weakened high suspensions near the bed were not enoughly advected and diffused vertically. The latter peaks 7, 8 and 9, however, represent that the water column was relatively fully saturated with the fluidized mud suspension. Additionally, the effect of horizontal advection was also incorporated in the peaks 5 and 8. That is, although current velocity of 5 cm/s at peak 5 was much weaker, the concentration was comparable to those of peaks 4 and 6. On the other hand, the concentation of peak 8 was much lower than those of peaks 7 and 9, although the current velocity was about doubled. These may be explained by tidal phase and the horizontal distribution of bed type. The facts that the content of mud increases southward as shown in Fig. 7 and flood current flows northeastward (KEPCO, 1994) make it possible to consider the concentration of flooding water mass to be much higher than ebbing water mass.

The second storm period started at 05:00 on 19th, during which time variation of the concentration reflecting the effect of fluidization happened earlier was highlighted at peaks 10~14. These concentration peaks have the nearly same phases as those of total shear stress without time lags. These nearly simultaneous responses of the concentrations to total bed shear stresses seem to be due to direct resuspension of the weekened bed during earlier storm before recovering pre-storm shear strength profile described with Fig. 3. Advection effect was also associated with at peak 11 in comparison with peak 12.

According to what described above, the peaks 4, 5 and 6 may be regarded as fluidizing but unsaturation period, the peaks 7, 8 and 9 as saturation period, and the peaks 10, 11 and 12 as refluidizing period before recovering pre-storm bed shear strength profile.

Therefore, bed processes including consolidation and fluidization seem to be very important although it is difficult to estimate them in a model. If the model in which the bed is immediately eroded by applying bed shear stress is applied to this case study, the amount of eroded and transported sediment at peaks 4, 5, and 6 should much larger than those at other peaks. The problem due to this time lag will become serious in determining the transport direction. For example, even though the maximum shear stress occurs at a flooding time, the maximum concentration may occur at a ebbing time. In this case study, in fact, peaks 4 and 6 occurred in ebb period, while peak 11 in flood period. Thus, the model without bed process algorithms will make a significant error in the point of sediment budget in this case area. This problem should become more severe in a depth-averaged model which directly move the eroded sediment into the water column. Pollutant transport models without these bed processes may also cause such problem because the behavior of the contaminants accumulated in mud beds are associated with that of fine grained sediments.

4. CONCLUDING REMARKS

Theories and experimental results on mud bed processes including consolidation and fluidization have been briefly reviewed. A field data set in a part of southwestern coastal zone of Korea have been reanalyzed and discussed in terms of the importance of understanding the history of bed shear strength profile. According to the reanalyzed results, a numerical model for mud or pollutant transports can cause a severe errors in determining the transport direction as well as the transport content unless the algorithms for estimating the bed processes are incorporated. And this problem will be highlighted in a macrotidal environment with high wave energy.

Incorporating consolidation and fluidization into a mud transport model requires many additional parameters for the determinination of the history of the shear strength profile. These parameters may be, of course, obtained through laboratory tests using flow-deposited or placed beds. However, even a flow-deposited bed can not represent bed conditions in the field including the stratifications of sediment composition and the content of organic matters which effect the shear strength profile.

Thus, considering that the characteristics of the properties and the processes of mud beds are site specific, a recommendable methods to grade up the validity of a mud transport model may be incorporating the algorithms for consolidation and fluidization, and calibrating its results with the field data obtained with a integrated monitoring system consisting of high frequency current meter, SS probe, wave and tide gauge, altimeter, and bulk density profiler.

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REFERENCES

Alexis, A., Bassoullet, P., Le Hir, P. and Teisson, C., 1992. Consolidation of soft marine soils: Unifying theories, numerical modelling and in situ experiments, *Proc. 23th Int. Conf. Coastal Eng.*, pp. 2949-2961.

Arulanadan, K., 1975. Fundamental aspects of erosion of cohesive soils, *J. Hydr. Div., ASCE*, **101**(HY5), pp. 635-639.

Berlamont, J., Ockendon, M., Toorman, E. and Winterwerp, J., 1993. The characterisation of cohesive sediment properties, *Coastal Eng.*, **21**, pp. 105 128.

Christensen, B.A., 1965. Discussion of erosion and deposition of cohesive soil (by E. Partheniades), *J. Hydr. Div., ASCE*, **91**(HY5), pp.301-308.

Christensen, R.W. and Das, B.M., 1973. Hydraulic erosion of remoulded cohesive soils, In *Soil Erosion: Causes and Mechanisms, Prevention and Control*, edited by Natural Res. Council, Highway Res. Board Special Report 135, pp. 8-19.

Diserens, A.P., Ockenden, M.C. and Delo, E.A., 1993. Application of a mathematical model to investigate sedimentation at Eastham Dock, Mersey Estuary, In *Nearshore and Estuarine Cohesive Sediment Transport*, edited by A.J. Mehta, Series No. 42 of Coastal and Estuarine studies, Am. Geophys. Union, pp. 486-503.

Delo, E.A., 1988. Estuarine mud manual, Report. SR 164, Hydraulics Research.

du Wit, P.J. and Kranenburg, C., 1992. Liquefaction and erosion of China Clay due to waves and current, *Proc. 23th Int. Conf. Coastal Eng.*, pp. 2937-2948.

Fukuda, M.K. and Lick, W., 1980. The entrainment of cohesive sediments in fresh water, *J. Geophys. Res.*, **85**(C5), pp. 2813-2824.

Gibson, R.E., England, G.L. and Hussey, M.J.L., 1967. The theory of one-dimensional consolidation of saturated clays: 1. Finite non-linear consolidation of thin homogeneous layers, *Geotechnique*, **17**, pp. 261-273.

Gularte, R.C., 1978. Erosion of cohesive marine sediment as a rate process, Ph.D. Thesis, Univ. of Rhode Island.

Hayes, M.O., 1979. Barrier island morphology as a function of tidal and wave regime, *In Barrier Islands*, edited by S.P. Leatherman, Academic Press, pp. 1-27.

Hayter, E.J., 1983. Prediction of cohesive sediment movement in estuarial waters, Ph.D. Thesis, Univ. of Florida.

Heathershaw, A.D., 1981. Comparisons of measured and predicted sediment transport rates in tidal currents, *Marine Geol.*, **42**, pp. 75-104.

Hunt, J.N., 1979. Direct solution of wave dispersion equation, *J. Wtway., Port, Coastal Ocean Div., ASCE*, **105**(WW4), pp. 457-459.

Jonsson, I.G., 1966. Wave boundary layer and friction factors, *Proc. 10th Int. Conf. Coastal Eng.*, pp. 127-148.

Kandiah, A., 1974. Fundamental aspects of surface erosion of cohesive soils, Ph.D. Thesis, Univ. of California.

KEPCO, 1994. A study on the reduction of thermal discharge effects around nuclear power plants-1st interim report (Youngkwang), 92-802, Korea Electric Power Company (in Korean with English summary).

KORDI, 1980. Oceanographic studies for Yeonggwang Nuclear Power Plant, BSPI 00019-1-35-1, Korea Ocean Research and Development Institute.

KORDI, 1992. Studies on the numerical modelling of fine-grained sediment transport (III), BSPG 00154-494-2, Korea Ocean Research and Development Institute (in Korean with English summary).

Krone, R.M., 1962. Flume studies of the transport of sediment in estuarial shoaling processes, Final report, Hydraulic Eng. Lab., Sanitary Eng. Res. Lab., Univ. of California.

Kuijper, C., Cornelisse, J.M. and Winterwerp, J.C., 1989. Research on erosive properties of cohesive sediment, *J. Geophys. Res.*, **94**(C10), pp. 14341-14350.

Kynch, G.J., 1952. A theory of sedimentation. *Trans. Faraday Soc.*, **48**, pp. 166-176.

Lambermont, J. and Lebon, G., 1978. Erosion of cohesive soils, *J. Hydr. Res.*, **16**(1), pp. 27-44.

Le Hir, P. and Karlikow, N., 1992. Sediment transport modelling in a macrotidal estuary: do we need to account for consolidation processes? *Proc. 23th Int. Conf. Coastal Eng.*, pp. 3121-3134.

Maa, P.-Y., 1986. Erosion of soft muds by waves, Ph.D. Thesis, Univ. of Florida.

Maa, J. P.-Y. and Mehta, A.J., 1990. Soft mud response to water waves, *J. Wtway., Port, Coastal and Ocean Eng., ASCE*, **116**(5), pp. 634-650.

Mehta, A.J., 1981. Review of erosion function for cohesive sediment beds, *Proc. 1st Indian Conf. on Ocean Eng.*, Indian Inst. of Technology, Vol. 1, pp. 122-130.

Mehta, A.J., 1986. Characterization of cohesive sediment properties and transport processes in estuaries, In *Estuarine Cohesive Sediment Dynamics*, edited by A.J. Mehta, Series No. 14 of Lecture Notes on Coastal and Estuarine Studies, Springer-Verlag, pp. 290-325.

Mehta, A.J., 1989. On estuarine cohesive sediment suspension behavior, *J. Geophys. Res.*, **94**(C10), pp. 14303-14314.

Mehta, A.J., Hayter, E.J., Parker, W.R., Krone, R.B. and Teeter, A.M., 1989. Cohesive sediment transport I: Process description, *J. Hydr. Eng., ASCE*, **115**(8), pp. 1076-1093.

Mehta, A.J. and Maa, P.-Y., 1986. Waves over muds: modelling erosion, *Proc. 3rd Int. Symp. River Sediment*, pp. 588-601.

Mehta, A.J., Parchure, T.M., Dixit, J.G. and Ariathurai, R., 1982. Resuspension potential of deposited cohesive sediment beds, In *Estuarine Comparisons*, edited by V.S. Kennedy, Academic Press, pp. 591-609.

Migniot, C., 1968. A study of the physical properties of different fine sediments and their behavior under hydrodynamic action, *La Houille Blanche*, **7**, pp. 591-620.

Montague, C.L., Paulic, M. and Parchure, T.M., 1993. The stability of sediments containing microbial communities: Initial experiments with varying light intensity, In *Nearshore and Estuarine Cohesive Sediment Transport*, edited by A.J. Mehta, Series No. 42 of Coastal and estuarine studies, Am. Geophys. Union, pp. 348-359.

Ockenden, M. and Delo, E.A., 1988. Consolidation and erosion of estuarine mud and sand mixture, Report SR 149, Hydraulics Research.

O'Connor, B.A. and Nicholson J., 1988. Mud transport modelling, In *Physical Processes in Estuaries*, edited by J. Dronkers and W. van Leussen, Springer-Verlag, pp. 532-544.

Parchure, T.M., 1984. Erosional behavior of deposited cohesiv sediments, Ph.D. Thesis, Univ. of Florida.

Parchure, T.M. and Mehta, A.J., 1985. Erosion of soft cohesive sediment deposits, *J. Hydr. Eng., ASCE*, **111**(10), pp. 1308-1326.

Partheniades, E., 1962. A study of erosion and deposition of cohesive soils in salt water, Ph.D. Thesis, Univ. of

California.

Ross, M.A., 1988. Vertical structure of estuarine fine sediment suspensions, Ph.D. Thesis, Univ. of Florida.

Raudkivi, A.J. and Hutchison, D.L., 1974. Erosion of kaolinite by flowing water, *Proc. Royal Soc. London.*, **A 337**, pp. 537-554.

Sheng, Y.P., Eliason, D.E. and Chen X.-J., 1992. Modelling three-dimensional circulation and sediment transport in lakes and estuaries, *Proc. 2nd Int. Conf. Estuarine and Coastal Modelling*, pp. 105-115.

Teisson, C. and Fritsch, D., 1988. Numerical modelling of suspended sediment transport in the Loire estuary, *Proc. IAHR Symp. on Math. Modelling of Sediment Transport in the Coastal Zone*, pp. 14-22.

Teisson, C., Simonin, O., Galland, J.C. and Laurence, D., 1992. Turbulence and mud sedimentation: A Reynolds stress model and a two-phase flow model, *Proc. 23th Int. Conf. Coastal Eng.*, pp. 2853-2866.

Toorman, E.A. and Berlamont, J.E., 1991. Hindered settling model for prediction of settling and consolidation of cohesive sediment, *Geo-Marine Letters*, **11**(3/4), pp. 179-183.

Toorman, E.A. and Berlamont, J.E., 1993. Mathematical modeling of cohesive sediment settling and consolidation, In *Nearshore and Estuarine Cohesive Sediment Transport*, edited by A.J. Mehta, Series No. 42 of Coastal and Estuarine studies, Am. Geophys. Union, pp. 167-184.

Thorn, M.F.C. and Parsons, J.G., 1980. Erosion of cohesive sediments in estuaries: An engineering guide, *Proc. 3rd Int. Symp. Dredging Technology*, Bordeaux, France, pp. 349-358.

Tsuruya, H., Murakami, K. and Irie I., 1990. Mathematical modelling of mud transport in Ports with a multi-layered model-Application to Kumamoto Port, Report 29(1), Port and Harbour Research Institute.

Yeh, H.Y., 1979. Resuspension properties of flow deposited cohesive sediment beds, M.S. Thesis, Univ. of Florida.

van Rijn, L.C., 1989. Handbook Sediment transport by currents and waves. Report. H 461, Delft Hydraulics.

van Rijn, L.C., 1993. Principles of sediment transport in rivers, estuaries and coastal seas, Aqua publications.

Villaret, C. and Paulic, M., 1986. Experiments on the erosion of deposited and placed cohesive sediments in an annular flume and a rocking flume, Report UFL/COEL-86/007, Univ. of Florida.