CHAPTER 209

Dispersion Process and the Settlement Pattern of Mud Dumped in Oceans

Eiji Yauchi¹ and Ken Katoh²

Abstract

The settlement of mud lumps dumped in oceans from barges was studied theoretically and the results were compared with data from field and laboratory experiments. The settling pattern and the load of initial turbidity were estimated by a non-dimensional dispersion index and the rate of turbidity load.

1 INTRODUCTION

Mud deposited on the bottom of rivers, lakes, or oceans are known to cause many problems. These problems can be classified into two groups. One is the siltation problem within channels, or basins at ports and harbors. As a result of the siltation, the port management body is forced to carry out dredging on a regular basis at a great deal of operational costs. The second problem is a consequence of the dredging, namely the disposal of the dredged mud either in the water or on land. In many instances, land disposal is infeasible because of the high salt content or the fineness of particles in the dredged mud. As a result, disposal of dredged mud in water is increasingly becoming a more frequently used option and therefore requires a more thorough study of its environmental impact.

While the dispersion characteristics of sand dumped in water are mainly affected by the diameter and specific weight of sand, the dispersion and settlement characteristics of dumped mud are affected by water content or cohesion, among other factors. As this field has not been studied sufficiently, the load of initial turbidity, or the falling velocity of dumped mud, has been taken to be the same as for cohesionless sand particles. However, dredged mud with low water content has a lower turbidity than sand and in numerical simulations the turbid area is seen to be larger than observed in the field.

In this paper, the results of a theoretical investigation of the settlement characteristics of mud lumps are presented along with a comparison of theoretical results with data from field and laboratory experiments.

¹TOA CORPORATION, Design Department, 5-Banchi, Yonban-cho, Chiyoda-ku, Tokyo, 102 Japan ²ditto, Mechanical Department

2 LABORATORY EXPERIMENT

2.1 EXPERIMENTAL APPARATUS

Experiments were conducted in the laboratory to investigate the settling characteristics of dumped mud. The tank used in the tests was 0.5 m wide, 2.5 m long and 1.0 m high, and the water depth was 80 cm, as shown in Fig.1.



Figure 1: Experimental Apparatus



Figure 2: Shear Meter

The water content of the mud was varied from 170% to 700% and the mud was dumped into the tank from a scaled down model of a 3 cm wide, 4 cm long, and 2 cm high barge. The dispersion process and the settlement pattern were monitored by a video camera. The load of initial turbidity was calculated from the observed dispersion of the mud and diffusion coefficient (Yauchi et. al. ;1989).

The shear stress of mud was measured using a vane shear meter shown in Fig.2, specially developed in order to measure the shear strength of soft mud. A stepping motor and a high-sensitivity torque meter were fitted to the axis of the shear meter and its rotation is maintained at a speed of 0.1 deg/s with an accuracy of 0.5%. The range of this shear meter is 1 pa to 10 kpa.

2.2 EXPERIMENTAL RESULTS

Fig.3(a) shows the result at a water content of 320% and at this water content the mud reached the bottom as one lump. At a higher value of water content, 429% as

shown in Fig.3(b), the mud lump begins to disintegrate and at a still higher value, 633%, depicted in Fig.3(c), the mud lump disperses.

Based on the experiments, the settlement of mud lumps was classified into three patterns, lump-settling, partial-dispersion and full-dispersion, as shown in Fig.4. Table 1 summarizes the results of the experiments.



(a) W=320%

(b) W=429%

(c) W=633%

Figure 3: Settling Photo



Figure 4: Settling Pattern

Mud	Water Cont.	Shear Str.	Diff. Coeff.	Turb. Rate.	Settl. Vel.
	W(%)	$\tau_{mud}(Pa)$	K(cm²/sec)	φ	w fo(cm/sec)
	177	860.4	0	0	26.3
	190	405.7	0	0	ļ
	258	122.5	0	0]
А	344	16.8	0.195	0.023]
	394	6.3	1.65	0.199]
	486	2. 6	6.04_	0.728	
	560	1.2	7.78	0.937]
	633	0.6	8. 03	_0.967	
	K _{max}		8.3	1.0	
	168	1176.0	0	0	27.0
В	194	362.6	0	0	
	320	25. 9	0	0	
	375	10.1	0.768	0.179	
	429	5.2	2. 53	0.588	4
	544	1.4	4. 08	0. 949	
	681	0.4	4. 28	0.995	
	Kmax		4.3	1.0	
С	216	399.8	0	0	27.8
	232	37.7	0	0	
	282	59.1	0	0	
	322	30.9	0	0	
	368	12.0	0	0	
	423	5.6	7. 37	0.689	
	482	2. 7	8.17	0.764	
	560	1.2	10.04	0.938	
	Kmax		10.7	1.0	

Table 1: Experimental Results

3 THEORETICAL ANALYSIS

3.1 SETTLEMENT PATTERN AND MODELING

Two models were considered in the theoretical analysis of the settlement pattern of mud lumps. The models are shown in Fig.5.



Figure 5: Modeling Type

In the first model, the mud lump is considered to be an elastic solid and in the second the mud lump is treated as a fluid with a high viscosity. If the mud lump is modeled as solid matter, the stress in the mud lump is easily analyzed by structural mechanics. While, if the mud lump is dealt with as a fluid, forces such as van der Waals' forces must be incorporated in the analysis. However, the measurement of van der Waals' forces is not easy and it is probably not very influential in the settling of mud lumps because of the big volumes of mud involved, over $500m^3$. Therefore, in this study, the mud lumps are assumed to remain intact and are treated as elastic matter.

3.2 FORCES ON AND RESISTANCE OF MUD LUMPS

The main forces acting on mud lumps during settling are (a) drag force, (b) skin friction, (c) vortex force behind the mud lump and (d) a fluctuating force due to rotation of the mud lump. If the mud lumps are assumed not to rotate and the effect of skin friction is omitted, the governing forces are drag force and vortex force. The vortex force is affected by the shape of the mud lumps and the falling Reynolds number. Thus if, the effect of the vortex force is included in a drag coefficient the only governing force that needs to be considered is the drag force.

The resistance of mud lumps is measured by the shear, compressive and tensile strengths. As these strengths are almost proportional to each other the shear strength was taken as the measure because it could be easily measured in situ.

3.3 NON-DIMENSIONAL DISPERSION INDEX

In laboratory tests the mud lumps begin to break at the center because of the bending moment. In this study the mud lumps were modeled as thin plates, as shown in Fig.6. The mud lump start disintegrating when the shear from the bending exceeds the shear strength of the mud. The equilibrium equation can be expressed as Eq.1,

$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{p}{\gamma} \tag{1}$$

where, w is the displacement, p is the force acting on the mud lump, and γ is the stiffness of the mud lump.



Figure 6: Schematic of a Thin Plate

It is difficult to obtain general solutions because Eq.1 is a non-linear equation. Thus, its solution is carried out analytically by considering the conditions of dumping mud.

The shape of the mud lumps dumped from barges is taken as rectangular parallelopiped. The mud lump starts to disintegrate at the center of mud lump at the region of high bending moment. Therefore, the mud lumps are considered to be simply supported. When the shape of mud lumps is a $a \times b \times h_{mud}$ rectangular parallelopiped domain, the boundary conditions are as per Eq.2.

$$w = 0 |_{x=0,x=a,y=0,y=b}$$

$$M_x = 0 |_{y=0,x=0,x=a,y=0,y=b}$$

$$M_y = 0 |_{x=0,x=a,y=0,y=b}$$
(2)

When Eq.2 is used together with Eq.1, Eq.3 known as Navier's solution is obtained.

$$w = \frac{1}{\pi^4 \gamma} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{a_{mn}}{(m^2/a^2 + n^2/b^2)^2} \sin\frac{m\pi x}{a} \sin\frac{n\pi y}{b}$$
(3)

The maximum bending moment at the center of the mud lumps is given by Eq.4 and Eq.5.

$$M_x = \frac{16pa^2\lambda_{ab}^2}{\pi^4} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{(\lambda_{ab}^2m^2 + \delta n^2)}{mn(\lambda_{ab}^2m^2 + n^2)^2}$$
(4)

$$M_y = \frac{16pa^2\lambda_{ab}^2}{\pi^4} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{(\delta\lambda_{ab}^2m^2 + n^2)}{mn(\lambda_{ab}^2m^2 + n^2)^2}$$
(5)

Representing the section modulus of the mud lump by Z, the flexural stress in the mud lump can be expressed by Eq.6.

$$\sigma_x = M_x/Z_x , \ \sigma_y = M_y/Z_y \tag{6}$$

A new parameter defined by the shear and bending stresses in the mud lumps is introduced for determining the settlement pattern.

$$\Psi = \frac{\sigma_{max}}{\tau_{mud}} \tag{7}$$

 Ψ is denoted as the non-dimensional dispersion index.

3.4 RATE OF TURBIDITY LOAD

Both the turbidity load and the variation of the non-dimensional dispersion index must be considered in order to be able to estimate the turbidity in numerical simulations. A new factor, the rate of turbidity load, ϕ , is defined to represent the load of initial turbidity. The factor ϕ is based on the rate of the load of initial turbidity, q, and the maximum turbidity load, q_{max} , as expressed in Eq.8.

$$\phi = q/q_{max} \tag{8}$$

The rate of turbidity load ϕ increases as the non-dimensional dispersion index increases. The factor ϕ is taken as a measure of the probability of dispersion of dumped mud lumps, as shown in Fig.7.



Figure 7: Probability of Disintegration of Mud Lumps

where, η is the fluctuation of Ψ , η_0 is the standard deviation of η , and B is a constant. If the bending stresses in a mud lump, σ , is taken to be distributed randomly, the mud lump shows signs of dispersion when σ is greater than η_1 or σ is less than η_2 .

Thus, ϕ is equal to one minus the integral between η_2 and η_1 of the density function of the bending stresses. In this paper the bending stresses were modeled by a Gaussian distribution, as shown in Eq.9.

$$\phi = 1 - \frac{1}{\sqrt{\pi}} \int_{\eta_{\star 2}}^{\eta_{\star 1}} e^{-t^2} dt
\eta_{\star 1} = B_{\star}/\Psi - 1/\eta_0,
\eta_{\star 2} = -B_{\star}/\Psi - 1/\eta_0,
B_{\star} = B/\eta_0,$$
(9)

where η_0 and B_* are determined by the critical values of the disintegration process.

3.5 SETTLING VELOCITY

The settling velocity is an important factor in the evaluation of the the rate of turbidity load. The terminal velocity of a particle settling in a fluid is given by Eq.10.

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$$w_f = \sqrt{(4/3)(s-1)gd/C_D}$$
(10)

where, s is the specific weight, d is a representative diameter, and C_D is the drag coefficient of the mud lump.

In this study, Wadell's representation equation is used in incorporating the shape factor, defined as C_D .

3.6 CRITICAL VALUES OF THE DISINTEGRATION PROCESS

In this study, the rate of turbidity load is defined by the rate of bending stress and shear strength of mud lump. However, the critical values of the disintegration process are defined in terms of the rate of bending stress and tensile strength. The relationship between tensile strength, σ_t , cohesive force, c, and shear strength, τ_{mud} of clay are given by Eq.11 and Eq.12.

$$\sigma_t = 2c \frac{\cos \theta_0}{1 + \sin \theta_0} \tag{11}$$

$$\tau_{mud} = \sigma_t \tan \theta_0 + c \tag{12}$$

where, θ_0 is the angle of internal friction.

If the clay is assumed to be ideal, $\theta_0 = 0$ and $\sigma_t = 2\tau_{mud}$, the critical values of the disintegration process of mud lumps can be expressed as follows.

$$\Psi_c = 2.0 \tag{13}$$

In the field, mud usually contains some sand and benthos, etc, and these reduce the tensile strength. Therefore in this study, Ψ_c is determined from laboratory experiments, as shown by Eq.14.

$$\Psi_c = 1.5 \sim 2.0 \tag{14}$$

Furthermore, we obtain $\eta_0 = 1.0$ and $B_* = 4.0$ from Eq.14 and Eq.9, when we take $\eta_0 = 1.0$ and $\eta_* = 1.0$.

3.7 COMPARISON WITH EXPERIMENTAL DATA

Fig.8 compares the theoretical results with those from laboratory experiments. Here, $C_D = 2.01$ and the Poisson rate, $\delta = 0$, are assumed.

On the whole, the theoretical predictions were in good agreement with the experimental data. In particular, they were in good agreement at the range of $\Psi > 20$, though the assumption of the mud lump being elastic can no longer be applied because at such values the lump is more like a fluid than a solid. The non-dimensional dispersion index is related to the settlement pattern and each pattern was classified using this index, as shown in Eq.15.

$$\begin{split} \Psi &< \Psi_1 \quad : \quad \text{Lump} - \text{settling type} \\ \Psi_1 &\leq \Psi &< \Psi_2 \quad : \quad \text{Partial} - \text{dispersion type} \\ \Psi_2 &\leq \Psi \quad : \quad \text{Full} - \text{dispersion type} \end{split} \tag{15}$$



Figure 8: Theoretical Predictions and Laboratory Data

From Fig.8, Ψ_1 and Ψ_2 were determined to be equal to 1.5 ~ 2.0 and 10 ~ 20, respectively.

4 FIELD EXPERIMENT

Field experiments were carried out to validate the theoretical predictions. Field measurements were made within a circle of 700 m radius centered around the dumping point at a depth of 41 m. The 50 percentile diameter of the mud used in the tests was 0.7 μ m and the mud contained some organic matter. The vertical and horizontal profiles of turbidity, water temperature and salinity, and the falling velocity were measured with the help of six turbidimeters, six salinometers, and three velocimeters. The three dimensional profile of the turbidity was, also, measured by means of an echo-sounding turbidimeter.

Fig.9 shows the vertical turbidity profile. Here, the abscissa is turbidity, and the ordinate is depth.

For small water contents, turbidity could be measured only at the bottom layers. Turbidity measured in the upper layers became larger as the water content of the mud increased. The dispersion indexes are 1.2, 2.6 and 40.1, respectively. The field data are in good agreement with the theoretical predictions.

5 CONCLUSIONS

The settlement pattern of mud lumps dumped in oceans were classified into three patterns. The settlement pattern and the turbidity load can be estimated by the non-dimensional dispersion index, Ψ , and the rate of turbidity load, ϕ .

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Figure 9: Vertical Turbidity Profile

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