SEDIMENTATION OF LAKE APOPKA MUD AND COMPARISON WITH OTHER SEDIMENTS

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2009
To my parents
ACKNOWLEDGMENT

I am thankful to the chair and members of my supervisory committee for their mentoring, the staff at the Coastal and Oceanographic Engineering Laboratory and my fellow graduate students for their continuous support. I am grateful to Dr. Eric Wolanski of James Cook University in Australia for his assistance in field work and for providing keen scientific observations. I thank my parents for their encouragement, which motivated me to pursue my studies at the University of Florida.
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LIST OF SYMBOLS

\( A \) Arbitrary constant

\( C \) Concentration

\( C_d \) Depth-averaged concentration

\( C_F \) Coefficient of consolidation

\( C_{fd} \) Concentration of settled deposit (pre-consolidation)

\( C_v \) Volume concentration of particles

\( C_{vm} \) Maximum volume concentration of particles

\( C_0 \) Initial concentration of slurry

\( C_1 \) Concentration of sediment in water sample

\( d_f \) Diameter of floc

\( e \) Void ratio

\( e_0 \) Ultimate or final void ratio

\( e_i \) Initial void ratio

\( e(\zeta,T) \) Void ratio corresponding to the material vertical coordinate and time factor

\( F \) Particle flux

\( g \) Acceleration due to gravity

\( h_f \) Final (settled) height of bed

\( h_0 \) Initial height of suspension

\( h_1 \) Position of lutocline at time \( t_1 \)

\( h_2 \) Position of lutocline at time \( t_2 \)

\( h^* \) Value on \( y \)-axis obtained by a tangent drawn through a point on settling curve

\( i \) Initial value
$K$  Permeability

$k_0$  Arbitrary constant

$k$  Damping factor for settling velocity

$k_b$  Damping factor due to buoyancy

$k_r$  Damping factor due to return flow

$k_v$  Damping factor due to viscosity

$N$  Total number of particles

$R_e$  Reynolds number

$T$  Normalized time factor

$t_{flc}$  Flocculation time

$t_{hin}$  Hindered settling time

$t_{un}$  Unhindered settling time

$t^*$  Point on $t$-axis obtained by a tangent drawn through a point on settling curve

$t_1$  Time at data point 1

$t_2$  Time at data point 2

$W$  Characteristic velocity

$w_s$  Settling velocity

$w_{sm}$  Hypothetical maximum settling velocity

$w_s0$  Stokes’ velocity

$w_{s1}$  Settling velocity without return-flow

$w_{s2}$  Settling velocity with return-flow

$w_{s3}$  Return-flow velocity

$Z$  Normalized or material vertical coordinate
\( Z_0 \)  
Material height

\( z \)  
Vertical co-ordinate

\( z_i \)  
Point on the z-axis in the z-t plot where the concentration is \( C_v \) at \( t=0 \)

\( z_0 \)  
Total thickness of soil

\( \alpha \)  
Arbitrary constant

\( \beta \)  
Rate of change of void ratio

\( \Delta \rho_f \)  
Difference in densities of flocs and water

\( \rho_b \)  
Wet bulk density

\( \rho_f \)  
Density of flocs

\( \rho_{fd} \)  
Pore fluid density

\( \rho_{mix} \)  
Density of sediment-water mixture

\( \rho_w \)  
Density of water

\( \rho_s \)  
Density of solid particles

\( \rho(\zeta,T) \)  
Density corresponding to material-coordinate and time factor

\( \sigma' \)  
Effective stress

\( \varphi_{vf} \)  
Floc volume fraction

\( \varphi_{vfs} \)  
Space-filling value of floc volume fraction

\( \varphi_{vs} \)  
Volume fraction of solid particles

\( \chi \)  
Sediment related constant

\( \zeta \)  
Material vertical coordinate
SEDIMENTATION OF LAKE APOPKA MUD AND COMPARISON WITH OTHER SEDIMENTS

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August 2009

Chair: Ashish J Mehta
Major: Coastal and Oceanographic Engineering

Sedimentation characteristics of fine sediment, which include settling and consolidation, are important processes in the dynamics of natural systems such as lakes and coastal waters. The present study was focused mainly on organic-rich dark mud, or muck, from Lake Apopka (AM) in central Florida, where turbidity and water quality are significant management issues. Laboratory column experiments were performed to estimate important parameters related to settling. The well-known theory of Kynch was relied on to estimate the unhindered and hindered settling velocities. Laboratory experiments were also performed to record the self-weight consolidation behavior of AM. An analytic model proposed by Been and Sills was used to estimate the coefficient of consolidation. To assess the effect of organic matter and clay mineral content on the settling and consolidation behaviors, a largely inorganic mud from the Gulf of Mexico (GM), a commercially available kaolinite clay (KS), and a 1:1 mixture of AM and kaolinite (AKS) were also tested.

The presence of organic matter appeared to enhance the settling rate of AM relative to AKS and KS, as high organic content led to the formation of large mucous-bound aggregates or flocs. The effect of size was seemingly more significant than the fall-retarding effect of floc
buoyancy because, according to the Stokes law, while the settling velocity is linearly proportional to the excess density of flocs, it has a quadratic dependence on floc size.

Individual flocs tend to lose their identity in the consolidation phase. Yet floc density plays a significant role in self-weight consolidation. The magnitude of the consolidation coefficient is a measure of the rate of consolidation; the smaller its value the slower the rate. Since AM flocs were lighter than GM the consolidation coefficient for AM was two orders of magnitude smaller than the coefficient for GM. In other words the rate of consolidation of AM was considerably slower than GM.
CHAPTER 1
INTRODUCTION

1.1 Motivation and Objective

Settling and consolidation behaviors of fine-grained sediments containing significant fractions of natural organic matter are important sedimentation processes that need to be understood in order to model sediment dynamics in natural systems such as lakes, estuaries and coastal waters. Accurate modeling of sedimentation parameters is important in the maintenance of navigation channels at port and harbors, and their operation during extreme conditions such as storms and hurricanes. Maintenance of water quality is also dependent on understanding the turbidity dynamics of these waters.

The objective of this study was to measure the settling and consolidation behaviors of selected fine sediments, and to evaluate important parameters such as the rate of settling and the coefficient of consolidation. The main focus was on highly organic sediment from Lake Apopka in central Florida. It is dark colored and is commonly referred to as muck. The derived parameters were examined on a comparative basis for purposes of quantifying the roles of organic matter and clay mineral content in governing the sedimentation behavior. Primary measurement emphasis was the settling behavior of these sediments, from which consolidation properties were inferred.

1.2 Scope and Tasks

The study included muck from Lake Apopka, largely inorganic mud from the Gulf of Mexico offshore of Louisiana, and a commercially available kaolinite. The main set of data was collected in laboratory columns meant to characterize the settling of dense fine sediment slurries. The following tasks were carried out:

1. Bottom sediment was obtained from Lake Apopka and mud from the Gulf of Mexico.
2. Laboratory column tests on the settling behavior were performed using the above sediments and also on a mixture of lake sediment and kaolinite.

3. The sedimentation theory of Kynch (1952) was used to evaluate the settling characteristics and to derive characteristic settling rates.

4. The consolidation phase of the settling process was approximately identified for each type of sediment used from the test data.

5. The consolidation theory of Been and Sills (1981) was applied to analyze the consolidation phase and to determine best-fit values of the consolidation coefficient.

6. The settling and consolidation behaviors of the sediments were compared in order to identify the roles of organic matter and clay minerals on sedimentation.

### 1.3 Outline of Chapters

The organization of the thesis is as follows. In Chapter 2, basic concepts of settling and consolidation are briefly summarized, including methods used for data analysis. The sediments used and the laboratory experiments have been detailed in Chapter 3. Chapter 4 presents the results of the experiments. Characteristic parameters for hindered settling and consolidation obtained by comparing the models with the results have been discussed and used to identify the role of organic matter in sediment from Lake Apopka, and the role of the dominant clay minerals in other sediments. Some relevant data have also been derived from previous investigations. In Chapter 5 the main findings of the study are summarized and recommendations for further work presented.
CHAPTER 2  
BASICS OF SEDIMENTATION

2.1 Settling and Consolidation Processes

Sedimentation as a general term is the process by which particles or flocs (made of cohesive particles or organically bound inorganic fine particles) fall to the bottom of the liquid to form a deposit.

The process of settling can be sub-divided into three stages: flocculation, unhindered settling and hindered settling. Flocculation of initially suspended fine sediment is the phase in which there is no actual settling. The main process is aggregation by Brownian motion and to a lesser extent differential settling whereby the suspension containing initially formed flocs and individual particles interact to form flocs typically larger than those initially present. The duration of this stage depends on the concentration and on the particle composition, and may last anywhere from seconds to minutes.

The second stage is unhindered settling in which the development of a marked concentration gradient or lutocline occurs. A second interface marking the bed layer develops near the bottom. When the initial concentration is uniform, as in the present study, the lutocline settles at a constant velocity since hindrance is not encountered. This is also known as constant-flux settling.

The third stage of the settling process is hindered settling where there is a non-uniform settling or decrease in the rate of fall of the lutocline. The lutocline falls until the time it meets the rising bed interface. This point in time marks the approximate completion of the settling process and the beginning of consolidation.

In the process of self-weight consolidation of present interest, as the bed material is compressed due to gravity, the space between particles decreases with the expulsion of pore
water from inside and between the flocs. Thus consolidation occurs due to the weight of particles themselves. Unlike the process of settling, the sediment does not behave like a collection of individual particles, but becomes a soil with properties described by parameters characteristic to consolidation. A particle framework associated with effective stresses develops. Since the framework is compressible the strains are initially large. Due to dewatering the bed height falls finally to a level where no further reduction occurs, except by the process of secondary consolidation in which particle rearrangement occurs in the absence of dewatering. Primary consolidation, which is the subject of present interest, can persist from minutes to days, or longer.

2.2 Studies on Settling

The problem of a single particle falling through a fluid has been examined using Stokes’ law. For multiple particles a solution was found by Einstein (1911) and others when the particle density is low and distance apart much greater than the size of particles. According to this solution the speed of fall (or the settling velocity) is,

$$w_s = w_{s0} (1 - \chi C_v)$$  \hspace{1cm} (2-1)

where $w_{s0}$ = Stokes’ settling velocity, $\chi = 2.5$ for hard spheres and $C_v$ = volume concentration of particles. Unfortunately, no easy theoretical explanation is available when the density of the particles is higher or when the concentration is high.

Kynch (1951) hypothesized that the problem could be solved by making the assumption that at any point in the suspension the settling velocity is dependent only on the local concentration of particles. This velocity can then be determined by the continuity equation, without actually knowing the details of the forces on particles. With this assumption Kynch evaluated the continuity equation for the settling of a suspension of similar particles. As the
particles have the same size and shape, their concentration is proportional to the volume fraction. Hence,

\[ F = C_v w \]

(2-2)

where \( F \) is the number of particles crossing a horizontal section per unit area and unit time.

Another assumption is that the concentration is the same across any horizontal layer. Therefore the particle flux is determined by the concentration alone. As it increases from zero to maximum \((C_{vm})\), the settling velocity decreases from a finite value to zero.

The sediment continuity equation is,

\[
\frac{\partial}{\partial t} \left( C_v dz \right) dt = F \left( z + dz \right) dt - F \left( z \right) dt
\]

(2-3)

where \( z \) is the height of the dispersed particles above the bottom.

Dividing Eq. (2-3) by \( dzdt \), the final form of the continuity equation is,

\[
\frac{\partial C_v}{\partial t} = \frac{\partial F}{\partial z}
\]

(2-4)

Using Eq. (2-2) for particle flux, the continuity equation can be written as,

\[
\frac{\partial C_v}{\partial t} + W \left( C_v \right) \frac{\partial C_v}{\partial z} = 0
\]

(2-5)

where the characteristic velocity \( W \left( C_v \right) = -dF / dC_v \).

This equation is interpreted in the following way. On a plot of position \( z \) against time \( t \) (Fig. 2-1), a curve is drawn through points with the same value of concentration. The co-ordinates \((z, t)\) and \((z+dz, t+dt)\) of two adjacent points on such a curve are related by

\[ C_v \left( z + dz, t + dt \right) = C_v \left( z, t \right) \]

(2-6)

i.e.
\[
\frac{\partial C_v}{\partial z} \, dz + \frac{\partial C_v}{\partial t} \, dt = 0
\]  
(2-7)

Combining Eqs. (2-5) and (2-7), the slope of the curve is given by

\[
\frac{dz}{dt} = W(C_v)
\]  
(2-8)

The slope must be a straight line as \( C_v \) is constant and therefore \( W \) is also constant. Therefore, on the \( z-t \) diagram the concentration is constant along straight lines whose slopes \( W \) depend only on concentration. One such line passes through every point in the diagram below the top of the suspension, and in a region where the density is continuous.

From the \( z-t \) plot it can be shown that the value of concentration at any point \( z \) is

\[
z = z_i + W(C_v) t
\]  
(2-9)

where \( z_i \) is the point on the \( z \)-axis along which the concentration is \( C_v \) at \( t=0 \) and the point on the \( z \)-axis where the line of constant concentration \( KP \) intersects. Now the point where the lines of constant concentration terminate has to be determined, i.e. the position of the curve \( AB \) representing the fall-curve of the top of the suspension. At any point \( P \), since the settling velocity of the surface is that of the particles at the surface, along \( AB \),

\[
\frac{dz}{dt} = -w_s(C_v)
\]  
(2-10)

The curve of fall is found by expressing \( C_v \) in terms of \( z \) and \( t \) in Eq. (2-9), which yields a differential equation. This equation can be integrated to find the curve of fall.

Another method to find the curve is to consider a level that is rising through the suspension at a velocity \( W \) (represented by \( KP \) in the Fig. 2-1), and across which particles of concentration \( C_v \) fall with velocity \( w_s(C_v) \). Hence in time \( t \) the number of particles that have crossed the level is \( C_v(W + w_s) t \) per unit area. The level reaches the surface at the point \( P \) when
the number of particles that have crossed the level equals the total number of particles. Using the initial distribution of particles,

$$N(z_i) = \int_{z_i}^{h_0} C_v dz_i$$  \hspace{1cm} (2-11)

where $h_0$ is the initial height of the suspension, the equation is found to be,

$$N(z_i) = C_v (W + w) t$$  \hspace{1cm} (2-12)

where $N$ is the total number of particles that can be represented as a function of $C_v$.

By combining Eqs. (2-9) and (2-12) the coordinates of a point (e.g. point $P$ on the line $KP$ in Fig. 2-1) on the line of constant concentration can be determined.

To determine the fall curve at the bottom of the suspension (i.e. $BC$ in Fig. 2-1), lines of constant concentration from the $t$ axis (i.e. the region below $OB$) are considered. The position of the fall curve is determined only by the end conditions, i.e. at $z = 0$ at the bottom. A reasonable assumption for the conditions along the $t$ axis is that near point $O$ there is a rapid increase in concentration to its maximum value, as a result of which $W$ decreases. Hence the equation of the lines is,

$$z = W(C_v) t$$  \hspace{1cm} (2-13)

By using the same argument as before, the number of particles that have crossed at each level of constant density is the total number of particles $N$ in the suspension where,

$$N = \int_{0}^{h_0} C_v dz_i$$  \hspace{1cm} (2-14)
Now it is seen from the Fig. 2-1 that below region \(OC\), i.e. along \(CD\), the suspension is stationary and has settled to its maximum concentration. Its depth is now \(h_f\) where,

\[
N = C_{vm} h_f
\]  

(2-16)

where \(C_{vm}\) is the maximum concentration.

### 2.2 Studies on Self-Weight Consolidation

Experimental studies on self-weight consolidation have been carried out by, among others, Work & Kohler (1940), Michaels & Bolger (1962), Tory & Shannon (1965), Owen (1970), McRoberts & Nixon (1976), Been (1980), Merckelbach (2000) and Bartholomeeusen (2002).

Gibson et al. (1967) developed the general form of the governing equation for consolidation. This equation has been solved for particular stress-strain and permeability relationships by, among numerous investigators, Lee (1979) and Lee & Sills (1981) and Been and Sills (1981). An important feature of their model is its ability to describe consolidation solely due to the self-weight of soil. Moreover an analytical solution is obtained and is easily applied by assuming that the coefficient of consolidation is constant.

In order to solve the governing equation analytically, Been & Sills (1981) assumed that the void ratio/effective stress relationship and the permeability/void ratio relationship are linear, and the coefficient of consolidation \(C_F\) is constant. Thus,

\[
\sigma^* = A - \alpha e
\]

(2-17)

where \(\sigma^*\) is the effective stress, \(e\) is the void ratio, \(A\) and \(\alpha\) are sediment-dependent constants, and,
\[ k = \rho_{fd} k_0 (1 + e) \]  
\[ \text{(2-18)} \]

where \( k \) is the permeability, \( k_0 \) is a constant, \( \rho_{fd} \) is the pore fluid density. The coefficient of consolidation is given by,

\[ C_F = -\frac{K}{\rho_{fd} (1 + e)} \frac{d\sigma'}{de} \]  
\[ \text{(2-19)} \]

In reality, due to large strains that initially develop in the soft soil it is often observed that the effective stress and permeability relationships are non-linear. However, the coefficient of consolidation tends to remain constant.

The governing equation is,

\[ \frac{\partial e}{\partial t} + \frac{\partial e}{\partial z} \left[ \frac{k}{\rho_{fd} (1 + e)} \frac{d\sigma'}{de} \right] + \left( \rho_s - \rho_{fd} \right) \frac{d}{de} \left[ \frac{k}{\rho_{fd} (1 + e)} \right] \frac{\partial e}{\partial z} = 0 \]  
\[ \text{(2-20)} \]

where \( z \) is the vertical coordinate and \( \rho_s \) is the density of the particles. Using assumptions made from Eqs. (2-17) and (2-19), Eq. (2-20) reduces to,

\[ \frac{\partial^2 e}{\partial t^2} = C_F \frac{\partial^2 e}{\partial z^2} \]  
\[ \text{(2-21)} \]

for \( 0 \leq z \leq z_0 \) and \( t \geq 0 \), where \( z_0 \) is the total thickness of the soil. This equation represents the vertical diffusion of the void ratio \( e \) with \( C_F \) representing the diffusivity.

The boundary condition of uniform initial void ratio \( e_i \), when one starts with uniform suspension concentration as in the present study, is

\[ e(z, 0) = e_i \]  
\[ \text{(2-22)} \]

where subscript \( i \) denotes the initial value of \( e \). Note that the void ratio remains constant at the surface as the effective stress at that level is zero, i.e.

\[ e(z_0, t) = e_i \]  
\[ \text{(2-23)} \]
The void ratio distribution in the $z$-direction for a fully consolidated soil depends on the void ratio-effective stress relationship, Eq. (2-17). It can be shown that this gives,

$$e(z, \infty) = e_i - \beta(z_0 - z)$$  \hspace{1cm} (2-24)

where, $\beta = (\rho_i - \rho_f)/\alpha$. As there is no flow at the base of the soil,

$$\left( \frac{\partial e}{\partial z} \right)_{z=0} = \beta$$  \hspace{1cm} (2-25)

The height of the slurry decreases with time. In order to have the height as a constant in the solution a material coordinate is defined. The advantage of the material coordinate is that the associated material height remains constant regardless of the settlement of the slurry. The normalized material co-ordinate $Z$ and time factor $T$ are defined as:

$$Z(z) = \int_0^z \frac{1}{1 + e_i} \, dz$$  \hspace{1cm} (2-26)

The material height is defined by,

$$Z_0 = \int_0^{h(t)} \frac{1}{1 + e_i} \, dz$$  \hspace{1cm} (2-27)

where $h(t)$ is the instantaneous height of the slurry.

$$T(t) = \frac{C_i t}{Z_0^2}$$  \hspace{1cm} (2-28)

By using the material coordinate a simpler form of Eq. (2-21) is obtained, i.e.

$$\frac{\partial e}{\partial T} = \frac{\partial^2 e}{\partial \zeta^2}$$  \hspace{1cm} (2-29)

with the conditions $\zeta = Z / Z_0$ for $0 \leq \zeta \leq 1$ and $T \geq 0$.

By applying the new boundary conditions the solution in terms of the void ratio distribution is given by,
\[ e(\zeta, T) = e_i - \beta Z_0 \times \left[ 1 - Z - 2 \sum_n \frac{\cos(m\pi Z)}{m^2 \pi^2} \exp\left(-m^2 \pi^2 T\right) \right] \] (2-30)

where \( n = 0, 1, 2, 3, \ldots \), and \( m = \frac{1}{2} (2n + 1) \).

Fig. 2-1. Settling of a suspension with time
CHAPTER 3
EXPERIMENTAL INVESTIGATION

3.1 Materials

3.1.1 Lake Apopka Mud (AM)

Sediment from the upper portion of the bottom was obtained from Lake Apopka (latitude 28° 36′ 22.22″ N; longitude 81° 37′ 39.99″ W) in central Florida (Fig. 3-1) near the UF0 station (Fig. 3-2). Lake Apopka is a 12,500 hectare shallow body of water located about 25 km northwest of the city of Orlando. The maximum depth at the center is approximately 2.7 m and the mean depth is about 1.7 m. The lake is fed by natural springs, rainfall and stormwater runoff. The only surface outflow from the lake is from the Apopka-Beauclair Canal.

Bottom mud was collected from the lake in March 2008 using a core sampler (Fig 3-3). The collected samples were stored in 25 liter plastic containers and kept in the laboratory at 26°C. The properties (floc-size, particle density and organic content) of the mud are given in Table 3-1.

Loss on Ignition (LOI) was 60% indicating high organic content of the mud. The particle density used for this study for the Lake Apopka mud (AM) is 1,690 kg/m³ as derived from laboratory tests (see Section 3.2.2). This value is lower than the typical value of 2,650 kg/m³ for inorganic sediment and can be attributed to the high organic content. The mean floc size measured was 160 µm (Fig. 3-4) using a laboratory microscope (see Section 3.2.3). The salinity of lake water obtained from the area of mud collection was 0.2, as determined from CTD measurements (Fig. 3-5).

3.1.2 Gulf Sediment

The Gulf of Mexico site (Fig. 3-6) from where mud (GM) was collected is located at 29° 26.47′ latitude and 92°3.68′ longitude. The sediment was captured in a grab-sampler in June
2008 and stored in 25 liter plastic containers at 26°C. Relevant properties of the mud are given in Table 3-1.

GM consists primarily of clay minerals. The dominant clay minerals are smectite (70%), illite (18%) and kaolinite (10%). Particle density was estimated as 2,520 kg/m$^3$ (see Section 3.2.2). The LOI for the sediment was 7%, which indicates that it is mainly inorganic.

### 3.1.3 Kaolinite

Commercially available kaolinite (KS) was used for study. The properties of the sediment are given in Table 3-1. The value of 2,650 kg/m$^3$ was used as the particle density. The floc size (140 µm) was estimated using a Canon EOS Rebel XTi 400D camera with a 100mm macro lens (see Section 3.2.3) and AutoCAD software. The KS suspension was prepared in local tap water, in which it readily flocculated.

### 3.2 Equipment and Test Procedures

#### 3.2.1 Main Apparatus

The main equipment consisted of three 1-liter graduated glass cylinders (Fig. 3-7) and an acrylic column shown in Figs. 3-8 and 3-9. The column had a height 1.85 m and was 11.1 cm in diameter. Six discharge ports (3.1 mm in diameter) with stoppers provided at elevations of 5, 15, 30, 55, 80, 105 and 130 cm were used for collecting suspension samples at different times. At each elevation the stopper was opened at the required time and the suspension was collected in a 20 ml bottle. A Mettler balance (see Fig. 3-10) was used for gravimetric determination of sediment concentration.

#### 3.2.2 Particle Density Measurement

The particle densities of AM and GM were determined in simple laboratory tests. A wet sample of concentration $C_1$ was heated in a laboratory oven for 24 h at 60°C. The dried sediment was weighed and mixed with a known volume of water. The density of the mixture $\rho_{mix}$ was thus
obtained. The particle density $\rho_s$ was estimated from $\rho_{\text{mix}}$ and mass balance Eq. 3-1. The particle densities determined are given in Table 3-1.

$$\rho_s = \frac{C_1 (\rho_s - \rho_w)}{\rho_{\text{mix}} - \rho_w} \quad (3-1)$$

Where $\rho_w = $ density of water (1,000 kg/m$^3$).

### 3.2.3 Measurement of Floc Size

The floc-size for AM was measured using a Digital Blue QX5 computer microscope (Fig. 3-11). A dilute concentration (0.8 kg/m$^3$) of the AM suspension was prepared, placed on a slide and viewed under the microscope at 200x magnification. To determine the size of the flocs a standard ruler was viewed under the microscope at the same focusing distance and magnification. As noted the mean floc size was found to be 160 µm.

Image-analysis technique was used to determine the floc size of KS. A selected mass (0.5g) of the sediment was mixed with 1 liter of water in a transparent glass (to avoid reflection) column and mixed well. When water became still, several pictures were taken at the mid-section with the high resolution camera (mentioned above). A standard ruler was also imaged at the same focusing distance to measure floc size. The size of each pixel, 6 µm, was determined (Fig. 3-12) from the image. Using AutoCAD and the image of the ruler the floc size was determined. The mean size was determined as 140 µm. The same approach was used for GM, but it was not possible to obtain a picture of a single floc owing to its very small size. However, it could be inferred that the size was less than 6 µm, given that the size of each pixel was 6 µm (Fig. 3-12).

### 3.2.4 Test Procedure using Graduated Cylinders

The sediments AM, GM and KS were initially wet-sieved using a 75 µm sieve. The wet-sieved sediment was then mixed with native water from the respective site (for AM and GM) in the 1-liter graduated cylinders to obtain a slurry with an initial density of 87.2 kg/m$^3$. Tap water
was used for kaolinite. The initial height of the slurry was noted. The slurry was then allowed to
settle over a period of 3 days. The position of the lutocline was noted at the end of 1, 2, 3, 4, 5,
10, 15, 30 and 45 min; 1, 2, 3, 4, 8, 12 and 18 h; and finally 1, 2 and 3 d. Fluid temperature was
noted at 1 h intervals and was found to remain almost constant at 26 °C.

3.2.5 Test Procedure in Acrylic Column

Consolidation tests were performed in the acrylic column for AM and GM. Each
sediment was wet-sieved using a 75 µm sieve. The sieved sediment was mixed with native water
from the respective sites in the acrylic column to obtain a slurry with an initial concentration of
40 kg/m³. The slurry was mixed well for a period of 15 min using a high-pressure air hose and
allowed to settle over a period of 3 h. The position of the lutocline was noted at the end of 1, 3, 6,
10, 15, 20, 30, 45, 60, 90 and 180 min. Measurements were also made at 24 h and 168 h for AM
and at the end of 24 h for GM. The slurry was mixed again and allowed to settle. This time
suspension samples were drawn from each of the discharge ports at the selected times in 20 ml
bottles. The samples were filtered using 0.45 µm Millipore filters (the weight of each clean and
dry filter was obtained using the Mettler balance before filtration). The filters were heated in a
laboratory oven at 50°C for 24 h. They were then weighed to obtain the mass of the sediment in
each sample. From data such as these the sediment density profiles at different times in the
column were derived.

3.2.6 Return Flow Test

A “return flow test” was performed for KS. The purpose of the test was to estimate the
effect of return-flow of fluid (which always occurs as the sediment settles) on the unhindered
settling velocity of the sediment as well as to assess of the effects of suspension viscosity and
buoyancy. These three factors are responsible for hindrance to settling which occurs at high
sediment concentrations. The test setup is shown in Fig. 3-12. A 1-liter graduated cylinder was fitted with a small capillary tube (1 mm in diameter) 5 cm above the base. A KS slurry with an initial concentration of 40 kg/m$^3$ was prepared as explained in Section 3.2.4 and allowed to settle in the cylinder. Simultaneously, 5 ml of commercially available Rhodamine-WT dye (liquid) was introduced through the capillary tube with a syringe. The position of the lutocline and the upward flow of the dye streak from the base of the column were noted at 1, 3, 6, 10, 15, 20 and 30 min. The settling velocity of the flocs in the presence of return flow, $w_{s1}$, and the return-flow velocity $w_{r3}$ were determined from the rate of lutocline settling and the upward flow of Rhodamine respectively.

### 3.3 Test Summaries

The tests in the graduated cylinders are summarized in Table 3-2. In Test 4, 43.6 g of KS was mixed with 50 ml of AM and in Test 5, 75 ml of AM was mixed with 21.6 g of KS.

The tests in the acrylic column are summarized in Table 3-3.
### Table 3-1. Basic properties of sediments

<table>
<thead>
<tr>
<th>Sediment</th>
<th>Clay/non-clay minerals</th>
<th>Native water salinity</th>
<th>Floc size (µm)</th>
<th>Particle density, $\rho_s$ (kg/m³)</th>
<th>Loss on ignition (LOI) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>Non-clay: sulfur, phosphorous, smectite, illite, kaolinite</td>
<td>0.2</td>
<td>160</td>
<td>1,690</td>
<td>60</td>
</tr>
<tr>
<td>GM</td>
<td>smectite, illite, kaolinite</td>
<td>24</td>
<td>&lt; 6</td>
<td>2,520</td>
<td>7</td>
</tr>
<tr>
<td>KS</td>
<td>kaolinite</td>
<td>0</td>
<td>140</td>
<td>2,650</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 3-2. Details of tests performed in glass cylinders

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Sediment</th>
<th>Initial density (kg/m³)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AM</td>
<td>87.2</td>
<td>Settling behavior of organic-rich sediment (muck)</td>
</tr>
<tr>
<td>2</td>
<td>GM</td>
<td>87.2</td>
<td>Settling behavior of mainly inorganic sediment</td>
</tr>
<tr>
<td>3</td>
<td>KS</td>
<td>87.2</td>
<td>Settling behavior of pure clay</td>
</tr>
<tr>
<td>4</td>
<td>AKS</td>
<td>87.2</td>
<td>Settling behavior of muck/clay mixture</td>
</tr>
<tr>
<td>5</td>
<td>AKS</td>
<td>87.2</td>
<td>Settling behavior of muck/clay mixture</td>
</tr>
</tbody>
</table>

### Table 3-3. Details of experiments in the acrylic column

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Sediment</th>
<th>Initial density (kg/m³)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>AM</td>
<td>40</td>
<td>Measure density profiles to compare with theory</td>
</tr>
<tr>
<td>6</td>
<td>GM</td>
<td>40</td>
<td>Measure density profiles to compare with theory</td>
</tr>
<tr>
<td>7</td>
<td>AM</td>
<td>40</td>
<td>Estimation of consolidation parameters</td>
</tr>
<tr>
<td>8</td>
<td>GM</td>
<td>40</td>
<td>Estimation of consolidation parameters</td>
</tr>
</tbody>
</table>
Fig. 3-1. Lake Apopka in central Florida

Fig. 3-2. UF0 station in Lake Apopka (coordinates: $81^\circ 37' 39.99''$, $28^\circ 36' 22.22''$)
Fig. 3-3. Acrylic push-core sampler used to collect mud from the lake

Fig. 3-4. A typical organic floc from Lake Apopka
Fig. 3-5. Salinity measurement in the lake by CTD (at a depth of 18.89 m relative to NAVD88)

Fig. 3-6. Sediment collection site in the Gulf of Mexico (coordinates: -92º03.68', 29º26.47'). Photo courtesy of David Robillard
Fig. 3-7. 1-liter graduated cylinders used in the experiments containing GM (left) and AM (right)

Fig. 3-8. Schematic drawing of apparatus used for consolidation tests

- Acrylic column (Height: 1.85m dia: 11.1 cm)
- Discharge port (dia: 3.1 mm)
- Settling floc
- Settled deposit
Fig. 3-9. Acrylic column for consolidation tests

Fig. 3-10. Mettler balance
Fig. 3-11. Digital Blue QX5 computer microscope for determination of floc size

Fig. 3-12. Image-analysis for KS floc size determination
Fig. 3-13. Schematic drawing of setup for return-flow experiment
CHAPTER 4
Analysis of data and results

4.1 Introduction

Analysis of the settling characteristics of Lake Apopka mud (AM) along with Gulf of Mexico mud (GM), kaolinite (KS) and Apopka mud + kaolinite mixture (AKS) is presented in Section 4.2. This analysis relies on the Kynch (1952) theory of sedimentation (Chapter 2). A comparison of the characteristic parameters representing the phases of settling (flocculation, constant-flux settling and hindered settling) for these sediments is given in Table 4-1. Reasons for observed variations in the values have been discussed.

The consolidation behaviors of AM and GM are examined in Section 4.3. The analysis is based on the Been and Sills (1981) self-weight consolidation theory (Chapter 2). Comparisons of the theoretical and experiment results have been made. The significance of values of the coefficient of consolidation (\(C_F\)) and the parameter \(\beta\) representing the rate of change in void ratio with height has been discussed.

4.2 Settling Phase

4.2.1 Data Trends

As described in Chapter 2, the settling of lutocline can be divided into three phases as shown in Fig. 4-1. The area enclosed by 0ABE represents the flocculation phase during which, however, there is no measurable settling or change in the position of the lutocline from A to B. The phase represented by the area within 0BDF can further be divided into two sub-phases. During the first sub-phase the rate of settling is uniform as hindrance to settling due to closely spaced particles is not encountered. When the initial suspension concentration is uniform over depth and the sediment is mono-sized, this sub-phase is known as constant-flux settling, because within it the product of settling velocity and concentration is constant. In the second sub-phase
settling is no longer linear but gradually decreases with time. This is the hindered settling phase. The settling particles attain their maximum concentration once they reach the base of the column. The area beyond the region 0DF is the consolidation phase. The rate of settling during this phase is very slow until no further reduction in bed height occurs.

For the sediments tested the measured change in the height of the lutocline is shown in Figs. 4-2 to 4-5. The description of settling in Fig. 4-1 can be extended to these figures. For example, in Fig. 4-2, which shows the settling of the lutocline for AM, the flocculation phase (which lasts less than a minute) is practically absent. Also, the fall of the lutocline from B to C is uniform, and signifies rapid, unhindered settling (lasting 5 min). From C to D the lutocline fall rate gradually decreases with time (lasting 8 h). Following point D there is no significant change in the position of the lutocline.

### 4.2.2 Unhindered Settling

The unhindered settling velocities in Table 4-2 were obtained from the rate of settling of the lutocline. The change in the height of the lutocline with time is (see Fig. 4-2):

\[
\frac{dh}{dt} = \frac{h_1 - h_2}{t_1 - t_2} \approx w_s
\]

where, \(w_s\) = settling velocity, \(h_1 = \) height at time \(t_1\) and \(h_2 = \) height at time \(t_2\).

Table 4-2 indicates that the settling of AM was much more rapid than for the other two sediments. In the lake itself the sediment seemingly settled as a dense fluid, similar to the disposal of mud slurry from a hopper dredger (e.g. Wolanski and Gibbs 1995). To demonstrate that process, water near the UF0 station (Fig. 3-2) in the lake was stirred with a pole. A cloud of turbid fluid appeared at the surface (Fig. 4-6) and settled rapidly, leaving “clear” surface water after some time. The settling velocity was very roughly estimated to be in the order of \(0.5 \times 10^{-3}\). 

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m/s, which is lower than, but somewhat comparable with, $1.4 \times 10^{-3}$ m/s measured in the laboratory (Table 4-2).

For further comparison, the settling velocity was also calculated from Stokes law (Eq. 4-2).

$$w_s = \frac{g \Delta \rho_f d_f^2}{18 \eta}$$

(4-2)

where $w_s$ = settling velocity, $\Delta \rho_f = \rho_f - \rho_w$ = difference between the density of floc $\rho_f$ = $1,088$ kg/m$^3$ (estimated from lab experiments) and the density of water ($\rho_w$ = $1,000$ kg/m$^3$), $\eta$ = dynamic viscosity of water ($1.0 \times 10^{-3}$ Pa.s), $d_f$ = diameter of flocs (= 160 µm). The settling velocity thus calculated is $1.2 \times 10^{-3}$ m/s, which compares well with $1.4 \times 10^{-3}$ m/s obtained from unhindered fall of the lutocline.

Fig. 3-4 shows a suspended floc photographed in the lake (using the previously mentioned Canon EOS Rebel XTi 400D camera with a 100mm macro lens). Floc structure comprises of an opaque core (dark brown regions) which could be a clay mineral or a silt-sized particle surrounded by a fluffy, nearly transparent mucous film (light-brown regions).

The flocculation phase (6 min) lasted longer for GM than for AM owing to the smaller size of the flocs of the former sediment (< 6 µm) than the latter (mean floc size 160 µm, see Section 3.2.3).

The organic content of fine sediment is an important parameter which influences flocculation. Its presence effectively reinforces the electrochemical bonds between the mineral flocs that can lead to faster and larger flocs formation. The longer flocculation phase of GM may have been due to its much lower organic content (7% LOI) than AM (60% LOI). The flocculation phase of KS (mean floc size 140 µm) lasted 5 min, which is comparable to GM (floc size < 6 µm, 7% LOI).
The duration from the start of flocculation to the end of hindered settling lasted close to 8 h for AM as seen from Table 4-1. It should be noted that the “end of hindered settling” is defined entirely in the qualitative sense and only for inter-comparison of the hindered settling rates of different sediments. As seen later, the onset of consolidation occurred much sooner than the times given in the table.

GM had a longer duration (close to 16 h), twice as much as AM. KS had the longest duration (approximately 18 h), which, however, was generally comparable to GM. As noted the rapid settling of AM was due to large flocs and possible enhancement by the tendency to settle as a dense fluid. GM and KS with smaller flocs settled more slowly.

The addition of kaolinite to AM increased the rate of settling of the mixture AKS (11.5 h) by almost 4 h over AM, and also increased the flocculation phase (from less than 1 min to 3 min). A likely reason for this increase in the flocculation phase was that the inorganic kaolinite particles reduced the adhesive effect of mucous in AM.

4.2.3 Hindered Settling

4.2.3.1 Basis of Analysis

Hindered settling velocities calculated from the fall rate of the lutocline are presented in this section, keeping in mind the qualitative nature of the definition of the “end of hindered settling”. Three effects modify the settling velocity of the individual floc. These include return flow in the column, suspension viscosity (which is greater than water viscosity) and the buoyancy of falling particles. Order-of-magnitudes of these effects are examined as part of this analysis.

4.2.3.2 Hindered Settling Velocity

The hindered settling velocities in Table 4-3 were obtained from Eq. (4-3).
where $h_s$ and $t_s$ are values on the $h$ and $t$ axes, respectively, obtained by drawing a tangent through any point on the interface settling curve (Fig. 4-7). In Table 4-3 these velocities are calculated for three conveniently selected values of $t_s$. It is seen that AM had an order of magnitude higher settling rate than GM and KS, which had almost the same settling rates. These trends can be explained in terms of floc size and organic content as in Section 4.2.2.

### 4.2.3.3 Effects of Return Flow, Viscosity and Buoyancy

The following equation for the settling velocity due to Winterwerp (2000) can be used to make an assessment of the effects of return flow, viscosity and buoyancy of the fluid that occur when particles settle in a laboratory column.

\[ w_s = w_{sm}k; \quad k = k_r k_b k_v \]  

where the velocity damping factor $k = k_r k_b k_v$ accounts for the corrections applied to the hypothetical maximum settling velocity $w_{sm}$ in the absence of any hindrance. Given $\phi_f^c = $ floc volume fraction and $\phi_f^{vfs} = $ space-filling value of $\phi_f^c$, the damping factor $k_r = 1 - \phi_f^{vfs}$ accounts for the decrease in the settling velocity due to return-flow, $k_b = 1 - \phi_f^c$ the buoyancy effect of the falling particles and $k_v = (1 + 2.5\phi_f^{vfs})^{-1}$ the increase in the viscosity (above water) of the settling suspension. Thus to evaluate these factors it is necessary to determine the value of $\phi_f^{vfs}$.

The analysis was done for KS, for which $\phi_f^{vfs}$ was estimated from the return-flow experiment described in Section 3.2.3. The determination of $\phi_f^{vfs}$ is as follows.

The settling velocity with return flow, $w_{s1}$, and without return flow, $w_{s2}$, are given by Eq. (4-5) and Eq. (4-6), respectively.
The rate of lutocline settling for KS in the return-flow test is shown in Fig. 4-8. The settling velocity, \( w_{s1} \) can be estimated from the slope of the settling curve. The value thus obtained is \( 5.4 \times 10^{-5} \) m/s.

The return-flow velocity was determined by observing the upward flow of Rhodamine-WT dye from the base of the column. The position of the dye streak was noted at different times over a period of 1 h. The return-flow velocity, \( w_{s3} \), was thus estimated as \( 2.04 \times 10^{-5} \) m/s. The value of the settling velocity without the return flow, \( w_{s2} \), can be determined from Eq. (4-7).

\[
w_{s2} = w_{s1} + w_{s3}
\]  

(4-7)

Dividing Eq. (4-5) and Eq. (4-6) the value of \( \phi_{vfs} \) is obtained, which is 0.28. From \( \phi_{vfs} \) the effect of return-flow, \( k_r = 0.72 \), and increase in viscosity, \( k_v = 0.59 \), are obtained.

For determination of \( k_b \), \( \phi_{sf} \) is derived from the measured suspension concentration \( C \) using the following mass balance.

\[
\phi_{sf} = \frac{C_d (\rho_s - \rho_w)}{\rho_s (\rho_f - \rho_w)}
\]  

(4-8)

Given \( C_d = 120.8 \) kg/m\(^3\), the depth-averaged concentration over the height of movement of the dye, \( \rho_s = 2,650 \) kg/m\(^3\), the density of the solid particles and \( \rho_f = 1,129 \) kg/m\(^3\), the density of the flocs, the value of \( \phi_{sf} \) is 0.58. Therefore, \( k_b = 0.42 \). The settling velocity damping factor, \( k \), thus determined is 0.18. Therefore, the percent reductions in the hypothetical maximum settling velocity \( w_{sm} \) are:
<table>
<thead>
<tr>
<th>Cause</th>
<th>% reduction in $w_{sm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return flow</td>
<td>28</td>
</tr>
<tr>
<td>Viscosity</td>
<td>41</td>
</tr>
<tr>
<td>Buoyancy</td>
<td>58</td>
</tr>
</tbody>
</table>

Note that the dynamic viscosity of kaolinite in freshwater for a concentration of 120.8 kg/m$^3$ is 9.83 times the viscosity of water (Engelund and Zhaohui 1984, Ross 1988).

4.2.2.3 Concentration Profiles

4.2.2.3.1 Determination from Settling Curve

Concentration profiles derived for AM and GM from the measured fall of the lutocline are shown in Figs. 4-10 and 4-11, respectively. The method to obtain the concentration at any elevation in the hindered settling zone is shown in Fig. 4-9. Lines drawn from points on the settling curve to the origin are lines of constant concentration. For example, at $t_1$ these lines are $0t_1$, $0t_2$ and $0t_3$. The intersection of the lines of constant concentration and $tt_1$ gives the elevations (i.e. $z_1$, $z_2$ and $z_3$) respective to the data points. At the elevations thus determined (e.g. $z_1$, $z_2$ and $z_3$), the corresponding concentrations $C(z,t)$ are given by Eq. (4-9),

$$C(z,t) = \frac{C_0h_0}{h_*(z,t)} \quad (4-9)$$

where $C_0$ is the initial concentration, $h_0$ is the initial height of the suspension and the height $h_*(z,t)$ is as explained in Eq. (4-3) and shown in Fig. 4-9. The concentration profile is thus obtained by plotting $C(t)$ with respect to $z$. Extending the same procedure, the concentration profiles at all the data points (i.e. $t_2$, $t_3$, ..., $t_8$) can be obtained.

For AM, the concentrations at different elevations at the end of 45 min, 2 h and 8 h are given in Tables 4-4, 4-5 and 4-6, respectively, and the profiles at the corresponding times are shown in Fig. 4-10. The 8 h profile shows that there is no significant change in concentration with height compared to the 45 min or the 2 h profile. It can be considered that consolidation...
began at this time as the concentration remained practically constant, i.e. it had reached its final value due to settling.

For GM, the concentration values calculated at different elevations at the end of 3 h, 8 h and 18 h are given in Tables 4-7, 4-8 and 4-9, respectively. The corresponding profiles are shown in Fig. 4-11. It can be seen that in the 3 h and 8 h profiles there is a considerable difference in the concentration values (2,142 kg/m³ for the 3 h profile and 1,318 kg/m³ for the 8 h profile) between the top and the base of the column as compared to the 18 h profile. The 18 h profile shows almost constant concentration in agreement with Fig. 4-3, which suggests that consolidation, can be considered to have begun at the end of 18 h.

In the settled deposit, the concentration at the start of consolidation is obtained from

\[ C_{fd} = \frac{C_0 h_0}{h_f} \tag{4-10} \]

where \( C_{fd} \) is the concentration of the settled (pre-consolidation) deposit and \( h_f \) is the final settled height of the bed.

### 4.2.2.3.2 Determination of Concentration from Settling Curve and Comparison with Data

Measured concentration profiles (as explained in Section 3.2.3) are now compared with the analysis using the Kynch theory. Results for GM at 10, 15 and 60 min are shown in Table 4-11 and in Figs. 4-13(a) to 4-13(c). The “theoretical” values were obtained from the settling of the lutocline measured during the experiment shown in Fig. 4-12 as described earlier. For comparison purposes, concentration values were converted to the corresponding densities using the mass balance Eq. (4-11).

\[ \rho_b = \frac{C(\rho_s - \rho_w)}{\rho_s} + \rho_w \tag{4-11} \]
where \( \rho_b \) is the wet bulk density, \( \rho_s \) is the particle density (1,690 kg/m\(^3\) for AM and 2,520 kg/m\(^3\) for GM) and \( \rho_w \) is the density of water (1,000 kg/m\(^3\)).

From Figs. 4-13(a) to 4-13(c) it is seen that the measured density profiles and those obtained from the rate of fall of the lutocline are in acceptable agreement at 10 min and 15 min. However, at 60 min there are noteworthy differences in the density values (with an average difference of 3 kg/m\(^3\)). Thus the theory is not applicable after consolidation begins. However, qualitatively the trends remain the same for all the profiles.

The settling of the lutocline for AM is shown in Fig. 4-15. Density profiles for this sediment have been compared at 15, 30 and 60 min. Details are given in Table 4-10 and in Fig. 4-15(a) to 4-15(c). It is seen that densities obtained from the lutocline settling rate and from measurements are in close agreement at 15 and 30 min. Agreement is less satisfactory (with a difference of approximately 4 kg/m\(^3\)) at 60 min.

### 4.3 Consolidation Phase

The transition between hindered settling and consolidation can be characterized in three ways:

1. A significant decrease in the rate of fall of the lutocline marked by a near-break in the slope of the interface in the plot of lutocline height versus time.

2. The point in time at which the falling lutocline meets the rising bed surface.

3. The concentration at which measurable effective normal stress first develops in the deposit.

The first definition is entirely qualitative. The second and the third definitions are close to each other even though notionally they are not coincident. The third definition is consistent with the mechanics of consolidation and is quantitative. The concentration range over which the onset
of effective stress occurs is 40 to 120 kg/m$^3$ (Winterwerp and van Kesteren 2004). Given the presence of mucous as a binding agent in AM it is likely that characteristic concentration applicable to this sediment was in the vicinity of 40 kg/m$^3$, while for the largely inorganic GM is was closer to the mean value of 80 kg/m$^3$. Thus the onset of effective stress in AM can be expected to have occurred at the wet bulk density 1,016 kg/m$^3$ and in GM at 1,048 kg/m$^3$.

Parameters defining the consolidation process including the coefficient of consolidation ($C_F$) and the rate of change in void ratio with height ($\beta$) were determined using the Been and Sills (1981) model reviewed in Chapter 2. Measured densities have been compared with the theory, and best-fit values of $C_F$ and $\beta$ are established. The significance of the values has been discussed and differences relative to the two sediments tested (AM and GM) have been noted.

**4.3.1 Determination of Consolidation Parameters**

Density profile measurements at 15 min, 1, 3, 24 and 168h for AM are given in Table 4-12 and are plotted in Fig. 4-16. Measurements at 10, 60, 90 min and 24 h for GM are given in Table 4-13 and plotted in Fig. 4-17.

Judging from the onset of consolidation based on the development of effective stress, it is likely that AM began to exhibit consolidation behavior after about 15 min from the start of the test, and GM after about 60 min. This is consistent with the plot for AM given in Fig. 4-18. It shows that the falling lutocline level became coincident with the rising level of the deposit at 15 min.

The consolidation analysis given below does not exclude the initial behaviors of the two sediments that strictly fall within the process of settling. This is in recognition of the similarities between hindered settling of dense slurries and early stages of consolidation, which make the transition between the two processes gradual in time.
For analysis of the results using the Been and Sills model, the initial void ratio \( (e_i) \) and the material height \( (Z_0) \) were determined using Eqs. (4-11) and (2-27), respectively.

\[
e_i = \frac{\rho_s}{C_0} - 1 \quad (4-11)
\]

where \( C_0 \) is the initial concentration of the slurry (= 40 kg/m\(^3\)) and \( \rho_s \) is the density of the solid particles (= 1,690 kg/m\(^3\) for AM and 2,520 kg/m\(^3\) for GM). The material height and initial void ratio obtained for both the sediments are given in Table 4-16.

A wide range of initially assumed values of coefficient of consolidation \( C_F \), from \( 10^{-1} \) to \( 10^{-4} \) mm\(^2\)/s (the value of \( C_F \) for natural sediments is usually between 0.50 and 0.90 m\(^2\)/yr), and the rate of change in void ratio with height \( \beta \) (0.1 to 1.8) were used to compute the void ratio distribution from Eq. (2.30). Void ratios at different times and elevations for AM and GM are given in Tables 4-15 and 4-16, respectively, and the corresponding profiles are shown Figs. 4-19 and 4-20, respectively. Theoretical density values at different times and elevations were obtained from the void ratios using Eq. (4-13).

\[
\rho(\zeta, T) = \frac{\rho_s - \rho_w}{1 + e(\zeta, T)} + \rho_w \quad (4-13)
\]

The densities for AM and GM thus obtained are given in Tables 4-17 and 4-18, respectively.

The theoretical density values have been compared with measured values for AM and GM in Figs. 4-21 and 4-22, respectively. Best-fit values of \( C_F \) and \( \beta \) are thus established and are given in Table 4-16.

### 4.4 Discussion of Results

#### 4.4.1 General Observations

From a series of experiments Elder and Sills (1984) determined that the rate of slurry deposition has an effect on the floc structure framework. A slower rate of deposition results in a
more open framework of the floc structure. This allows the individual flocs to attain a higher strength before being loaded by the sediment arriving later. In other words, for a slurry with a slow rate of deposition the bed remains thicker and less dense than a slurry with a higher rate of deposition.

Extending the same argument, the settling rate of AM being higher than GM should have resulted in a much thicker and less dense bed for GM than AM. However, measurements at the bottom show that AM had a very low bed density (1,018 kg/m$^3$). This is attributed to the fact that AM was high in LOI (60%). Also, the measurements were made at the end of 3 h, a short duration. Thus it took AM longer to consolidate than GM, which had a higher bed density (1,120 kg/m$^3$) at 3 h. The coefficients of consolidation for the two sediments reflect the difference in the rates of consolidation. These coefficients have been compared with values from literature for sediments with somewhat similar properties (Table 4-17).

For a given sediment, the $\beta$ coefficient depends on the initial void ratio. A high initial void ratio leads to a high value of $\beta$. In the case of GM the initial void ratio was 62, which can be considered high. Hence the value of $\beta = 1.5$ was also high. For AM the low value of $\beta = 0.8$ resulted from a low initial void ratio of 20.3. These values of $\beta$ have been compared with those from other investigations in Table 4-16.

For a broader comparative analysis, available properties of sediments in the present study and those referenced from similar studies are summarized in Table 4-17. For these sediments, characteristic parameters for flocculation settling, unhindered settling, hindered settling and consolidation are given in Table 4-18.

Settling related parameters $t_{floc}$ (flocculation time), $t_{un}$ (time for unhindered settling), $w_s$ (unhindered settling velocity) and $t_{hin}$ (hindered settling time) are plotted against LOI (Figs. 4-24...
through 4-28), considering LOI to be a significant parameter in keeping with the study objective (Chapter 1). Overall the governing roles of organic matter as well as mineral composition are quite evident. Considering KS, which was inorganic and AM, which was highly organic (60%), the flocculation time was lower for AM than KS.

Settling data on AM, AKS and KS can be compared because AKS was a 1:1 mixture of KS and AM. In the unhindered mode AM settled significantly faster than KS, as seen from the values of \( t_{un} \) and \( w_s \) (Table 4-18). AKS showed an intermediate trend with respect to \( t_{un} \), although its settling rate was similar to that of KS. In contrast to unhindered settling, hindered settling characterized by \( t_{hin} \) was less dissimilar for the three sediments.

The rapid unhindered settling rate of AM compared to KS may be explained by the fact that AM flocs were larger (mean value 170 µm) than those of KS (125 µm). In Stokes settling the diameter plays an important role because the settling velocity is proportional to diameter squared.

As would be expected GM showed a different unhindered settling behavior, since both its mineral composition and possibly organic composition (of marine origin) differed from KS (a mined clay) and AM (lake muck). GM and KS are unlikely to have been influenced significantly by LOI because GM was low in LOI and KS had none. The main difference between these two sediments was that GM, which contained smectite, was as a result more cohesive than KS, and accordingly had a longer flocculation time (6 min) than KS (4 min). Smectite typically forms tightly packed aggregates while kaolinite flocs are larger with a more open structure. This is evident from the floc densities (1,969 kg/m³ for GM versus 1,006 kg/m³ for KS). GM flocs, once formed, settled more rapidly in the unhindered mode than KS (61x10^{-5} m/s for GM versus 5.3x10^{-5} m/s for KS). It appears that the effect of the difference in floc diameters was

52
overwhelmed by the substantial difference in floc densities. On the other hand, the rate of fall of GM was lower than AM (61x10^{-5} m/s for GM versus 140x10^{-5} m/s for AM).

The hindered settling rates of AM, KS, AKS and GM were closer to each other than the corresponding unhindered rates. Overall, \( t_{\text{hin}} \) varied between 6 and 16 h, a factor of 2.7 compared with of 5 to 128 min in the unhindered mode, amounting to a factor of 25.6. Note that \( t_{\text{hin}} \), which was subjectively estimated, does not mark the onset of consolidation (which begins earlier). The usefulness of \( t_{\text{hin}} \) is solely for inter-comparison among sediments for their rate of hindered settling in the general sense.

As mentioned previously, the settling velocity of KS was hindered by 28% due to the return flow effect, 41% due to the viscosity effect and 58% due to the buoyancy effect. In other words viscosity and buoyancy effects were significant. One would expect that the same general observation would apply to the other sediments.

Relative to GM, from Table 4-18 we observe that in a single test reported by Robillard (personal communication), while the flocculation time \( t_{\text{floc}} \) was nearly the same (5 min) as 6 min in the present study, \( t_{\text{un}} \), \( w_s \) and \( t_{\text{hin}} \) were different. It is believed that these differences were due to the process of initial mixing of the slurry. As mentioned, a high-pressure air hose was used in the present study. On the other hand Robillard mixed the slurry by vigorous shaking. Lower rate of unhindered settling (19x10^{-5} m/s) in his test compared to the present study (61x10^{-5} m/s) suggests that air-hosing produced larger flocs in the present study. In the hindered settling mode the same behavior persisted; in the present study \( t_{\text{hin}} \) was 16 min compared to 53 min in the test of Robillard.

Comparing the consolidation characteristics in Table 4-18 we note that consolidation of AM was slow (\( C_F \) value 0.0045 mm^2/s) in comparison with KS and GM, which consolidated
much more rapidly ($C_F$ values of 0.4 and 0.6 mm$^2$/s, respectively). During consolidation individual flocs lose their identity and floc density governs the self-weight effect. AM flocs were much lighter (density 1,088 kg/m$^3$) than GM (1,969 kg/m$^3$). This difference also resulted in high void ratios ($e$) within AM compared to GM. At the bottom the “final” value of $e$ was 36.5 for AM (Fig. 4-20) against 20 for GM (Fig. 4-21).

Singapore marine clay and Combwich mud (Table 4-18) consolidated slowly, at rates closer to AM than to KS or GM.

**4.4.2 Effects of LOI and Mineral Composition**

Based on the above observations it can be inferred that the presence of organic matter assisted in the settling process of mineral sediment. Higher organic content led to the formation of larger flocs, thereby increasing the rate of settling. The settling rate enhancement effect of floc size was more significant that the retarding effect of density because according to Stokes law, the settling velocity is linearly proportional to the excess density of flocs but has a quadratic dependence on floc size. In the tests conducted differences in floc size played a more significant role in the settling process than differences in floc density.

During consolidation flocs tend to lose their individual identities. As a result floc size does not have as much effect on the rate of consolidation as excess floc density. This may explain why the consolidation time increased with increasing organic matter, in spite of floc density reduction in the case of AM and AKS relative to KS.

The type of clay mineral also influences floc density and size. The presence of smectite led to a longer flocculation time and formation of smaller flocs of GM compared to KS. The unhindered and hindered settling rates of GM were also lower than those of KS.

The tendency of smectite to form tightly packed aggregates meant a higher bed density of GM compared to KS. As a result the consolidation time of GM was shorter compared to KS.
Table 4-1. Sedimentation phase durations

<table>
<thead>
<tr>
<th>Phase</th>
<th>AM</th>
<th>KS</th>
<th>GM</th>
<th>AM+KS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flocculation</td>
<td>&lt; 1min</td>
<td>4 min</td>
<td>6 min</td>
<td>3 min</td>
</tr>
<tr>
<td>Unhindered settling</td>
<td>5 min</td>
<td>2 h</td>
<td>10 min</td>
<td>28 min</td>
</tr>
<tr>
<td>Hindered settling</td>
<td>8 h</td>
<td>16 h</td>
<td>16 h</td>
<td>11.5 h</td>
</tr>
</tbody>
</table>

Table 4-2. Unhindered settling velocities

<table>
<thead>
<tr>
<th>Sediment</th>
<th>$h_1$ (mm)</th>
<th>$h_2$ (mm)</th>
<th>$t_1$ (min)</th>
<th>$t_2$ (min)</th>
<th>$w_s$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>275</td>
<td>190</td>
<td>2</td>
<td>3</td>
<td>1.4x10^{-4}</td>
</tr>
<tr>
<td>GM</td>
<td>232</td>
<td>50</td>
<td>10</td>
<td>15</td>
<td>6.1x10^{-4}</td>
</tr>
<tr>
<td>KS</td>
<td>194</td>
<td>146</td>
<td>30</td>
<td>45</td>
<td>5.3x10^{-5}</td>
</tr>
<tr>
<td>AKS</td>
<td>247</td>
<td>147</td>
<td>5</td>
<td>10</td>
<td>2.5x10^{-5}</td>
</tr>
</tbody>
</table>

Table 4-3. Hindered settling velocities

<table>
<thead>
<tr>
<th>Sediment</th>
<th>Time (min)</th>
<th>$h_*$ (mm)</th>
<th>$t_*$ (min)</th>
<th>$w_s$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>45</td>
<td>128</td>
<td>1500</td>
<td>1.42x10^{-6}</td>
</tr>
<tr>
<td>GM</td>
<td>60</td>
<td>60</td>
<td>2000</td>
<td>5.00x10^{-7}</td>
</tr>
<tr>
<td>KS</td>
<td>180</td>
<td>105</td>
<td>3000</td>
<td>5.83x10^{-7}</td>
</tr>
</tbody>
</table>

Table 4-4. Concentrations at different elevations at the end of 45 min for AM

<table>
<thead>
<tr>
<th>Elevation (z) (mm)</th>
<th>$h_*$ (mm)</th>
<th>$C_0$ (kg/m$^3$)</th>
<th>$h_0$ (mm)</th>
<th>$C$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>53</td>
<td>60</td>
<td>180</td>
<td>346</td>
<td>1038</td>
</tr>
<tr>
<td>32</td>
<td>56</td>
<td>180</td>
<td>346</td>
<td>1112</td>
</tr>
<tr>
<td>16</td>
<td>52</td>
<td>180</td>
<td>346</td>
<td>1198</td>
</tr>
<tr>
<td>11</td>
<td>44</td>
<td>180</td>
<td>346</td>
<td>1415</td>
</tr>
<tr>
<td>4</td>
<td>42</td>
<td>180</td>
<td>346</td>
<td>1519</td>
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<tr>
<td>3</td>
<td>41</td>
<td>180</td>
<td>346</td>
<td>1519</td>
</tr>
<tr>
<td>1</td>
<td>41</td>
<td>180</td>
<td>346</td>
<td>1519</td>
</tr>
</tbody>
</table>
Table 4-5. Concentrations at different elevations at 2 h for AM

<table>
<thead>
<tr>
<th>Elevation (z) (mm)</th>
<th>( h^* ) (mm)</th>
<th>( C_0 ) (kg/m(^3))</th>
<th>( h_0 ) (mm)</th>
<th>( C ) (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>52</td>
<td>180</td>
<td>346</td>
<td>1198</td>
</tr>
<tr>
<td>30</td>
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<td>180</td>
<td>346</td>
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<td>180</td>
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</tr>
<tr>
<td>1</td>
<td>41</td>
<td>180</td>
<td>346</td>
<td>1519</td>
</tr>
</tbody>
</table>

Table 4-6. Concentrations at different elevations at 8 h for AM

<table>
<thead>
<tr>
<th>Elevation (z) (mm)</th>
<th>( h^* ) (mm)</th>
<th>( C_0 ) (kg/m(^3))</th>
<th>( h_0 ) (mm)</th>
<th>( C ) (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>42</td>
<td>180</td>
<td>346</td>
<td>1483</td>
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<tr>
<td>28</td>
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<td>14</td>
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<td>0</td>
<td>41</td>
<td>180</td>
<td>346</td>
<td>1519</td>
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Table 4-7. Concentrations at different elevations at 3 h for GM

<table>
<thead>
<tr>
<th>Elevation (z) (mm)</th>
<th>( h^* ) (mm)</th>
<th>( C_0 ) (kg/m(^3))</th>
<th>( h_0 ) (mm)</th>
<th>( C ) (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
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<td>187</td>
<td>370</td>
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<td>370</td>
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<td>0</td>
<td>15</td>
<td>187</td>
<td>370</td>
<td>4613</td>
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Table 4-8. Concentrations at different elevations at 8 h for GM

<table>
<thead>
<tr>
<th>Elevation (z) (mm)</th>
<th>( h^* ) (mm)</th>
<th>( C_0 ) (kg/m(^3))</th>
<th>( h_0 ) (mm)</th>
<th>( C ) (kg/m(^3))</th>
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<td>370</td>
<td>4613</td>
</tr>
</tbody>
</table>
Table 4-9. Concentrations at different elevations at 18 h for GM

<table>
<thead>
<tr>
<th>Elevation (z) (mm)</th>
<th>h* (mm)</th>
<th>C0 (kg/m³)</th>
<th>h0 (mm)</th>
<th>C (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>17</td>
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<td>370</td>
<td>4070</td>
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Table 4-10. Density measurements for AM and values obtained using the Kynch theory

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Table 4-11. Density measurements for GM and values obtained using the Kynch theory

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Table 4-12. Density measurements for AM and values using the Been and Sills model

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Table 4-13. Density measurements for GM and values using the Been and Sills model

| z (cm) | Time: 10 min | Expt. | Density (kg/m$^3$) | Theo. | Density (kg/m$^3$) | Expt. | Density (kg/m$^3$) | Theo. | Density (kg/m$^3$) | Expt. | Density (kg/m$^3$) | Theo. | Density (kg/m$^3$) | Expt. | Density (kg/m$^3$) | Theo. | Density (kg/m$^3$) | Expt. | Density (kg/m$^3$) | Theo. |
|-------|-------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|
| 130   | 1037        | 1024  | 1015           | 1024  | 1014           | 1024  | 1014           | 1114  | 1024           | 1086  | 1027           | 1086  | 1027           | 1086  | 1027           | 1086  | 1027           | 1086  |
| 105   | 1037        | 1026  | 1034           | 1026  | 1034           | 1028  | 1032           | 1033  | 1032           | 1033  | 1032           | 1033  | 1032           | 1033  | 1032           | 1033  | 1032           | 1033  |
| 80    | 1041        | 1029  | 1038           | 1038  | 1033           | 1032  | 1033           | 1032  | 1033           | 1032  | 1033           | 1032  | 1033           | 1032  | 1033           | 1032  | 1033           | 1032  |
| 55    | 1040        | 1033  | 1043           | 1040  | 1043           | 1040  | 1040           | 1040  | 1040           | 1040  | 1040           | 1040  | 1040           | 1040  | 1040           | 1040  | 1040           | 1040  |
| 30    | 1040        | 1039  | 1045           | 1050  | 1046           | 1050  | 1046           | 1050  | 1046           | 1050  | 1046           | 1050  | 1046           | 1050  | 1046           | 1050  | 1046           | 1050  |
| 15    | 1044        | 1043  | 1057           | 1058  | 1058           | 1058  | 1058           | 1058  | 1058           | 1058  | 1058           | 1058  | 1058           | 1058  | 1058           | 1058  | 1058           | 1058  |
| 5     | 1048        | 1049  | 1093           | 1069  | 1069           | 1069  | 1069           | 1069  | 1069           | 1069  | 1069           | 1069  | 1069           | 1069  | 1069           | 1069  | 1069           | 1069  |

Table 4-14. Void ratios for AM at different times ($C_F = 4.5 \times 10^{-3} \text{ mm}^2/\text{s}$ and $\beta = 0.8$)

<table>
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<tr>
<th>z (cm)</th>
<th>Void Ratio</th>
<th>z (cm)</th>
<th>Void Ratio</th>
<th>z (cm)</th>
<th>Void Ratio</th>
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Table 4-15. Void ratios for GM at different times ($C_F = 6 \times 10^{-1}$ mm$^2$/s and $\beta = 1.5$)

<table>
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<tr>
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<th>Void Ratio</th>
<th>$z$ (cm)</th>
<th>Void Ratio</th>
<th>$z$ (cm)</th>
<th>Void Ratio</th>
<th>$z$ (cm)</th>
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<td>53.8</td>
<td>105</td>
<td>62.0</td>
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Table 4-16. Parameters used for the calculation of $C_F$ and $\beta$

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<th>$e_i$</th>
<th>$\rho_s$ (kg/m$^3$)</th>
<th>$Z_0$ (mm)</th>
<th>$C_F$ (mm$^2$/s)</th>
<th>$\beta$</th>
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Table 4-17. Properties of sediments used and referenced

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<th>Non-clay minerals/materials</th>
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<th>Floc dens. (kg/m$^3$)</th>
<th>Disp. Part. size (µm)</th>
<th>Floc size (µm)</th>
<th>LOI (%)</th>
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<td>AKS</td>
<td>Lake Apopka and kaolinite</td>
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<td>sulfur, phosphorous</td>
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<td>1002</td>
<td>-</td>
<td>150-180</td>
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</tr>
<tr>
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<td>sulfur, phosphorous</td>
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<td>1088</td>
<td>-</td>
<td>160-180</td>
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<td>Gulf of Mexico (LA)</td>
<td>smectite, illite, kaolinite</td>
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<td>1969</td>
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<td>7</td>
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<td>Gulf of Mexico (LA)</td>
<td>smectite, illite, kaolinite</td>
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<td>1765</td>
<td>0.7</td>
<td>&lt; 6</td>
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<td>kaolinite, illite</td>
<td>calcite, feldspar</td>
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* From test conducted by David Robillard (personal communication).
Table 4-18. Characteristic parameters for settling and consolidation

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<th>$w_s$ (x10$^{-5}$ m/s)</th>
<th>$t_{hin}$ (h)</th>
<th>$C_F$ (x10$^{-3}$ mm$^2$/s)</th>
<th>$\beta$</th>
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</table>

$^a$ From test conducted by David Robillard (personal communication).

Fig. 4-1. Phases of sedimentation (defined as settling plus consolidation)
Fig. 4-2. Change in the position of the lutocline with time for AM

Fig. 4-3. Change in the position of the lutocline with time for GM
Fig. 4-4. Change in the position of the lutocline with time for KS

Fig. 4-5. Change in the position of the lutocline for AM+KS mixture
Fig. 4-6. Photograph (February 29, 2008) of a turbid cloud reaching the surface due to stirring in Lake Apopka. This cloud appeared to settle as a dense fluid (courtesy Dr. Eric Wolanski)

Fig. 4-7. Determination of $h_*$ for hindered settling velocity

$h_0 = 350 \text{ mm}$
Fig. 4-8. Settling of lutocline for KS in the return-flow test

Fig. 4-9. Determination of concentration profile in the hindered settling zone from settling of lutocline

$h_0 = 350 \text{ mm}$
Fig. 4-10. Concentration profiles for AM using the theory of Kynch

Fig. 4-11. Concentration profiles for GM using the theory of Kynch
Fig. 4-12. Settling of lutocline for GM in acrylic column

Fig. 4-13(a). Comparison of density profiles at 10 min for GM
Fig. 4-13(b). Comparison of density profiles at 15 min for GM

Fig. 4-13(c). Comparison of density profiles at 60 min for GM
Fig. 4-14. Settling of lutocline for AM in acrylic column

Fig. 4-15(a). Comparison of density profiles at 15 min for AM
Fig. 4-15(b). Comparison of density profiles at 30 min for AM

Fig. 4-15(c). Comparison of density profiles at 60 min for AM
Fig. 4-16. Measured density profiles for AM

Fig. 4-17. Measured density profiles for GM
Fig. 4-18. Upper and lower interfaces vs. time for AM. Initial concentration was 40 kg/m$^3$.

Fig. 4-19. Void Ratio distribution at different times for AM.
Fig. 4-20. Void ratio distribution for GM

Fig. 4-21(a). Comparison of measured and theoretical density values at 15 min for AM
Fig. 4-21(b). Comparison of measured and theoretical density values at 60 min for AM

Fig. 4-21(c). Comparison of measured and theoretical density values at 180 min for AM
Fig. 4-22(a). Comparison of measured and theoretical density values at 10 min for GM

Fig. 4-22(b). Comparison of measured and theoretical density values at 60 min for GM
Fig. 4-22(c). Comparison of measured and theoretical density values at 90 min for GM

Fig. 4-23. Unhindered settling velocities of the sediments plotted as a function of LOI
Fig. 4-24. Flocculation time of the sediments plotted as a function of LOI

Fig. 4-25. Unhindered settling time of the sediments plotted as a function of LOI
Fig. 4-26. Hindered settling time of the sediments plotted as a function of LOI

Fig. 4-27. Rate of change of void ratio for the sediments plotted as a function of LOI
Fig. 4-28. Coefficient of consolidation of the sediments plotted as a function of LOI.
CHAPTER 5
SUMMARY AND CONCLUSIONS

5.1 Summary

The sedimentation behavior of fine sediments inclusive of settling and consolidation phases was experimentally examined in this study. Of particular interest was the settling and consolidation characteristics of highly organic muck in Lake Apopka situated in central Florida. Water quality issues including high levels of turbidity are matters of concern for this lake. With emphasis on this sediment, the main objectives of the study were as follows:

1. To experimentally evaluate the settling and consolidation behaviors of selected fine sediments in order to determine important parameters governing the rates of unhindered and hindered settling, and the coefficient of consolidation.

2. To experimentally estimate the effects of return flow, buoyancy and viscosity on the hindered settling velocity.

3. To assess the effects of organic matter and mineral content on the settling and consolidation processes.

With these objectives in mind the study was conducted for three sediments: muck from Lake Apopka (AM), mainly inorganic mud from the Gulf of Mexico offshore of Louisiana (GM) and a commercially available kaolinite (KS). A 1:1 (by weight) mixture (AKS) of AM and KS was also tested. Settling column experiments were performed for these sediments. The Kynch theory of sedimentation was relied on to estimate characteristic settling parameters including flocculation time, unhindered settling velocity and hindered settling velocity. A “return-flow test” was performed for KS to evaluate the effects of return-flow, buoyancy and viscosity (of the suspension relative to water) on the hindered settling velocity.

Consolidation experiments were performed for AM and GM. The characteristic parameters $C_F$ and $\beta$ were estimated by using the Been and Sills analytic model for self-weight consolidation. Lastly, the settling and consolidation parameters for the sediments were inter-
compared to assess the effects of organic matter and mineral content on the settling and consolidation processes.

5.2 Conclusions

5.2.1 General Observations

1. Flocculation time for AM was the least compared to GM and KS. The addition of KS to AM (resulting in AKS) reduced the flocculation time of KS as expected.

2. The unhindered and hindered settling rates for AM were the highest. KS had the longest settling time that was also comparable to GM. Addition of KS to AM increased the settling time for AKS.

3. The coefficient of consolidation for AM was much smaller than that for GM.

5.2.2 Detailed Observations on the Settling Behavior

1. Comparison of the settling data for AM, KS and AKS showed that AM settled significantly faster ($1.4 \times 10^{-3}$ m/s) in the unhindered mode. AKS showed an intermediate trend ($2.5 \times 10^{-5}$ m/s) in the unhindered zone, though its settling rate was closer to KS ($5.3 \times 10^{-5}$ m/s).

2. The rapid settling of AM in the unhindered zone ($1.4 \times 10^{-3}$ m/s) was due to larger floc sizes (mean value 170 μm) compared to KS (mean value 125 μm).

3. GM showed a different behavior in the unhindered zone possibly due to its low organic content (7% LOI) and also its mineral composition, which was different from AM (and KS).

4. The difference in the settling behaviors of GM and KS was believed to be due to the presence of smectite in GM, which made it more cohesive than KS. Consequently, GM had a greater flocculation time (6 min) than KS (4 min).
5. The characteristic ability of smectite to form tightly packed aggregates resulted in GM having higher floc density (1,969 kg/m$^3$) compared to KS (1,006 kg/m$^3$), which tends to have a more open floc structure. Hence GM settled much faster (6.1x10$^{-4}$ m/s) than KS (5.3x10$^{-5}$ m/s) in the unhindered zone where the floc density played a dominant role in contrast to floc size.

6. The hindered settling rates of AM, GM, KS and AKS were closer to each other than the corresponding unhindered rates. The hindered settling time ranged overall between 6 h and 16 h, which was much lower (in terms of the time ratio 16/6 = 2.7) compared to the unhindered settling time, which varied from 5 min to 128 min (ratio 25.6).

7. The percentage reduction in the settling velocity of KS due to each of the velocity damping (hindered settling) effects determined from the return-flow test were as follows:

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>% Reduction in $w_{sm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return flow</td>
<td>28</td>
</tr>
<tr>
<td>Viscosity</td>
<td>41</td>
</tr>
<tr>
<td>Buoyancy</td>
<td>58</td>
</tr>
</tbody>
</table>

As observed, buoyancy and viscosity played a dominant role in the reduction of settling velocity for KS. Note that at the kaolinite concentration of 120.8 kg/m$^3$ characteristic of the return flow test, the viscosity of the suspension was about 10 times the viscosity of water. The same general observation regarding the contributions to hindered settling may apply to the other sediments in the qualitative sense.
8. The single test by Robillard using GM showed that the flocculation time in his test (5 min) was similar to the present study (6 min). However, there were considerable differences between the two tests in the hindered and unhindered settling times and in the settling velocities (1.9x10^{-4} m/s for the test conducted by Robillard and 6.1x10^{-4} m/s in the present study). These differences were likely to be due to the method used for initial mixing of the slurry. A high-pressure air hose was used in the present study whereas Robillard mixed the slurry by vigorous shaking. The higher rate of unhindered settling in the present study (1.9x10^{-4} m/s) than in Robillard’s test (6.1x10^{-4} m/s) suggests that air-hosing produced larger flocs.

5.2.3 Detailed Observations on the Consolidation Behavior

1. Comparison of consolidation characteristics showed that AM consolidated much more slowly (4.5x10^{-3} mm^{2}/s) than KS (4x10^{-1} mm^{2}/s) and GM (6x10^{-1} mm^{2}/s).

2. A slurry with a slower rate of deposition develops a bed that is thicker and less dense than that formed by a slurry with a faster rate of deposition. According to this argument one would expect AM, with a faster rate of settling, to have a higher bed density than GM. However, density measurements made at the end of 3 h showed that the AM deposit had higher density (1,018 kg/m^{3}) than GM (1,120 kg/m^{3}). This suggested that the high organic content of AM (60% LOI) likely played a significant role in the consolidation process.

3. Individual flocs lose their identity in the consolidation phase. Yet floc density plays a significant role in self-weight consolidation. AM flocs (1,088 kg/m^{3}) were lighter than GM (1,969 kg/m^{3}). This corroborates the slower consolidation rate of AM (C_F = 4.5x10^{-3} mm^{2}/s) compared to GM (C_F = 6x10^{-1} mm^{2}/s).
4. The difference in floc densities AM and GM resulted in higher void ratio for AM. The final void ratio was 36.5 for AM compared to 20 for GM.

5. The rate of change of void ratio, $\beta$, for AM was 0.8 and 1.5 for GM.

6. Consolidation coefficients of Singapore marine clay ($2.5 \times 10^{-2}$ mm$^2$/s) and Combwich (UK) mud ($8.2 \times 10^{-3}$ mm$^2$/s) showed much slower consolidation rates which were much closer to AM ($4.5 \times 10^{-3}$ mm$^2$/s) than to KS ($4 \times 10^{-1}$ mm$^2$/s) or GM ($6 \times 10^{-1}$ mm$^2$/s).

7. Based on the above observations it can be inferred that the presence of organic matter assisted in the settling process of sediment. High organic content led to the formation of large mucous-bound flocs of AM, thereby increasing the rate of settling relative to KS and AKS. The settling rate enhancement effect of floc size was more significant than the fall retarding effect of floc buoyancy because according to Stokes’ law, the settling velocity is linearly proportional to the excess density of flocs but has a quadratic dependence on floc size.

8. For AM, selecting the unhindered settling velocity $w_s = 140 \times 10^{-5}$ m/s, mean floc diameter $d_f = 170$ µm and kinematic viscosity (nominally that of water) $\nu = 10^{-6}$ m$^2$/s, the fall Reynolds number $Re = w_s d_f / \nu = 0.238$, which is well within the Stokes range.

9. In the tests conducted differences in floc size seemingly played a more significant role in the settling process than differences in floc density.

10. During the process of consolidation flocs tend to lose their individual identity. As a result floc size does not have as much effect on the rate of consolidation as excess floc density. This may explain why the consolidation time was longer for AM and AKS compared to KS, in spite of the lower floc densities of AM and AKS (relative to KS).
11. Clay mineral influences floc density and size. The presence of smectite in GM is believed to have led to a longer flocculation time and formation of smaller flocs of GM compared to KS. Likewise the unhindered and hindered settling rates of GM were also reduced compared to KS.

12. The tendency of smectite to form tightly packed aggregates meant that the density of consolidating bed of GM was higher than that of KS. As an outcome the consolidation time of GM was less than KS.

5.3 Recommendations

1. Use of a high-resolution video camera and imaging technique are recommended for the calculation of the settling velocity of a range of sediment types in the laboratory.

2. Testing of different mixtures of the Lake Apopka mud is recommended by adding other clay materials such as bentonite and illite to observe the effect of clay minerals on the settling rate.

3. It is recommended that return flow tests be performed using AM and GM to quantitatively determine the effects of viscosity, buoyancy and return-flow on the unhindered settling velocity.
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Ajay Sampath was born in 1984 in Tamil Nadu, India. He received his bachelor’s degree in marine engineering in 2006 from Tolani Maritime Institute, India, after which he worked as a marine engineer for the Mediterranean Shipping Company (SA) of Hong Kong. He was admitted to the University of Florida in 2007 for the master’s program in coastal and oceanographic engineering. His current research interests include sedimentation in coastal, estuarine and lake waters.