อิทธิพลของพีเอชและสภาพนำไฟฟ้าที่มีผลต่อความเร็วในการตกตะกอนของตะกอนที่ปนเปื้อนตะกั่ว

นางสาวเอธยา จงวิสุทธิสันต์

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INFLUENCE OF pH AND EC ON SETTLING VELOCITY OF LEAD CONTAMINATED SEDIMENT

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A Thesis Submitted in Partial Fulfillment of the Requirements
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Thesis Title	**INFLUENCE OF pH AND EC ON SETTLING VELOCITY OF LEAD CONTAMINATED SEDIMENT**
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Field of Study	**Environmental Management**
Thesis Advisor	**Thidarat Bunsri, Ph.D.**

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เอธยา จงวิสุทธิสันต์: อิทธิพลของพีเอชและสภาพนำไฟฟ้าที่มีผลต่อค่าความเร็วในการตกตะกอนของตะกอนที่ปนเปื้อนตะกั่ว. (Influence of pH and EC on settling velocity of lead contaminated sediment) อ. ที่ปรึกษาวิทยานิพนธ์หลัก: ดร. ธิดารัตน์ บุญศรี, 109 หน้า.

อิทธิพลของพีเอช และสภาพนำไฟฟ้าที่มีต่อความเร็วการตกตะกอน และการชะละลายของตะกั่วจากตะกอนที่ปนเปื้อนด้วยตะกั่วถูกจำลองเชิงเทคนิคในงานวิจัยนี้ ชุดคอลัมน์ทดสอบการตกตะกอนที่มีเส้นผ่านศูนย์กลางภายใน 47 มม. และความสูง 300 มม. ถูกสร้างขึ้น ตะกอนที่ใช้ทดลองถูกปนเปื้อนด้วยตะกั่วที่ความเข้มข้น 20,250 มก./กก. และมีทรายเป็นองค์ประกอบหลัก สารละลายตะกอน (ซเลอรี) ถูกสังเคราะห์ด้วยความเข้มข้น 3% (โดยน้ำหนัก) สารละลายตะกอนต่างๆจัดทำโดยการแช่ตะกอนลงในน้ำปราศจากประจุ, 3.6% ไฮโดรคลอริค (โดยน้ำหนัก), 1.2% โซเดียมไฮดรอกไซด์ (โดยน้ำหนัก), 1% โซเดียมคลอไรด์ (โดยน้ำหนัก) และ 2% โซเดียมคลอไรด์ (โดยน้ำหนัก) ความเร็วการตกตะกอนถูกคาดการณ์โดยกฎของสโตกส์ และเดียทริช (Dietrich) Corey shape และ Complicating factor ถูกเติมลงเพื่อดัดแปลงในกฎของสโตกส์ และเดียทริช ผลการทดลองแสดงให้เห็นว่า ความเร็วการตกตะกอนของตะกอนขึ้นอยู่กับขนาดของอนุภาคตะกอน สภาพนำไฟฟ้าและพีเอชสามารถส่งผลต่อปฏิกิริยาระหว่างตะกอนและไอออนในสารละลาย ตะกอนที่แขวนลอยในสารละลายที่สภาพนำไฟฟ้ามีค่าสูงสามารถถูกทำให้ละลาย และตะกอนแขวนลอยจะสะสมในสารละลายภายใต้สภาวะธรรมชาติ ตะกอนที่มีอนุภาคขนาดเล็กจะถูกทำให้ตกจมช้ากว่าตะกอนอนุภาคขนาดใหญ่ อนุภาคตะกอนสภาพกรดจะถูกกัดกร่อน และขนาดอนุภาคเล็กลง ทำให้เกิดการฟุ้งกระจายอย่างมาก อนุภาคถูกห่อหุ้มด้วยไฮดรอกไซด์ภายใต้สภาวะที่เป็นด่าง ขนาดและความหนาแน่นของอนุภาคจะเพิ่มขึ้น นำมาซึ่งความเร็วตกตะกอนที่สูงขึ้น อนุภาคขนาดใหญ่ในน้ำเค็มจะตกจมช้ากว่าอนุภาคขนาดเล็ก ซึ่งเกี่ยวข้องกับแรงทางไฟฟ้าที่ดึงอนุภาคขึ้นด้านบน อนุภาคอิสระของตะกั่วสามารถหลุดออกจากตะกอนที่แขวนลอย และตกจม อนุภาคขนาดเล็กถูกสะสมอยู่ใกล้พื้นผิวน้ำ ไอออนของตะกั่วก็ตรวจพบในปริมาณมากในระดับความสูงเดียวกัน อนุภาคละเอียดเหล่านี้เป็นแหล่งกำเนิดของตะกั่ว หากอนุภาคเหล่านี้ถูกทำให้ตกจมและตะกั่วถูกปรับเสถียร การเคลื่อนย้ายของตะกั่วจะถูกลดลง สภาพด่างสามารถลดการเคลื่อนที่ของตะกอน และตะกอนที่มีตะกั่วปนเปื้อน การเปลี่ยนแปลงของพีเอช และสภาพนำไฟฟ้ามีอิทธิพลต่อการตกจม และการหลุดออกของตะกั่วจากตะกอนที่มีการปนเปื้อน

สาขาวิชา...การจัดการสิ่งแวดล้อม... ลายมือชื่อนิสิต..

ปีการศึกษา..............2553................ ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก..........................

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ATAYA JONGWISUTTISUN: INFLUENCE OF pH AND EC ON MOVEMENT OF LEAD CONTAMINATED SEDIMENT. ADVISOR: THIDARAT BUNSRI, Ph.D., 109 pp.

The influence of pH and electrical conductivity on settling velocity and releasing of lead from sediments were technically simulated in this study. The series of settling column with an inner diameter of 47 mm and height of 300 mm were fabricated. The utilised sediment was contaminated with lead at the concentration of 20,250 mg/kg and sand was predominantly composition. The sediment slurry was synthesised with a concentration of 3% (w/w). The prepared sediment slurries was governed by soaking sediments into deionised water, 3.6% (w/w) HCl, 1.2%NaOH (w/w), 1%NaCl (w/w) and 2%NaCl (w/w) solutions. The settling velocity was predicted by Stokes and Dietrich law. The Corey shape and complicating factors were inserted to modified Stokes and Dietrich law. The results showed that the settling velocity of sediment was highly depended on the particle size of sediment. The electrical conductivity and pH could affect the reactions between sediments and ions in the solution. The particles suspended in highly electrical conductivity solution could be dissolved and they accumulated into the solution. Under natural condition, the small particle could be settled slower than large particle. The particles in acid condition were eroded and their size was reduced, resulting in highly dispersion. The particles were bound to hydroxide under alkaline solution. The size and density of particles were increased, conducting high the settling velocity. The large particles with saline solution could be settled down slower that the small ones, dealing with the upwards electromotive force. The free Pb could release from suspended particles and bottom sediment. The fine particles were accumulated near the surface, the Pb ions were highly presented at the same elevation. The fine particles were the source of Pb. If the particles could be settled down and the Pb could be stabilised, the migration of Pb was reduced. The alkaline condition could reduce the movement of sediments and Pb bound sediments. The change of pH and EC could influence the settlement and release of Pb from the contaminated sediments.

Field of Study Environmental Management Student's Signature Ataya Jongwisuttisun

Academic Year 2010 Advisor's Signature Thidarat

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CHAPTER I

INTRODUCTION

1.1 Statement of purpose

The recent reports stated that the contamination of heavy metals in environment including of air, water and soil became a worldwide environmental issue. Heavy metals were contaminated in sediments and water in every major rivers and lakes. Sediment was the largest storage and they were sources of various types of heavy metals, which were acknowledged as mobile or immobile sources. The heavy metals contaminated sediments played a properly important role in metal transport. Clean freshwater was the most important for human and other livings as water was used for all activities such as drinking, cooking and cleaning. In any circumstances, whenever heavy metals were contaminated in environmental such as water, soil, sediments and groundwater, they could induce a harmful impact on all living beings. Some heavy metals were categorised as dangerous and toxic substances that could harm to living organism and human. The preceptors could incidentally take heavy metals through food chain and water (Casas and Sordo, 2006). The mining activities were accounted as the source of heavy metals. Coincidently, the mines were always located in the remote area, which water supply may not be accessed. The people often abstracted the groundwater for drinking and everyday uses purposes. The people lived around the mine always suffered and risked to get sick from heavy metal poison diseases as a consequence of heavy metals contaminations (Casas and Sordo, 2006).

Thailand is located in tropical zone that had heavy rainfall in monsoon season. However, the runoff water might carry many contaminants, especially heavy metals and organic constituents resulting in poor quality water source. The seriousness of water quality relied upon the areas whichever runoff flowed through as the water could leach the components contained in the soil surface. Most of mines and their disposal area as well as the area surrounded mines had fertile of natural ores and enriched of soil minerals. The lands were typically functioned as agricultural and arable area. The mines required to excavate soil to earn minerals in deep soil layer while agriculture harvested soil mineral on the surface. The mines could make larger heavy metal exposure comparing to agricultural uses. Besides, mining was one of the heavy industries found in western region of Thailand. The mines were always located in the upland, which was an upstream. The slag or residual contained high concentration of heavy metals could be flushed downstream as well as the infiltration could leach them downwards from soil surface into groundwater. Not only surface water contained heavy metal but also groundwater was contaminated (Bird et al., 1960).

The remediation of water, sediment and soil were seriously undertaken as an important issue. The fundamental indicated that the heavy metals tended to be accumulated in sediments under the natural conditions. The heavy metals adhered sediments could be carried along the water bodies due to advection and dispersion mechanism. The distribution of heavy metal was observed in many forms such as water-soluble species, colloids, suspended forms and sedimentary phases. The release of heavy metals from sediments mainly depended upon the equilibrium of reactions such as adsorption, ion exchange, precipitation and others. These reactions were accounted as the source/sink term. The release of heavy metals from sediments could also occur all the time even during transportation process. In some conditions, more than 99% of heavy metal could enter and accumulate into river (Samans, 1949).

By some limitation, heavy metals could fix into sediment for some certain periods. Under variation of the physical–chemical characteristics of water conditions, the heavy metals could re-enter the overlying water and become available to living organisms (Eggleton and Thomas, 2004). The form of heavy metals, the way of distribution of heavy metals and sediment transport depended upon the environmental factors. The environmental factors had influenced to movement of heavy metals including pH, conductivity and size of particle. The environmental factors could possibly influence to the solubility of heavy metals entrapped sediments and movement of sediment that suspended in the water bodies (Eggleton and Thomas, 2004). Therefore a systematic experiment should be setup to describe the influence of environmental factors on releasing of heavy metals from sediments and sediment transport.

The movement of sediment and release of heavy metals from sediments under weathering condition had relied upon the environmental factors, mainly pH, ionic strength and salinity. In fact, the sediments might be contained some contaminants, especially heavy metals. These heavy metals could dissolve and escape from both of bottom sludge and suspended particles. In order to estimate the dissolubility of heavy metals from sediments, the settling velocity was required to be estimated. During settling period, sediments could be fully contact with water and other constituents, which could either enhance or retard the dissolubility of heavy metals. The sediments investigated in this study were collected from Klity stream, Kanchanaburi, Thailand. They were sand predominantly and they could be classified as a non cohesive and rigid particle. If these particles were discrete particles with a spherical shape, they were expected to possibly be technically estimated using Stokes' law. There were several reported had confirmed that the whole of natural particles were not rigid and sphere, the shape of particles may change due to the chemical reaction and mechanical diffusion. So, the settling velocity could be estimated by using Dietrich's formula in case of rough particles and adding Corey Shape Factor (*csf*) for non spherical particles. However, the environmental factors that could influence the change of particles were involved neither Stokes' law nor Dietrich's formula. The complicated factor was employed to convert the environmental factors including of pH, ionic strength and salinity as the dimensionless terms. The correlations between pH and EC on settling velocity of sediments were defined using the Dietrich's equation with reaction. The assumption was made based upon the fact that reaction from change pH and EC in the system could create an upward drag force on particles. This effect was large enough to fluidise sediment or prevent the settlement. The term of solid concentration (ϕ) was added to determine an actual setting velocity for developed equation (Basson et al., 2009).

1.2 Objectives

Under natural conditions, most of heavy metals were accumulated onto sediments. The heavy metals could be carried along the water bodies due to advection and dispersion mechanism. However, the heavy metals could also release from sediments during transportation process. The main objective of this research was to fully understand the impact of pH and EC that could enhance and/or limit the movement of sediments and the release and/or entrap lead contaminated sediments. The specific objectives are:

- To define the influence of pH and EC on settling velocity of sediments and to verify a set of governing dimensionless terms for correlations the settling velocity of sediment.
- To evaluate the optimum conditions that could effectively retard and stability of lead content in settleable and suspended sediments.

1.3 Scope

According to the established objective, the scopes of research were:

- To verify the existing mathematical models described the vertical movement of sediment and all observation was investigated using the laboratory scale experiments, which was proposed to be used in model calibration.
- To define the influence of pH and EC on releasing of soluble Pb, the Pb concentration profiles were employed using the laboratory scale settling column.

1.4 Expected research outcomes

As soon as the thesis was completely undertaken, the expected outcomes were:

- Understanding the influence of pH and EC onto the movement of sediment.
- Evaluating the possible key parameters controlling the migration of lead adhered sediment.

1.5 Chapter organisation

This thesis includes five chapters. Chapter 1 Introduction described the overview and conceptual boundary of the thesis. Chapter 2 Literature Review contained the theories and fundamentals related to the development of researches as well as the useful historical data. This background information effectively supported the concept and critical thinking of this thesis. Chapter 3 Research Methodology provided the detail design of experimental apparatus, materials and testing methods were used for determinations of sample characteristics. The observations were discussed and presented in Chapter 4 Results and Discussions. The major findings and future recommendations were summarised and they were given in Chapter 5 Conclusion. The schematic of chapter organisation is given in Figure 1.1.

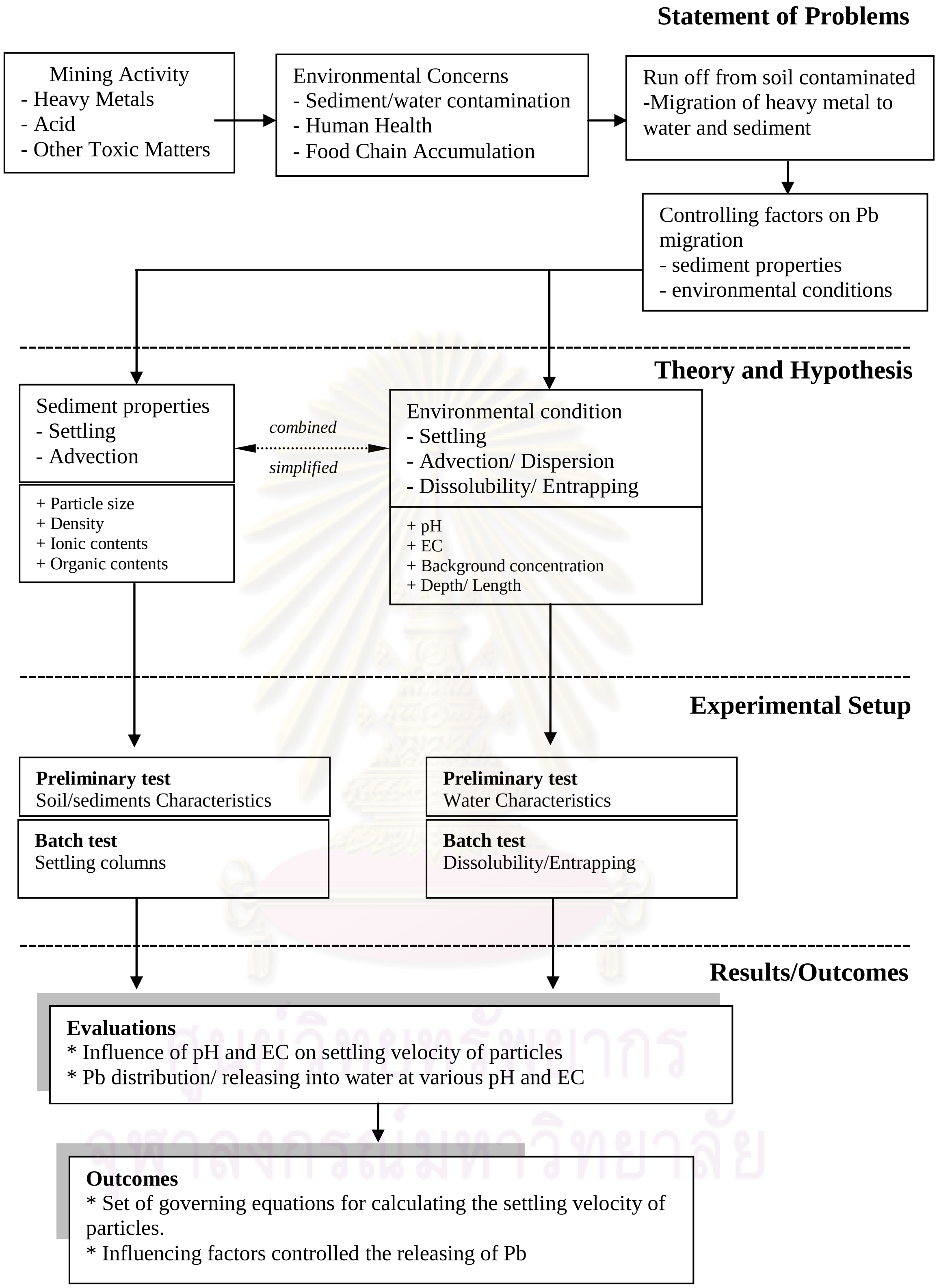

Figure 1.1 Schematic diagrams for thesis development

CHAPTER II
LITERATURE REVIEWS

2.1 Sedimentation

Sedimentation (settling) was the separation technique that was commonly applied to sort out the suspended particles that were heavier than water. The sedimentation of particles was based on the gravity force from the differences in density between particles and the fluid. Sedimentation was accumulated at the bottom of water body. Sediments could sink down due to gravitational force. Patterns of sediment settling could be classified into 4 types as presented in Table 2.1 (Metcalf and Eddy, 1991).

Table 2.1 Type of settling (Metcalf and Eddy, 1991)

Type	Description	Examples
Discrete (type 1)	individual settling, low solids concentration.	grit, sand
Flocculant (type 2)	dilute suspension, particles flocculate, mass and settling rate increase with depth	primary and upper secondary settlers
Hindered (type 3)	intermediate concentration, mass settles as a unit, interface at top	secondary clarifiers
Compression (type 4)	high concentration, structure formed, compression causes settling	sludge

Type I Discrete settling, the assumption was made that size, shape and specific gravity of the particles do not change with time and settling velocity remains constant. If a particle was suspended in water, there were two forces applied to particles (1) force of gravity: $F_G=\rho_p g V_p$ and (2) buoyant force quantified by Archimedes law as: $F_b=\rho g V_p$. With F_G is force of gravity, ρ_p is density of particle, V_p is volume of particle and ρ is density of fluid (Metcalf and Eddy, 1991).

Type II Flocculent Particles, flocculation caused the particles to increase in mass and settle at a faster rate (Metcalf and Eddy, 1991).

Type III Hindered or Zone settling, the mass of particles tended to settle as a unit with individual particles remaining in fixed positions with respect to each other. In hindered settling, the velocity gradients of particle were affected by the presence of nearby particles. So the normal drag correlations did not apply. Also, the particles in settling displace liquid, which flowed upward and make the particle velocity relative to the fluid greater than the absolute settling velocity. For uniform suspension, the settling velocity could be estimated from the terminal velocity for an isolated particle using the empirical equation of Maude and Whitmore (Metcalf and Eddy, 1991).

Type IV Compression, the concentration of particles was so high that sedimentation can only occur through compaction of the structure (Metcalf and Eddy, 1991).

2.2 Settling velocity

The settling velocity (V_C) of a sediment particle was defined as the rate at which the sediment settles in a stagnant fluid. The settling velocity was relied on grain size, sensitive to the shape (roundness and sphericity) and density of the grain as well as to the viscosity and density of the fluid. The settling velocity could reflect the migration of particles and it was a key parameter on transport of heavy metals due to advection. A free body diagram (FBD) of the sphere was sketched, the sphere and all of the internal and external forces acting on the sphere were illustrated after the particle was dropped into the fluid. Figure 2.1 shows a sketch of the force in the entire system (force balance on settling particles).

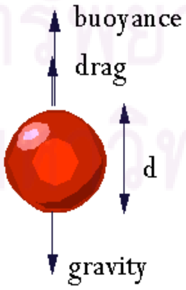

Figure 2.1 Free-body diagram of a sphere in a quiescent fluid (Shearer, 1987)

The FBD had listed the major three forces acting on the sphere that were F_b, F_D, and F_G. The first two forces arisen from the buoyancy effect of displacing the fluid and from the viscous drag of the fluid on the sphere, respectively. Both forces acted upwards, the buoyancy could 'float' the sphere (F_b) and the drag force (F_D) inversed the acceleration of gravity. The only force acting downwards was the body force resulting from gravitational attraction (F_G). By summing up all these forces, (the vertical direction was positive), the balance of force can be written as (Shearar, 1987):

$$F_D + F_b = F_G \qquad (2.1)$$

The gravitational force was only force acting downwards from gravitational attraction. The gravitational force is shown in Equation (2.2)

$$F_G = (\rho_S - \rho)gV \qquad (2.2)$$

where ρ_s is density of particle, ρ is density of fluid, g is acceleration due to gravity, V is volume of particle

Stokes' law could be technically applied to estimate the settling velocity of a sphere in a fluid. Stokes' law was valid with laminar flow condition (Reynolds number was less than 1.0). The assumptions of Stokes' law were made for determining the settling velocity of a single, spherical particle in a viscous fluid. Particles were moving through a fluid, experiencing a resistive drag force, which was velocity and viscosity dependent (Bird et al., 1960). Stokes' law was especially applied when the viscosity and mass density of an unknown fluid were constants all the time. Viscosity was a fluid property that indicated the resistance to shear within a fluid. The frictional drag force (F_D) depended on the particle velocity, fluid density, fluid viscosity, particle diameter and the drag coefficient C_D (dimensionless). The frictional drag force is defined as given (Bird et al., 1960):

$$F_D = \frac{C_D A \rho v^2}{2} \qquad (2.3)$$

where F_D is the drag force of the fluid on a sphere, C_D is drag coefficient, v is the velocity of the particle, and A is cross-sectional or projected area of particles at right angles to v.

According to Newton's law, the settling velocity equation from the gravitational with the frictional drag force for spherical particle is defined by (Shearar, 1987):

$$V_C = \left(\frac{[\rho_s - \rho]}{\rho} \frac{2g}{C_D} \frac{V}{A} \right)^{1/2} \qquad (2.4)$$

where V_C is settling velocity [mm/s], g is acceleration due to gravity [mg-mm/s^2], ρ_s and ρ are density of particle and fluid, respectively [mg/mm^3]. V is volume of particle [mm^3], A is cross sectional area of particle [mm^2] and C_D is drag coefficient [-].

The drag coefficient (C_D) was a non-dimensional number that depends on the shape of the particle, the fluid's kinematic viscosity and grain size. The drag coefficient was different value depending on flow regime surrounding the particle was laminar or turbulent. The relationship between drag coefficient and Reynolds number (Re) of spherical particle are described as follows (Bird et al., 1960).

For small particle, Re<0.5 and Re<<1: $C_D \approx \frac{24}{\mathrm{Re}} = \frac{24v}{uD}$ (2.5a)

For sphere, Re<0.5: $\frac{VD}{A} = \frac{2D^2}{3}$ (2.5b)

where u, D and v are velocity [mm/s], spherical diameter [mm] and kinematic viscosity [mm^2/s]. Stokes' law can be simplified as follows.

Reynolds Number (Re) was a dimensionless parameter that represents the ratio of viscous to inertial forces in a fluid. The Reynolds number is written as follows (Harris, 2003).

$$\mathrm{Re} = \frac{vD\rho}{\mu} \qquad (2.6)$$

where μ is the fluid viscosity. A way to obtain such reduced Reynolds number is considering very small solid spheres as in the case of suspensions (Dolz et al., 2004).

By substituting the C_D for small and sphere (Equations 2.5a and 2.5b) into Equation 2.4, V_C was yielded as (Harris, 2003):

For small particle, Re<0.5 and Re<<1: $V_C = \frac{(\rho_S - \rho)g}{12\mu}\frac{V}{A}D$ (2.7a)

For sphere, Re<0.5: $V_C = (\rho - \rho_S)gD^2$ (2.7b)

where μ is fluid viscosity [mg/s-mm] and $v = \mu / \rho$.

In case of a sphere, rigid and discrete particle was settled down in the laminar flow (Re<1), the settling velocity could be simplified as (Harris 2003):

$$V_C = \frac{1}{18\mu}(\rho_s - \rho)gD^2 \qquad (2.8)$$

where $C_D = \frac{24}{\mathrm{Re}}$, V_C is settling velocity, μ is fluid viscosity, ρ_s is density of particle, ρ is density of fluids, C_D is drag coefficient, Re is Reynold’s number and D is diameter of particle.

In case of non-sphere particle, the settling V_C was calculated by adding the Corey shape factor (*csf*). Stokes’ law with *csf* factor could be expressed as follows (Xie and Zhang, 2001).

$$V_C = \frac{1}{18\mu}(\rho_s - \rho)gD^2 csf \qquad (2.9)$$

where $csf = \frac{c}{\sqrt{ab}}$, $C'_D = csf\,\frac{24}{R_e}$, V_C is settling velocity, *csf* is shape factor, a, *b* and *c* are the longest, intermediate and shortest axes of the particle, respectively. µ is fluid viscosity, ρ_s is density of particle, ρ is density of fluids, C_D is drag coefficient, Re is Reynold’s number and D is diameter of particle.

Dietrich (1982) had suggested that the particles were naturally coarse and not spheres. Natural particles tended to have lower V_C than perfectly round spheres because both decreased in spherity and increased in angularity tend to decrease V_C. More oblong particles (less spherical) tended to have lower V_C because (1) the larger-cross sectional area seemed to be directed perpendicular to transport path, (2) flow separation (increases drag) was more likely to occur for non-spherical particles and (3) oblong particles may rotate, follow wobbling paths until settling. Angular particles also might have lower V_C than roughness; because the increasing of roughness on particle surface could increase the drag force, typically the large particles. The traditional way to estimate V_C was used the Equation 2.4, assuming that the C_D could be estimated by the relationship for spheres and then a correction factor for deviations of roundness and angularity were substituted. The variables V_C^* and D^* were proposed as the non-dimensional settling velocity and the non-dimensional grain size, respectively. Variable C_D was modified and substituted into Equation 2.4, which was called Dietrich's settling curve. The equation is provided as follows (Jose and Ole, 2003).

$$C_D = \frac{1}{3}\left(\alpha + \sqrt{\alpha^2 + 16\beta / \mathrm{Re}}\right)^2 \qquad (2.10)$$

with $$\frac{1}{V_{C*}} = \alpha + \frac{\beta}{S_*} \qquad (2.11a)$$

$$S_* = \frac{d}{4v}\sqrt{(S-1)gD} \qquad (2.11b)$$

$$V_{C*} = \frac{V_C}{\sqrt{(s-1)gD}} \qquad (2.11c)$$

$$V_{C*} = \begin{cases} S_* / 4.5 & S_* < 1 \\ 1.83 & 150 < S_* < 4 \times 10^4 \end{cases} \qquad (2.11d)$$

where V_{C*}, S_* are dimensionless settling velocity [mm/s] and fluid sediment parameter, α and β are constants and S is specific gravity [-].

Wu and Wang (2006) had proposed the equations for calculating the settling velocity of the rough particles as follows.

$$V_C = \frac{Mv}{ND}\left[\sqrt{\frac{1}{4} + \left(\frac{4N}{3M^2} D_*^3\right)^{1/n}} - \frac{1}{2}\right]^n \qquad (2.12)$$

By, $M = 53.5e^{-0.65csf}$ $N = 5.65e^{-2.55csf}$ $n = 0.7 + 0.9csf$ $D_* = \dfrac{(\rho_s - \rho)gD^3}{\rho v^2}$

where V_C is settling velocity [mm/s], *M*, *N* and *n* are the coefficients obtained from the statistical curve fitting, D_* is non-dimensional grain size, *D* is diameter of particle, *csf* is shape factor, ρ_s is density of particle, ρ is density of fluids and v is kinematic viscosity.

The series of equations shown above had been made in accordance with the assumption that a single particle was settling in stagnant water and there were no reactions between particles together with the constituents in water. Besides, the drag coefficient was reasonably well estimated by the drag coefficient for a sphere. In the marine environment, particularly where fine-grained silts and clays were present, these assumptions may not cover. The environmental factor could be change water property and reaction occurred in system and these may create an upward drag on neighboring particles. In hindered settling regimes, the upward forces became large enough to keep sediment fluidised and to prevent settling.

Basson et al. (2009) had derived the equation to describe the apparent settling velocity (V'_C) of particles with reaction. The equation is provided as follows.

$$V'_C = V(\phi) V_C \tag{2.13}$$

with $V(\phi) = (1-\phi)^{n-1}$ (2.14a)

$$n = \begin{bmatrix} 4.65 + 19.5 D^{/} / V_C, \; for \quad \mathrm{Re} \le 0.2 \\ (4.35 + 17.5 D^{/} / V_C)\,\mathrm{Re}^{-0.03}, \; for \quad 0.2 < \mathrm{Re} \le 1 \\ (4.45 + 18 D^{/} / V_C)\,\mathrm{Re}^{-0.1}, \; for \quad 1 < \mathrm{Re} \le 200 \\ 4.45\,\mathrm{Re}^{-0.1}, \; for \quad 200 < \mathrm{Re} \le 500 \\ 2.39 \; for \quad 500 < \mathrm{Re} \end{bmatrix} \tag{2.14b}$$

where V_C is settling velocity from Dietrich’s settling curve with *csf*, V'_C is apparent settling velocity from Dietrich’s curve coupled the reaction, $V(\phi)$ is complicating factor, ϕ is solid concentration, Re is Reynolds number and $D^{/}$ is diameter of column.

Hindered settling was often accounted for by estimating an actual settling velocity. The equation could be simplified as (Harrie, 2003):

$$V'_C = (1-\phi)V_C \tag{2.15}$$

The sediment settling velocity could be determined once the value of drag coefficient was estimated. It was difficult to develop a relation for drag coefficient for all flow conditions and sediment in a real field condition because Stokes (1851) was valid only the calculation of settling velocity of ideal sphere under larminar flow. Many researches had developed empirical sediment settling velocity formula that could overcome the limitation of Stokes' law (Rubey, 1933; Zhang, 1989; Van Rijn, 1989; Zhu and Cheng, 1993; Cheng, 1997; Ahrens, 2000; and Jose, 2003). All formula from these researches were suitable for calculating the settling velocity of non-cohesive sediments but these formulas did not accurately predict the settling velocity for cohesive sediments. Cohesive sediments could be flocculated during transport process and the size of the falling sphere had been increased. Therefore, the flocculation effect on settling speed should be incorporated.

Settling properties were traditionally determined by using settling column. Leersnyder (1993) had concluded that the settling velocity could be effectively determined using the technique described by Driscoll et al. (1986). The settling velocity depended on the particle size, shape, roughness and density, for example, a large and high density as well as round shape particles could present the high settling velocity. Wulf (1984) was investigated the error that produced by shape factor in Stokes' law. The deviation of settling velocity from Stokes' law could be increased by the mass and size of sphere. The particles with the same mass, but different shape could represent the different settling velocity (V_C), since the settling velocity was relied on the surface area of particles. Xie and Zhang (2001) studied Corey shape factor and spherity of non-sphere particle. The shapes of non-sphere particles and surface properties of particle were the controlling factors to the settling velocity of particle. Wu and He (2010) had investigated the measurement of particle size distribution of a domestic sewage using Malvern® laser scattering technique and determination of settlement efficiency. This technique could be applied to determine the extremely high settling velocity of the extremely fine grained particles. The measurement of the size and displacement of the extremely fine particles (less than micron) could be proceeded even the fine particle was co-settled with large particles.

The shape and density of sewage solids were technically analysed after co-settling process. The settlement coupling particle sizes, shapes and density of raw sewage sludge were mathematically modeled. The modified model could estimate the settling velocity of discrete and flocculants with a high accuracy.

2.3 Environmental factors

In aquatic environment, the distribution of heavy metal could identify the forms of heavy metals. The major forms were included water-soluble species, colloids, suspended forms and sedimentary phases. In appropriate conditions, more than 99% of total concentration of heavy metals was observed in sediments (Peng et al., 2009). Heavy metals could also release from the sediment under the appropriate physical-chemical characteristics of water, soil and sediments. Thus, the influence of the environmental factor onto heavy metals releasing from sediments could be identified. The major environmental factors affected the releasing of heavy metals were including of pH and conductivity.

2.3.1 pH

pH was the key factor that could influence the dissolubility of heavy metals (Selim and Kingery, 2003). pH could affect the ionic charge on the surface of sediments, the H^+ could replace the other cationic metals due to ion exchange. The precipitation of heavy on sediment relied on the pH value (Matos et al., 2001). pH could also affect the absorption of metals, when pH decreases, the mobility and solubility of metals was increased (Gundersen and Steinnes, 2003). The dissolved metals could also co-precipitate and adhere onto these aggregates as well as the naturally derived sediment particles (Smith et al. 1998). The increase of pH could be conducted by liming process. The lime pH adjustment process could increase in metals adsorption and precipitation (Matos et al., 2001). The settling of heavy metal in streams could be significantly influenced by sediment physical characteristics under a proper pH level. The suitable pH level controlled the precipitation of heavy metals was provided in Table 2.2 (Peng et al., 2009). Under highly pH condition (alkaline condition), Pb could be sorbed onto iron oxide (Lumsdon and Evans, 1987).

Table 2.2 Suitable pH values for heavy metal release from sediments (Peng et al., 2009)

Metals species	pH limit
Zn	6.0-6.5
Cd	6.0
Ni	5.0-6.0
As	5.5-6.0
Cu	4.5
Pb	4.0
Al	2.5
Fe	2.5

Sansalone et al. (1995) suggested that heavy metal concentrations were significantly correlated to suspended solids content in highway runoff. The partitioning of metals in the particulates and dissolved forms was influenced by pavement residence time, pH of rainwater, and the physical characteristics of the sediments and the solubility of the metals. Sansalone et al. (1996) and Sansalone and Buchberger (1997) had concluded that metal mobility could be increased in acidic stormwater. Zn, Cd and Cu could release in dissolved forms while Pb, Fe and Al were mainly carried out in the particulates. The fraction of dissolved metals increased with decreasing rainfall and pH and increasing average pavement residence time. Martinez and Motto (2000) had claimed that the solubility of lead, zinc and copper could be increased when an acidic pH was presented. The mass transfer of each heavy metal was specific to concentration of soluble forms remained in the solution. At the typical pH ranged between 5.5 and 6, Pb, Zn and Cu could be dissolved. Pb, Zn and Cu could be highly dissolved at pH levels of 5.2, 6.2 and 5.5, respectively.

2.3.2 Electrical conductivity (EC)

Electrical conductivity (EC) reflected the quantity of conducting particles in the solution, which was helpful to know the change of ion density in the filtration. The electric conductivity rate could be implied to an ion density in filtration. Soil electrical conductivity was normalised measurement of soil conductance (resistance^{-1}) by the distance and cross sectional area through which a current travels. EC of soil paste had traditionally been used to assess soil salinity (Rhoades et al., 1989). Several laboratory studies, using disturbed soil samples, had been conducted to correlate with adsorption and mobility of heavy metals. Electrical potential distribution across sediments was mainly depended upon the EC in soils/sediments pore solution or in electrolytes. The fraction of the electrical potential drop in sections near anode was declined over time. Furthermore, the EC value was the important factors that could affect the mobility of heavy metals. Lin et al. (2002) had observed the salt intrusion and flood of salty water could enhance the mobility of Heavy metals.

The changes of EC were greatly depended upon pH values. EC values significantly increased with increasing pH. Among all ionic species in electrolytes, H^+ and OH^- largely contributed to EC due to their high molar ionic conductivities (Chang and Liao 2006, Li et al., 2009). Thus, the variation of pH values greatly affected the conductivity of electrolytes. The increase of sediment EC was probably related to the reinforcement of pore fluid ionic strength as a result of sediment mineral dissolution and ions mobilisation from electrolytes via electromigration and/or electroosmosis. Water formation and heavy metals precipitation may cause the decrease of sediment EC (Li et al., 2009).

The ionic concentration or ionic strength had affected to thermodynamic or kinetic reactions of ion. Both of pH and EC related to the ionic strength of water. Debye- Hückel law could express the relationship among pH, EC and ionic strength. The equations are presented as (Debye and Hückel, 1923):

$$Log\gamma_{\pm} = -Jz_{+}z_{-}I^{1/2} \qquad (2.16a)$$

$$I = \sum \frac{1}{2} m_i z_i^{\,2} \qquad (2.16b)$$

where $\gamma_{\pm}$ is mean ionic activity co-efficient, z is number of charge ion, I is ionic strength, J is Debye- Hückel constant (if aqueous solution at 298 K the value of J is 0.5115 mole$^{-1/2}$L$^{1/2}$) and m is molar conductivity of a electrolyte.

2.4 Lead (Pb)

Lead was a soft metal, highly malleable, ductile, and a relatively poor conductor of electricity. It could highly resist to corrosion. Lead had been used widely for metal products such as cables and pipelines. Lead was one of four metals that had the most damaging effects on human health. Under natural condition, metallic lead was observed but its content was very low. Lead was usually found in ore combined with zinc, silver and copper and these metals were extracted together. Galena (PbS) was the main lead mineral that contain 86.6% of lead, the others were anglesite ($PbSO_4$) and cerrussite ($PbCO_3$) (Samans, 1949).

Lead was always observed naturally in the environment including of air, water and soil. However, lead contamination were claimed to be a result of human activities dealing with the application of lead in gasoline, which could destroy the equilibrium of a natural lead-cycle. In automobile engines, lead and it derivatives were contained in fuel, when the fuel was combusted, the lead salts (chlorines, bromines and oxides) was emitted with exhaust gas. The larger particles of lead could drop to the ground and it could directly pollute the soil or surface water, the smaller particles could travel long distances and remain in the atmosphere. The lead-air pollutant could be stripped due to wet deposition. The human activities could much more extend the input of lead than the natural deposition. So, the lead contained pollutants could bring many impacts to all living beings around the world (Samans, 1949). The major pathways of lead get enter to human body including of ingestion and inhalation. Lead could enter human body through uptake of food (65%), water (20%) and air (15%). Lead could merely harm to human health after up taking from food, air or water.

Lead was a dangerous chemical as it could be accumulated in individual organisms, entirely food chains. Lead had many effects to human health and environment. It could be accumulated in human body and could attack in the brains, kidneys and disrupted the biosynthesis of hemoglobin and anemia or nervous systems (Casas and Sordo, 2006).

2.5 Lead contaminated sediments

According to the monitoring of water quality in Thailand, the water sources in several areas had contained lead with a higher level than allowable limit for drinking water. A survey report the heavy metals in natural water is presented in Table 2.3. Most of lead contaminated groundwater was found in the mines and industrial areas. Solid waste and industrial wastewater were also contaminated to environment, if they were not properly treated (Black Smith Institute, 2004). In Thailand, the lead contaminated areas were, Bannungsata District in Yala, Pattani River in Pattani, and Thongpapoom District in Kanchanaburi (Pusapukdepob, 2007).

Table 2.3 Possible range of heavy metals concentration presented in natural water sources (Bryan, 1984)

Metals	Natural seawater (μg/L)	Fresh water (μg/L)
Cadmium	0.015-0.118	0.07
Copper	0.892-0.240	1.80
Lead	0.001-0.015	0.20
Mercury	0.011-0.033	0.01
Nickel	0.228-0.693	0.30
Zinc	0.007-0.640	0.10

Klity was a large creek in Kanchanaburi province. Klity stream flowed past Klity Bon Village, Klity mine area, Thidadoy Waterfall through Lum Lue Canal, and finally pours down at Srinakarin Dam. The stream could be divided into 2 reaches that flowed from the east to the north. The northern stream passed Bor Ame Mining, which was a very important lead carbonate mine (Pusapukdepob, 2007). In 1998, the report had stated that Klity stream was contaminated by lead. The illegal discharge of wastewater from mining process was pointed out as the source of lead contaminants. The villagers consumed water from Klity stream was faced with lead poison. The Pollution Control Department, Ministry of Science, Technology and Environment, had investigated and reported that the wastewater was illegally dumped from Lead Concentrate (Thailand) Co., Ltd. that located at Thongpapoom, Kanchanaburi (Pusapukdepob, 2007). The company refused this claim as the illegal wastewater dump had never been done. They believed that the problem was begun when the storage of ore tailings was slipped during heavy rain. The lead sediments were carried with runoff and flowed to Klity stream (Pusapukdepob, 2007).

Pollution Control Department had collected sampling water, sediment and aquatic animals from the Klity stream. The monitoring data showed that the concentration of lead level in water was increased after passing through mine and the lead contamination became seriously in downstream. Lead contamination in surface waters were in the range of 0.17-0.40 mg/L, this was much higher than the allowable concentration level that was 0.05 mg/L (Thailand Standards). In sediment samples, lead level was in the range of 38,900-65,771 mg/kg that was 20-100 times higher than lead content in normally natural condition. Accumulated of lead in fish were ten times higher than allowable concentration level in food that was 1 mg/kg (Pollution Control Department, 2001). WHO drinking water standards had limited the concentration of lead in water, which was less than 0.01 mg/L (WHO standards, 1993). Therefore, aquatic animals, such as fish, shrimp, shell and crab in Klity stream were not safe to be consumed.

2.6 Summary

Lead was accounted as the major pollutants that could be found both sediments and water. Lead contamination at Klity creek could pose the serious health problem to the local people. The Pb bound to sediments was classified as mobile and immobile source of contaminants. To carefully solve the migration of Pb and Pb contaminated sediments, the pattern of settling of sediments had to be understood. However, there were little known the mechanism that could affect the migration of free and sediment bound Pb under the real field condition. The pH and EC were the major water characteristics that were changed dealing with environmental condition. The experiments were investigated to observe the pattern of sediment settling and Pb releasing from sediment under systems with various pH and EC conditions. The details of experiments were presented in the next chapter.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Overview

The lead (Pb) contaminated soil was considered as this issue may impact to human health. The mechanism between soil and heavy metals could either trap or stabilise that directly reduce the exposure of heavy metals. The release of heavy metals from sediments had relied upon the environment factors, mainly pH, Electrical Conductivity (EC). The lead contaminated sediments were classified as sand particles. Generally, the settling velocity was technically estimated by using Stokes' law. However, natural condition the whole of particle was not sphere, this study Stokes' law coupled Corey Shape factor (*csf*) was employed to estimate the settling velocity of non-sphere particle and Dietrich's equation was applied to calculate the settling velocity of rough particles. EC and pH factors could influence the density of fluid and charge of particle, leading to oscillation of settling velocity. The correlations between pH and EC on settling velocity of sediments were defined using the complicated factor. The laboratory experiments, image processing and settling columns were arranged to provide data of the one dimension (1-D) of vertical transport and profile concentration of lead and these obtained data were supported to model calibration. A series of experiments were setup and the methodology was investigated in this chapter. The whole experimental setup is overviewed in Figure 3.1.

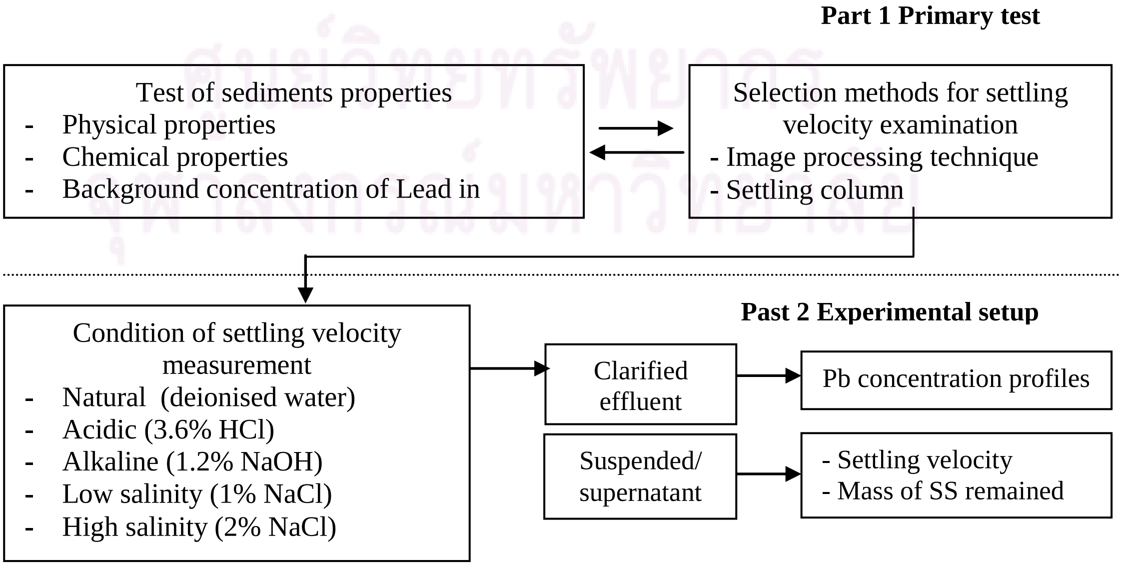

Figure 3.1 Overall experiments undertaken in this research

3.2 Materials and methods

3.2.1 Sediment samples

Sediment sample was collected from agriculture area, Klity stream, Kanchanaburi province. The sediment sample contained high background concentration of lead. Physical and chemical properties of sediment were analysed in accordance with the ASTM standards (ASTM, 1997).

3.2.2 Methods for contaminated sediment properties determination

Sediment properties were analysed to level the background concentration and the composition. The parameters and analytical methods are given in Table 3.1.

Table 3.1 Parameters and analytical methods for testing of sediment properties

Parameter	Analytical method	Reference
Physical properties		
Particle size distribution	Sieving in combination with hydrometer method	ASTM (1997)
Sediment classification	The textural triangle nomenclature	ASTM (1997)
Hydraulic conductivity	Standard test method for permeability	ASTM (1997)
Bulk density	Soil compaction reduces the air volume of the soil	Ministry of Agriculture and Food (1990)
Sediment water content	Oven drying method	ASTM (1997)
Specific gravity	Soil particle density	ASTM (1997)
Chemical properties		
Organic matter (%)	Walkley-Black procedure	Schnitzer (1982)
Sediment pH	Electrode pH meter method	ASA-SSSA (1982)
Electrical conductivity, EC	Conductivity meter method	ASA-SSSA (1982)
Cation exchange capacity, CEC	Ammonium saturation	Rhoades (1982)
Total phosphorus	Perchloric acid digestion and Stannous chloride method	Olsen and Sommers (1982)
Soluble phosphorus	Stannous chloride method	Olsen and Sommers (1982)

The prepared sediment slurry was carefully prepared to control the SS contents. The procedure for sediment slurry preparation and the examination of sediment slurry was clearly explained in the following subtopic.

3.2.3 Methods for preparing the sediment slurry

The sediment slurry was prepared with a constant concentration of 3% (w/w). For the control test 30 g of sediments was added into 1 L of deionised water. Sediment slurries under acid, alkaline and saline conditions were prepared at the concentration of 3% (w/w) too. The critical conditions of Pb dissolubility and precipitation were at pH levels of 4 and 12, respectively (Lumsdon and Evans, 1987). Samples of 3% sediment slurries with pH 4 and 12 were prepared by adding the dried sediment into the specified pH solutions. The acidic solution was prepared with a constant pH of 4 using 0.1 M HCl (3.6% HCl) and alkaline solution with pH of 9 was prepared by 0.1 M NaOH (1.2% NaOH). Besides, the releasing of Pb related with electrical conductivity of solution. In this case, the possible exposure of sediments into saltwater could pose the releasing of Pb. Synthetic samples of seawater and brackish water were 1 and 2% (w/w) of NaCl solution, respectively. The saline water was synthesised with concentration of 1 and 2% (w/w) of NaCl. The sediment samples were weighed for 30 g, and they were mixed with the specified solutions of 0.1 M HCl, 0.1 M NaOH, 1 and 2% (w/w) NaCl. The initial pH and EC of the sediment slurry samples were measured regularly.

3.2.4 Methods for determination lead contaminated in sediment

Contaminated sediment and slurry were analysed to investigate the concentration of lead. As they had contained solid particles, the examination of total Pb required either thermal or chemical extraction. Prior to analyse concentration of lead by inductively coupled plasma optical emission spectrometer (ICP-OES), the sample was digested by microwave follow the method of microwave digestion method. After digest the sample, the supernatant was cooled down. The extracted solution was quantitatively transferred to a 100 ml volumetric flask and it was diluted to the specified volume with reagent water. The sample extract solution was filtered to grab the insoluble material by Whatman glass fiber filter paper (GFC/C) with the 0.45 μm pore. The sample solution was filtrated until it was clear without any remaining particles. The prepared sample was fixed by the concentrated HNO_3 (<pH2) acid (EPA, 1986). The forms of Pb contained in sediments were determined using the sequential extraction techniques (Tessier 1979). This techniques could be determined the forms of Pb by series of extraction reagent. The procedure of sequential extraction could be explained as follows.

1) Exchangeable form: The sediments were leached by 1 M of $MgCl_2 \cdot 6H_2O$ solution. The free Pb ion could be presented in the extracting solution.

2) Bound to Carbonates form: The sediments were mixed with 1 M of NaOAc solution. The Pb glued with carbonates was extracted.

3) Bound to Iron and Manganese Oxides from: The sediments were extracted by 0.04 M of $NH_2OH \cdot HCl$ solution. Pb bound to iron and manganese oxide was sensitive to redox reactions between constituents in water.

4) Bound to Organic Matter: The sediments were mixed with solutions of 0.02 M of HNO_3, 30% H_2O_2 and 3.2 M of NH_4OAc. The bioaccumulated Pb could be emitted into extracting solution.

5) Residual (Inert): The residual solids were digested with microwave digester. The crystal structures of Pb or highly stable Pb were examined.

The settling velocity of sediment slurry was test under the controlled condition. As the settling velocity was test with disturbing from the external forces. The methods for testing of settling velocity were presented in the following section.

3.3 Selection of methods for settling velocity measurement

Two techniques for measurement settling velocity were employed in this study. One was image processing and another one was sediment sampling and analysis. These both techniques had the different advantage on determining of settling velocity of very fine particles. The suitability and accuracy of these methods were examined in order to select the highly reliable tool to generate the highly reasonable data, which could be further used in model calibration process. The details of laboratory apparatus setup were described as follows.

3.3.1 Image processing

The image processing technique was commonly used to determine the velocity of particles. The settling plate was fabricated from acrylic plate with height of 20 cm, width of 30 cm and a space between plates was 0.7 cm. The fabricated settling plate is presented in Figure 3.2. The reason for investigating the settling velocity from the settling plate was according to the plain surface of plate could reduce the reflection of light when taking the frames by VDO camera. The VDO camera model Cannon 500D with a marcolens 105 mm was used to capture the photos of particles the frequency of snapshot was 24 shutters per second, ISO400. The devices were calibrated by using the modified chalk particles with a concentration of 2% (w/w). The modified chalk particles were white tiny particles with low water permeability. The particles were relatively round and less reaction to the constituents in the specified solution. The completely mix solution of modified chalk slurry was poured into settling column and the VDO record was started. The photo taken was digitised for every 2 seconds to evaluate the displacement of particle.

Figure 3.2 Settling plate

The synthesis Pb contaminated sediment slurry was tested with the same devices and the same procedure used for device calibration. The settling plate was installed on the top of built in concrete wardrobe. This location was highly stable and far away from the walkway, so the external forces were eliminated during the test.

3.3.2 Settling column test

The settling column was investigated to estimate settling velocity of particles. The settling column was fabricated from acrylic tube with an inner diameter of 4.3 cm and height of 35 cm. The settling column is presented in Figure 3.3. The column was placed on the top of built in wardrobe. The prepared sediment slurry was poured into the settling column. The sediments and clarified effluent were sampled at every 5 cm deep, within 4, 6, 8, 10, 12 and 24 hours. The control temperature was at 25 ºC. The most concern was made on the sampling techniques, which could less disturb the particles. The image processing could not be applied to the settling column as the reflection of light and the distorting of images. So, the sampling had been start from the top portion to reduce the disturbing on the remaining sample at the lower part of column

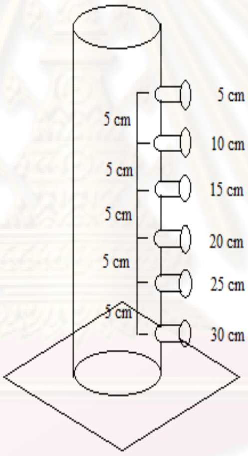

Figure 3.3 Settling column

After collecting the sample, the slurry sample was portioned as insoluble and soluble material by filtration unit. The insoluble portions were analysed to estimate the suspended solids (SS) and Pb content. The filtrated effluent was determined the soluble Pb concentration by followed the methods of ASTM (1997) and APHA (2005). The settling velocity was determined from the contour lines of % SS removal at specified depth and time.

The settling velocity yielded from measurement was compared with the calculated ones. The mathematical model was introduced to describe the behavior of particles under various pH and EC condition.

3.4 Mathematical model

The settling velocities obtained from the experiments were compared to the calculated results. Mathematical models including Stokes' and Dietrich laws were used to describe the downwards movement of sediment if the sediment could show the behaviour as the given assumption. Both models would valid in case particles were under laminar flow (Re <1).

In case of a sphere rigid and discrete particle, the settling velocity (V_C) could be estimated by Stokes' law. If particles were non-sphere particle, the Corey shape factor (*csf*) was coupled with Stokes' law.

In case of the spherical, naturally coarse particles, the settling velocity could be simulated by Dietrich equation. If particles were non-sphere particle, the Corey shape factor was combined with Dietrich law.

If the particles were active, they could react with constituents in the solution and each other. In this case, particles may change in both shape and size and the Strokes law was invalid. Only Dietrich law could be valid to the change of physical properties of particles. Dietrich equation with complicating factors were applied to describe the apparent settling velocity (V'_C) of particles with reaction.

The settling velocity of particles was compared to the experimental data. The statistical tool, especially root mean square residue (R^2) was introduced to justify the reliability of determination. The mathematical models were applied from Stokes' law, Stokes' law coupled *csf* factor, Dietrich law, Dietrich law coupled *csf* factor until Dietrich law coupled *csf* and complicating factors. The settling pattern of particles could be reasonably described.

The releasing of Pb could be described using the simple reaction models, such ionisation, ion exchange and precipitation. The possible reactions were applied to criticise the relation between pH and EC on Pb releasing and settlement of particles.

3.5 Summary

This chapter presented the apparatus and methods used in settling plate and settling column. The experimental setup was carried out to examine the influence of pH and EC on settling velocity of particles and the key parameters on releasing of Pb from sediments. The synthesis sediment slurries were prepared. Dealing with the heterogeneity of sediments and the sensitive of settling velocity on the external forces, the experimental setup and methodology used in this study were carefully undertaken. The experiments and analytical process was repeated least 5 times to ensure the accuracy of the experimental data. The findings were discussed and the theories were applied to explain the mechanisms that could be a result of pH and EC.

CHAPTER IV

RESULTS AND DISCUSSION

Transport of contaminated sediment was investigated as it was basic information in engineering applications involving the controlling of solids particle suspension in water. The lead contaminated sediment and the artificial sediment slurry were characterised. The pattern of settling and the settling velocity of sediment were examined in the various solution including of deionised water, acid and alkaline solution and artificial salt water. Regarding the experimental setup, the apparatus such as settling plate and settling column were carefully setup to ensure that the sediments were forced to be settled down under the balance of force system. The various equations including Stokes' law, Dietrich equation and complicating factor were applied to describe the pattern of settling and the settling velocity of sediments. The releasing of lead after sediment settling was determined to estimate the influence of dispersion and reaction between sediment and solution onto change of sediment properties. The results were discussed and presented in this section.

4.1 Sediment characteristics

Sediment sample utilised in this research was collected from agricultural area located at downstream of Klity creek, Kanchanaburi, Thailand. This area was enriched of soil mineral and there were many smelters constructed in this acid mine area. The sediments samples were collected at from irrigating channel. The characteristics of sediment are presented in Appendix A. The physical appearance of sediments is presented in Figure 4.1.

Figure 4.1 Physical appearance of sediment

The sediments looked like sandy soil. After soaking with the deionised water, sediments could almost settle down. The clarified water was relatively clear, only small amount of particles were suspended into the clarified effluent. At this stage, the settling pattern of sediment was assumed to be discrete settling that was Type I settling. According to the naked eye observation, the particle was relative round. The summary of sediment characteristics are given in Table 4.1.

Table 4.1 Sediment characteristics

Parameters	**Value**
Physical properties	
Water content (%)	0.59
Bulk density (g/cm^3)	1.21
Hydraulic conductivity (cm/sec)	3.15×10^{-4}
Specific gravity	2.61
Particle size distribution (%)	
>2 mm.	2.27
0.425-2 mm.	31.6
0.075-0.425 mm.	53.4
< 0.075 mm.	12.8
Sediment texture (%)	
Sand	89.1
Silt	4.15
Clay	6.73
Sediment classification	Sand
Uniformity	5.04
Chemical Properties	
Organic matter (%)	10.1
Sediment pH (1:5)	7.31
EC (µS/cm)	33.6
CEC (meq/100g)	12.3
TP (mgP/kg)	62.6
Soluble P (mgP/kg)	0.81
TKN (mgN/kg)	0.23
Alkalinity (mgCaCO$_3$/kgsoil)	29.6

Sediment sample was mainly consisted of sand, approximately 89% of soil texture was sand particle. Based on the sieve analysis, it was observed that the particle size of the sediment was ranged between 0.075-0.425 mm. So, the sediments were relatively rigid as they could crash with each others during the transport. The moisture content of the sediment was low. However, sediment contained high content of organic matters, which might be originated from organic residues released from harvesting. Phosphorus content was relatively high and the most phosphorus was in the insoluble form. TKN was also highly concentrated in sediments. The pH (1:5) of sediment was 7.31 and it was under neutral condition. The EC and CEC were 33.58 µS/cm and 12.3 meq/100g, respectively and they referred that the sediment contained a small portion of exchangeable cations, so they could not significant disturb the electrical conductivity.

The sediments were contaminated with high concentration of lead that was 20,250 mg/kg. The background concentration of lead in sediment was 10-550 mg/kg (Department of Agriculture, 1999). The allowable lead content limit in sediments was 55 mg/kg. The form of lead observed in sediments was examined using the sequential extraction process. The result is presented in Table 4.2. Lead observed in sediments was mostly bounded onto carbonate compounds, which was reversible soluble, if the pH of system was in acidic range.

Table 4.2 Forms of lead adhered onto sediment

Chemical form	**(%)**
Exchangeable	0.62
Bound-to-carbonates	69.99
Bound-to-Fe & Mn oxides	17.86
Bound-to-organic matter	3.31
Residual (Inert)	8.21

According to the physical observation, the sediments were sand predominantly and they could be classified as a non-cohesive and rigid particle. Therefore, it might behave as discrete particles with a spherical shape during the settling process. The settling velocity might be technically estimated using Stokes' law. The process of lead dissolving was also mentioned as it could affect the sediments and water properties.

The influence of releasing of lead on settling velocity was determined using mass balance technique.

4.2 Selection of methods for settling velocity measurement

Two techniques of settling velocity measurement were introduced in this study. One was the image processing technique and another was sediment sampling and analysis. The image processing technique could be applied to measure the settling velocity without disturbing the system. This technique was suited for highly contrast of colour between sediment and water. The colour of the modified chalk particles was white. The filter was inserted to make a high contrast between chalk particle and solution. In order to prove the suitability of this technique, the low permeability of chalk particles with a specific gravity of 2.26 were introduce to this study. The settling velocity obtained from the various conditions including of brackish, saline and saltwater were examined. The NaCl solution was prepared at 0, 10, 20 and 35 ppt, with 2% (w/w) of modified chalk particles. The temperature of synthesis water was at 28^{o}C. The values of dynamic viscosity of NaCl at concentrations of 0, 10, 20 and 35 ppt were 0.0009634, 0.0008724, 0.000879 kg/m-s, respectively. The density of NaCl at 0 ppt was 996.2 kg/m^3 and the density of NaCl at concentration of 10, 20 and 35 ppt was closed to 1011 kg/m^3, respectively.

The settling velocity of modified chalk particle was determined using Stokes' law. The observation and calculation were compared. It was found that the image processing technique could examine the particle velocity effectively and Stokes' law was valid as the high R^2 value was obtained in every conditions of experimental settling. The result is presented in Figure 4.2. This could be assumed that the modified chalk particle was rigid and sphere. Besides, the specific density of particles was not too high to capture the displacement using the VDO camera. The observation of particle during settling process is given in Figure 4.3. The distortion of scenes was eliminated. The particles were spheres and the discrete flocs were obviously seen. There was no doubt that the Stokes' law could effectively fit to the observation. The smaller particles could be well estimated using Stokes' law rather than the bigger particles. The reason for this was relied on the finding that the size of particles could be well measured as there was no effect of shadow that could enlarge the particles size. Without Corey shape factor (*csf*), the settling velocity of particle could be well predicted. It could confirm that the particles were spheres.

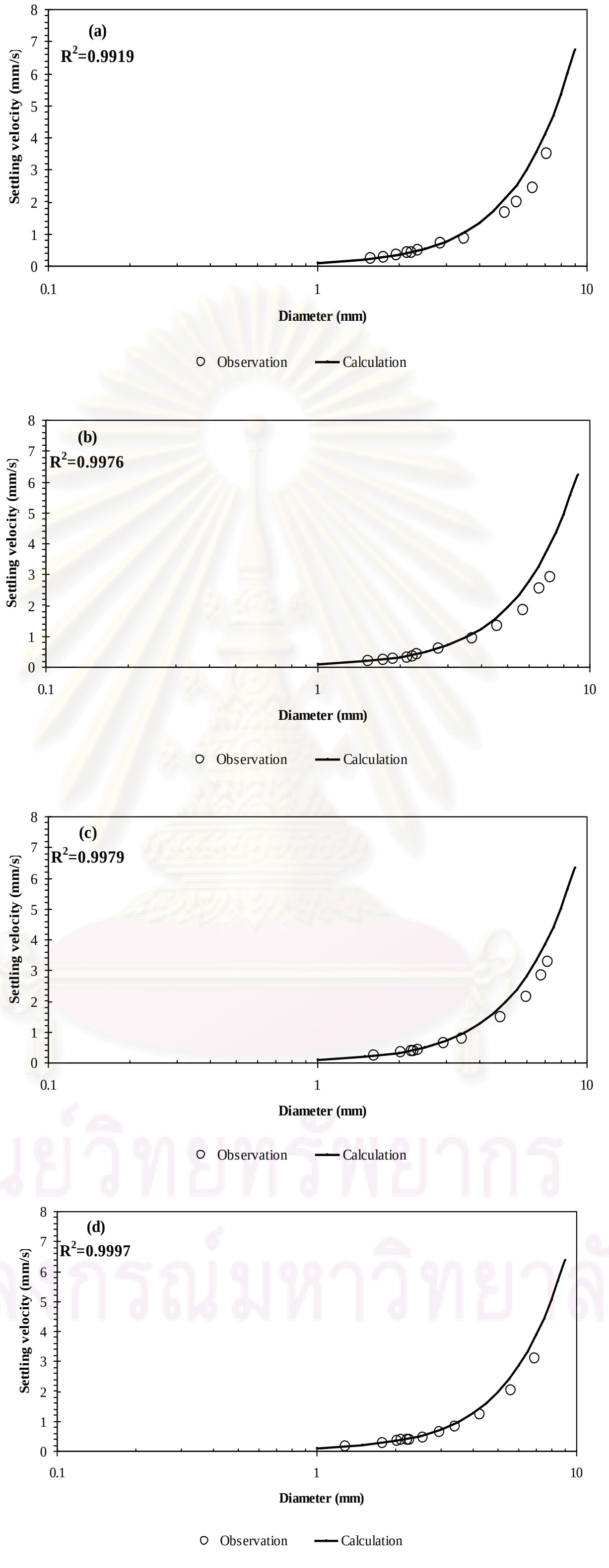

Figure 4.2 Settling velocity measurement and simulations obtained from Stokes' law in the systems with NaCl concentrations at (a) 0, (b) 10, (c) 20 and (d) 35 ppt

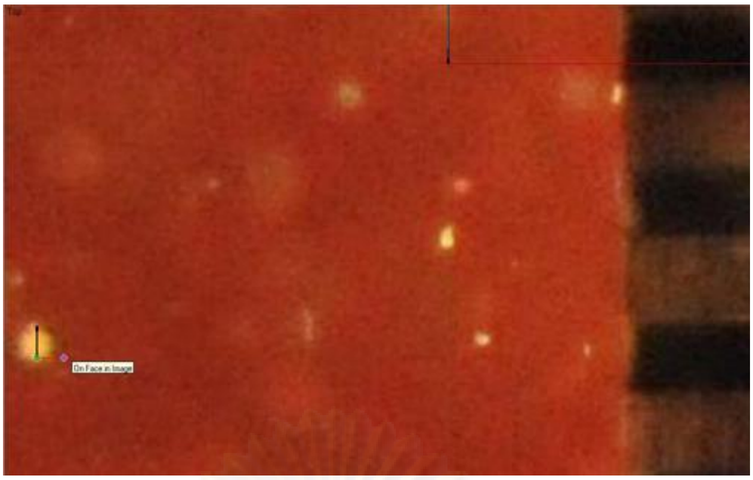

Figure 4.3 Appearance of modified chalk particle observed in settling plate

The image processing technique was applied to the lead contaminated sediment. The displacement of sediments was digitised and Stokes' law was applied to estimate the settling velocity. The test was operated at 25°C, the density and dynamic viscosity of water were 997.13 kg/m^3 and 0.000891 kg/m-s, respectively. The results were expressed in Appendix B. The observation and calculation are illustrated in Figure 4.4.

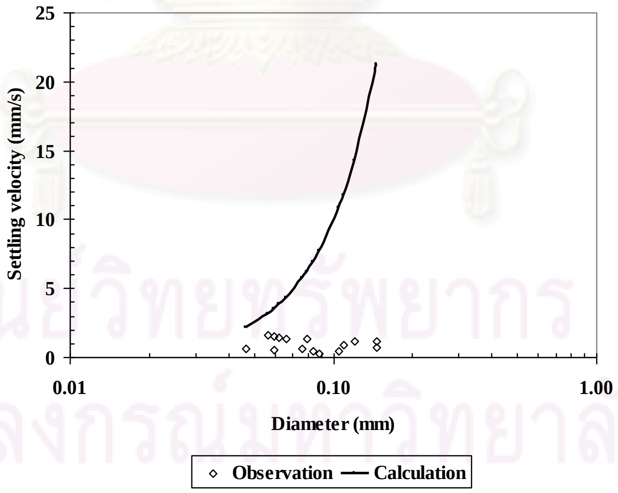

Figure 4.4 Settling velocity measurement and simulation of utilised sediment in the systems with deionised water

The settling velocity of sediment could not be examined by the settling plate. The reason for this was made based on the fact that sediments were mixed grain particles. The sand particles settled down in few seconds, which was difficult to identify the particles size and displacement. Only the fine particles could be captured in the frame. The sediments with particle size 0.050-0.230 mm were still dispersed in deionised water. These particles were a mixture consisting of silt and clay particles as the diameter of particles of silt was ranged between 0.05 and 0.002 mm and clay was less than 0.002 mm, respectively. However, the density of silt and clay was not equaled to the sediment sample that was 2610 kg/m^3. The density of remaining particles was assumed to be silt particle and the recommended value was 1280 kg/m^3 (USDA 2011). The calculation of settling velocity of the remaining particles is presented in Figure 4.5.

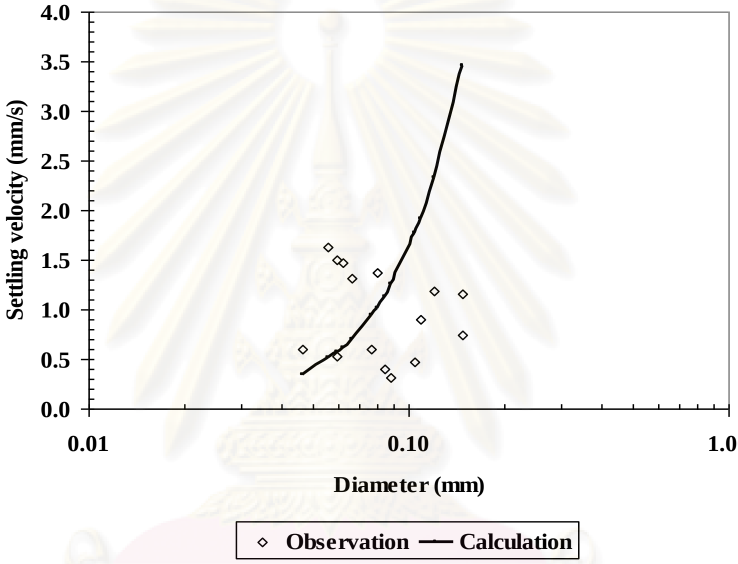

Figure 4.5 Settling velocity measurement and simulation of fine particles in utilised sediment in the systems with deionised water

Even though the density and kinetic viscosity were adjusted to be suitable for these fine particles, the settling velocity was inaccuracy predicted. The assumption was made in accordance with the observation that the silt and clay particles were not spherical and non-rigid particles. The snap shot taken in the settling plate is presented in Figure 4.6. The particles looked similar to oval shape and non-discrete. The particle was relatively fine and the contrast between the sediments and solution was not clearly seen even the filter was used.

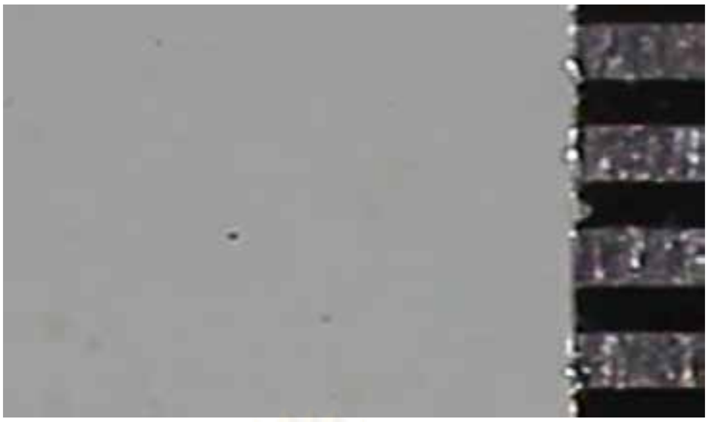

Figure 4.6 Appearance of lead contaminated particle observed in settling plate

The measurement of settling velocity was determined using settling column by grabbling samples from sampling ports. The results of settling velocity were discussed in the following topic.

4.3 Settling velocity of sediments

4.3.1 Natural condition

The suspended solids were separated from water samples and the SS removal at every depth at various time were plotted as SS contour line. The relationship between settling velocity and %Suspended Solids (%SS) removal was evaluated. The particle size of sediments was justified using the particle size distribution curve. The SS concentration contour of sediments in deionised water is presented in Figure 4.7. The raw data was given in Appendix C.

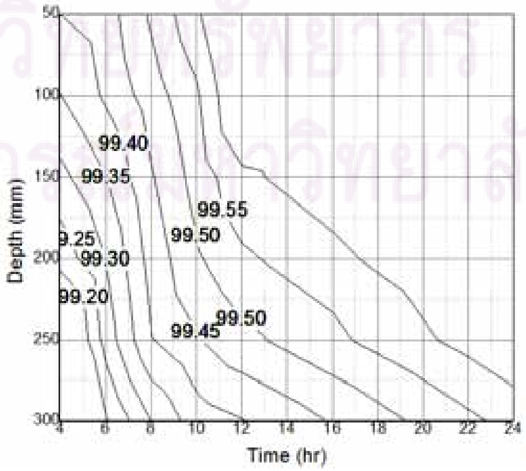

Figure 4.7 Contour of SS removals obtained from sediment settling column with deionised water

It was observed that almost sediment sank within a few minutes. Only very fine particles were remained in deionised water. Based on the particle size distribution curve, the sediments with particle size 0.004-0.008 mm were still dispersed in deionised water. These particles were a mixture consisting of silt and clay particles. Due to the limitation of sampling, the hourly sample collection could be arranged. The particle size observed in this test was ten times smaller than the ones measured using the image processing technique. To examine the shape of particles, the settling velocity was fitted with Stokes' law. The result agreed with Stokes' law, however, there were some oscillation. So, it could be confirmed that the particles was the non-spherical particles. According to the image processing techniques, the 2-D observation indicated that the particle looked similar to oval or cone. The Corey shape factor, *csf* was applied to predict the spherity of particle. Referring the image processing techniques, the value of spherity was 0.6-0.8. This referred that the ratio between the shortest side of particle and geometric mean square of the longest and intermediated sides of particle. In case of spherical shape factor was 1.00. So, these particles were classified as sphere-liked particles. The assumption was made that the density of silt particle was 1280 kg/m^3 (USDA 2011). By adding the *csf*, it was found that the shape factor was significantly affect to the settling velocity of these particles. The results are illustrated in Figure 4.8.

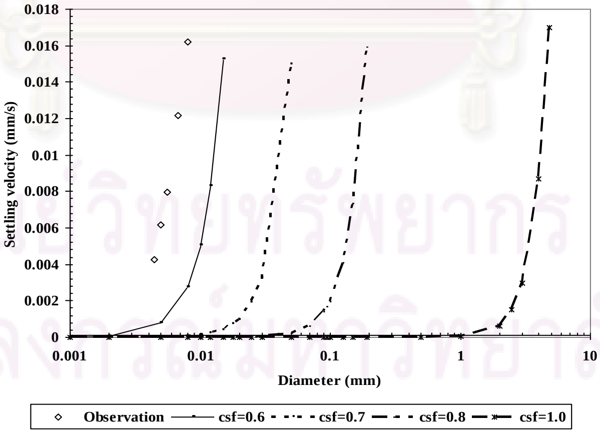

Figure 4.8 Measured and simulated settling velocity of particles in deionised water fitted with Stokes' law

It could be confident that the particle was not ideal sphere. By trial and error, the shape factor of particles was 0.54. The result is presented in Figure 4.9. To be achieved the best prediction of these Pb contaminated silt, the assumption was made on the change of roughness of particles. As observed in the image processing technique, the blurred surface of particle suggested that particle may swell or be combined with others. The settling velocity was estimated using Dietrich settling curve as this equation was included the roughness of particle and shape factor. The terms of fluid sediment parameter (S*) and dimensionless of settling velocity (W*) were introduced to determine the correction of roughness and shape function, which was useful for estimating the drag coefficient. Stokes' law with *csf* could well predict the settling velocity of sediment as the high R^2 value was 0.99. The results are presents in Figure 4.10.

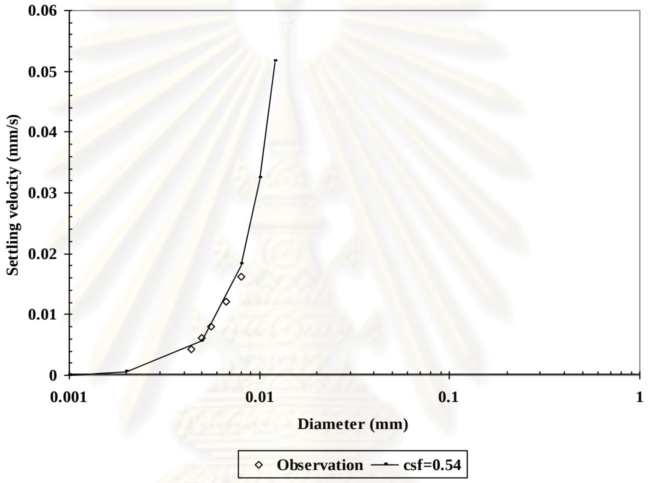

Figure 4.9 Measured and simulated settling velocity of particles in deionised water fitted with Stokes' law coupled *csf* factor

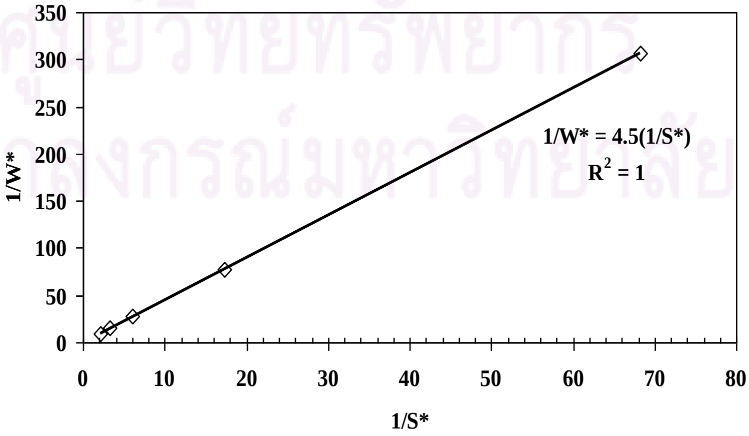

Figure 4.10 Relationship between 1/S* and 1/W* of soaked particles in deionised water

The slope (B) was 4.5 and y-intercept (A) was 0.0, they were different from spherical grain that A and B were 0.79 and 4.6. These dimensionless terms were applied to estimate the settling velocity of these contaminated silt particles. The result is provided in Figure 4.11. The Dietrich settling curve could make a good correlation to the observation data as the high R^2 value was 0.97. When the *csf* at 0.54 was applied to calculate the settling velocity, it was observed that the calculation obtained from Dietrich settling curve could well compete with the simulation yielded using Stokes' law. Dietrich equation with *csf* could well predict the settling velocity of sediment as the high R^2 value was 0.99. As the particles were rough, the surface of particles calculated using Dietrich settling curve was enlarged. The settling velocity obtained from Dietrich settling curve was little lower that another calculated using Stokes' law. This might reflect that the roughness may not significantly affect to the settling velocity of particles in deionised water. As there was no interaction between deionised water and particles, the surface of particles was still same. The roughness also reflected the porosity of particles. Thus, the particles may insignificantly be eroded or swelled after soaking with deionised water.

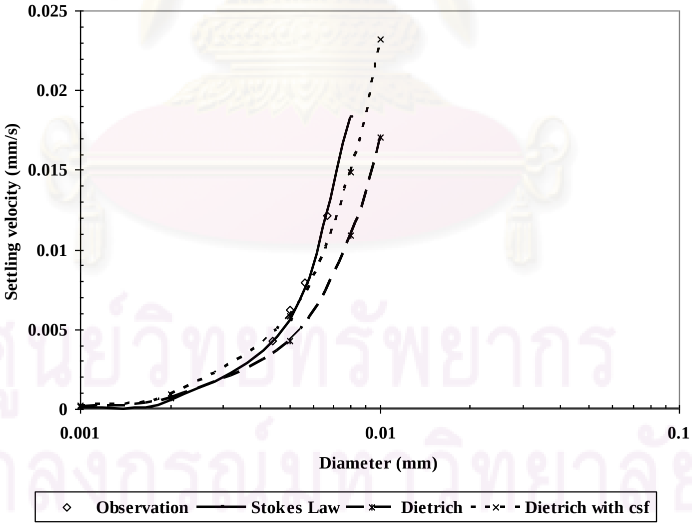

Figure 4.11 Measured and simulated settling velocity of particles in deionised water fitted with Dietrich Settling Curve

This indicated that the particles suspended into deionised water were non-sphere silt or clay particles. The surface of particles was rough. These particles suspended in a laminar flow condition with Reynolds number was much lesser than

1.0. The particles could be assumed as the discrete particles and there was no interaction between each particle as these was dissolved in deionised water.

4.3.2 Acidic condition

The sediments were soaked with 3.6% HCl, the pH of sediment slurry was 4.0. The contour of SS removal observed in settling column test is given in Figure 4.12. The observation data was provided in Appendix C. The particle size was ranged between 0.001 and 0.003 mm. The smaller particles size related to the fracture of particles due to either the corrosivity of the acid solution or the reaction between silt and clay together with acid solution.

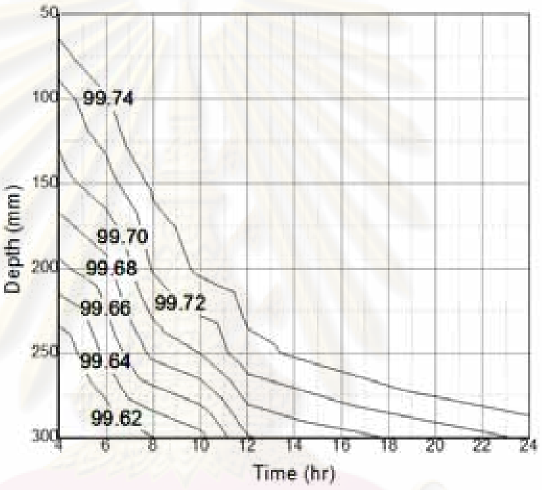

Figure 4.12 Contour of SS removals obtained from sediment settling column with 3.6% HCl solution

The density of 3.6% HCl was 997.194 kg/m^3 and the dynamic viscosity was 0.0019 kg/m-s. The settling velocity of these particles was calculated using Stokes law with *csf* factor. The results are shown in Figure 4.13. The *csf* value at 0.54 was not fitted to the particle shape. By trial and error the suitable values of *csf* factor was between 0.43-0.44. Stokes' law with *csf* had presented the high R^2 value that was 1.00. The values of Reynolds number was very low as a result of reducing of the particles size. It could be suggested that the particles was eroded, the particles may be fractured. In this case, the roughness of particles may possibly change. In order to predict the settling velocity of these rough particles, the Dietrich setting curve was applied. The relationship between 1/S* and 1/W* is presented in Figure 4.14. The relationship was still same as the one obtained in previous case.

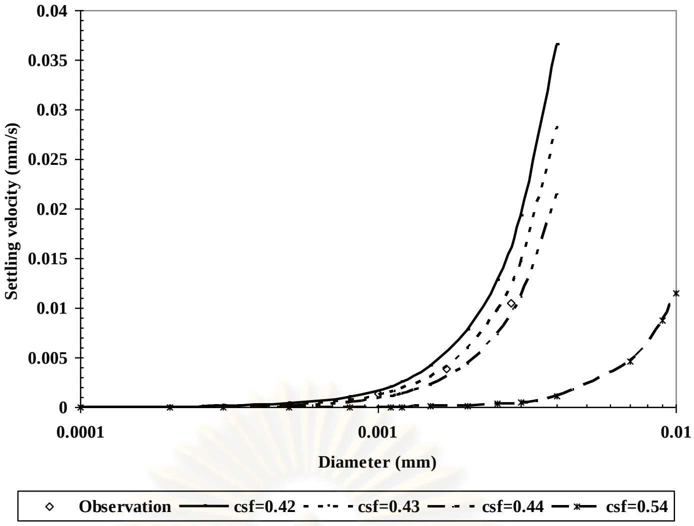

Figure 4.13 Measured and simulated settling velocity of particles in 3.6% HCl solution fitted with Stokes' law coupled *csf* factor

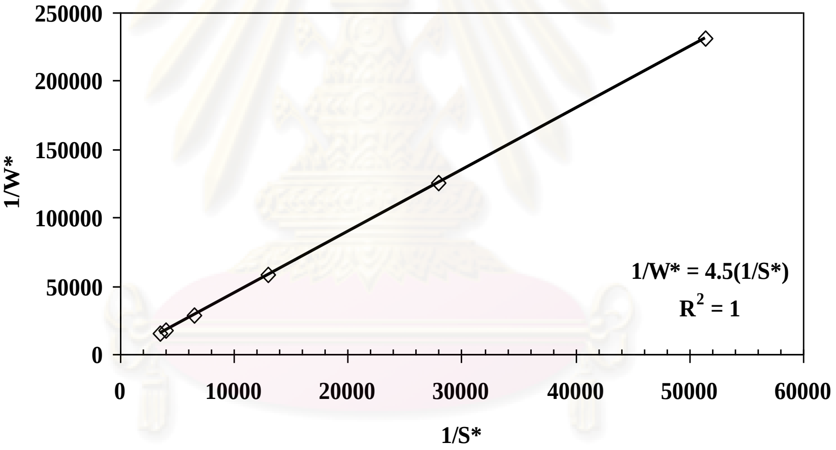

Figure 4.14 Relationship between 1/S* and 1/W* of soaked particles in 3.6% of HCl solution

The Dietrich settling curve was applied to examine the velocity of these particles. The results are provided in Figure 4.15. This was observed that the settling velocity of particles estimated using the Dietrich settling curve was lower than the calculated ones using Stokes' law. This associated with the fact that the rough particles could be slowly settled down. When the *csf* factor was applied, the settling velocity was lower than others. This could confirm that the settlement of rough and fractured particles could consume a longer period. Dietrich equation with and without *csf* had presented the R^2 value that was 0.97.

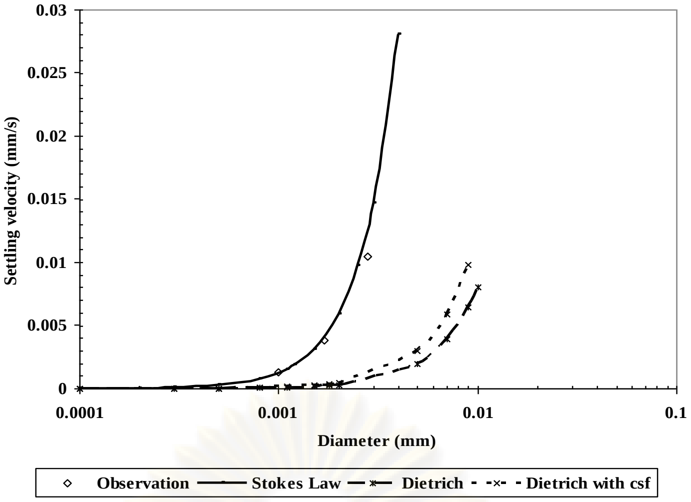

Figure 4.15 Measured and simulated settling velocity of particles in 3.6% of HCl solution fitted with Dietrich Settling Curve

Another assumption was made on the fact that acid solution could react to the particles. The complicating factor was introduced to estimate the possible settling velocity of particles in acid solution. The complicating factor was defined based upon the concentration of SS remained in the effluent (ϕ). It was found that the SS concentration in the effluent was higher than the maximum SS concentration obtained from effluent samples of deionised settling column $(\phi_{\max})$. Therefore, the term of $1-\phi$ had presented the negative value, it was adjusted to be 1.00. The constant *n* was defined as a parameter depended on the geometric mean of particle diameter and diameter of settling column (43 mm) and the value of *n* for this case was 4.62. The settling velocity of particles is shown in Figure 4.16. By inserting the reaction factor the velocity of particles seemed to be lower than the others. Dietrich equation with reaction had presented the R^2 value that was 0.98.This could reflect the fact, the settlement of ionic particle was very slow as the ions adhered on the particle may create the upward drag force and the electromotive force on adjacent particles. The large particles could adsorb more ionic constituents, which could destroy the stability of ionic balance. The apparent settling velocity seemed to be reduced comparing to the settling velocity of discrete particles.

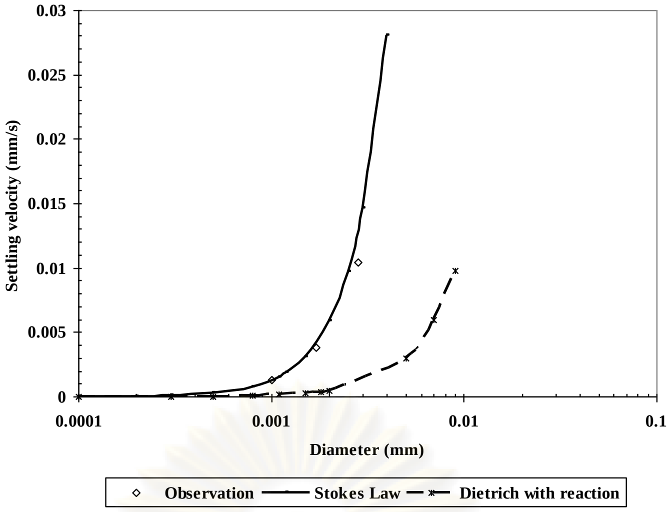

Figure 4.16 Measured and simulated settling velocity of particles in 3.6% HCl solution fitted with Stokes' law coupled the *csf* factor and Dietrich settling curve coupled with reaction

4.3.3 Alkaline condition

The sediments were soaked in alkaline solution that was 1.2% NaOH solution. The pH of system was 12. The density of solution and dynamic viscosity were 997.148 kg/m^3 and 0.00121 kg/m-s, respectively. The experimental data were given in Appendix C. The %SS removal contour is presented in Figure 4.17.

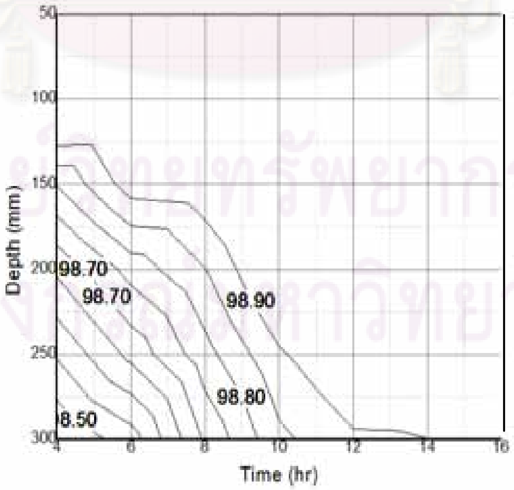

Figure 4.17 Contour of SS removals obtained from sediment settling column with 1.2% NaOH solution

The particle size observed in this test was 0.011-0.014 mm, the particle was relatively larger than the ones soaked into deionised water. The settling velocities of sediments were calculated with Stokes' law and the *csf* factor was determined. The results are illustrated in Figure 4.18. It was observed that the suitable values of *csf* factor were ranged between 0.58, which was closed to the value of *csf* factor governed from the settling column with deionised water. It could be noticed that the same value of *csf* factor was obtained in a same particle size. Therefore, this revealed that *csf* factor depended only the size of particles. Stokes' law with *csf* was highly accepted as the R^2 value was 1.00. The reaction between alkaline solution and particles may change the properties of particles. So, the Dietrich settling curve was applied to provide more details on settling pattern and mechanisms of these particles. The relationship between 1/S* and 1/W* is presented in Figure 4.19. It was observed that the same relationship between 1/S* and 1/W* was obtained. Therefore, the roughness of particles after soaking with deionised water, acidic and alkaline solution was not significantly changed.

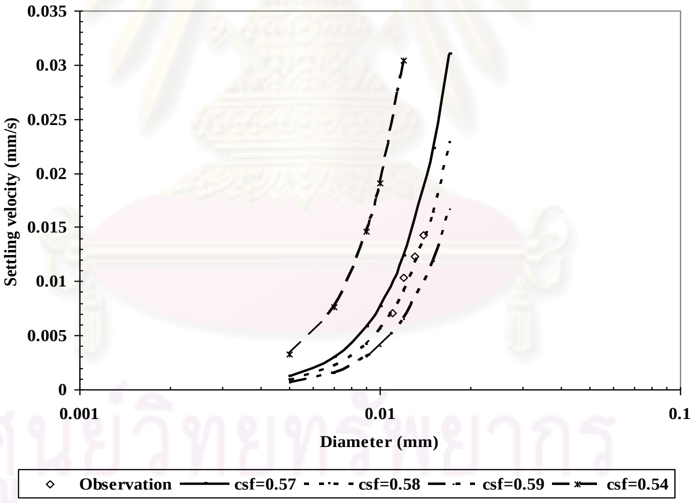

Figure 4.18 Measured and simulated settling velocity of particles in 1.2% NaOH solution fitted with Stokes' law coupled *csf* factor

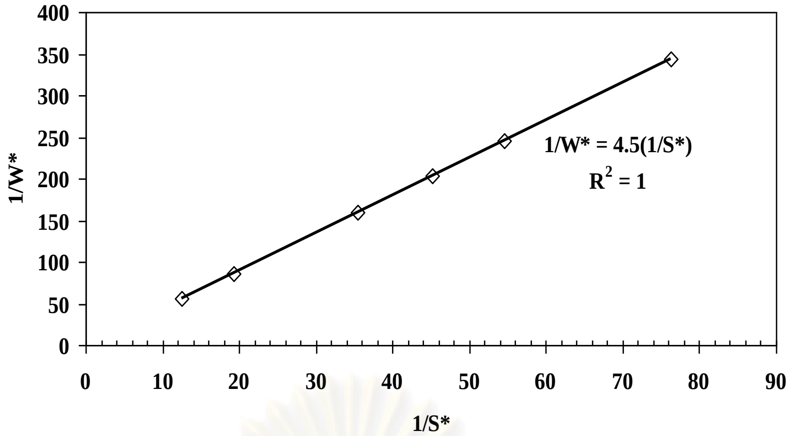

Figure 4.19 Relationship between 1/S* and 1/W* of soaked particles in 1.2% NaOH solution

According to the roughness of particles, the settling velocity calculated from Dietrich settling curve and Stokes' law was not different. This might be associated with the fact that roughness was not change dramatically. The shape of particles was key parameter that controlled the settling velocity of particles. Dietrich equation with and without *csf* had presented the R^2 value that were 1.00 and 0.99. The results of settling velocity calculated using Dietrich without *csf* and with *csf* factor as well as with complicating factor is presented in Figure 4.20.

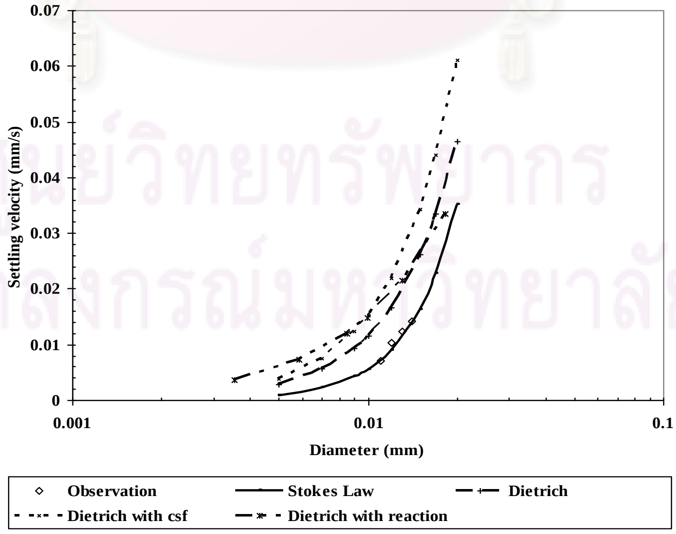

Figure 4.20 Measured and simulated settling velocity of particles in 1.2% NaOH solution fitted with Dietrich Settling Curve

The value of SS concentration (ϕ) in effluent was less than the maximum SS concentration $(\phi_{\max})$ and the different was 0.065 mg/L. The value of constant n was 4.62. The estimated settling velocity, where the roughness of particles was changed due to reaction, the settling velocity was higher than the apparent settling velocity. Dietrich equation with reaction had presented the R^2 was 0.99. This could reflect that the precipitation of particles due to hydroxide particulate forming could influence the settling velocity of particles. The settling velocity was increased, when the size of particle was increased. The settling velocity of particles under hydroxide precipitating was reduced comparing to the other case that involved only the change in particle roughness. This referred that the hydroxide precipitation could increase the density of particles. The behaviour of particles in acid condition was contrast from the alkaline condition.

Due to the limitation of sampling collection techniques, the data obtained from the settling column was not enough to justify the best fitted equation for evaluating the settling velocity of the contaminated silt and clay particles. In particular, the acid and alkaline solution could react with constituents bounded into particles. However, the complicating factor could simply reflect the influence of reaction between sediment particles and ions consisted in the solution.

4.3.4 Saline condition

The saline solution, which was assumed less react with particles were introduced to the settling column tests. The particles soaking with 1%NaCl was poured into the settling column test. The obtained raw data were described in Appendix C. The contour of %SS removal is presented in Figure 4.21. The sizes of particles were ranged between 0.008 and 0.01 mm. The particles size observed in this test were same as the one observed in settling column with deionised water. However, the particles seemed to be more uniform than that one in settling column with deionised water. The density of 1%NaCl solution was 997.148 kg/m^3 and the dynamic viscosity was 0.00108 kg/m-s. Stokes' law was applied to estimate the settling velocity of this column test. The suitable *csf* factor was 0.57, which was closed to the one obtained from the settling column with deionised water and 1.2% of NaOH. This revealed that the shape of particles of this case was not significantly different from the control column with deionised water applying. Stokes' law with *csf* was valid as the R^2 value was 0.91. The results are provided in Figure 4.22.

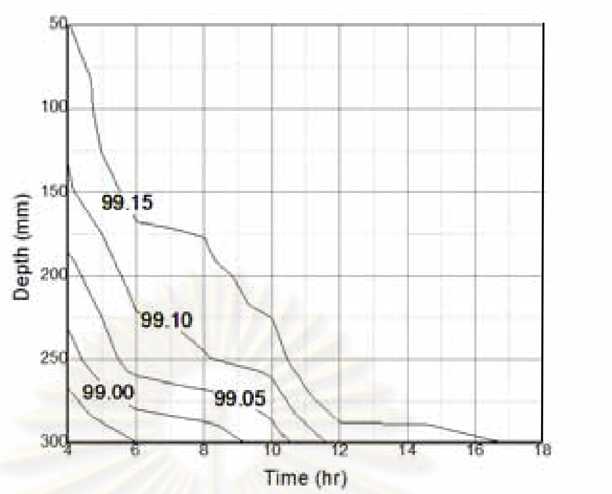

Figure 4.21 Contour of SS removals obtained from sediment settling column with 1.0% NaCl solution

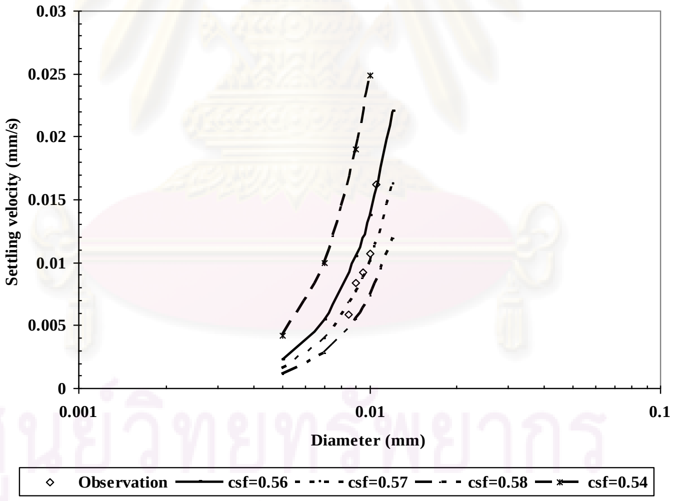

Figure 4.22 Measured and simulated settling velocity of particles in 1.0% NaCl solution fitted with Stokes' law coupled *csf* factor

To be confirmed the influence of roughness on the settling velocity of the particles, the Dietrich settling curve was applied. The results of 1/S* versus 1/W* is given in Figure 4.23. The results were presented the same relationship between 1/S* and 1/W*, indicating the particles were in laminar flow condition and the roughness was not significantly differed from the control experiment. The roughness of particles was insignificantly changed as a result of erosion on the sediment surface may slightly occur. The Na^+ ion could fill the pores of particles and the particle surface might be smoothening. One more concern was the swelling of particles, it could reduce the particles density.

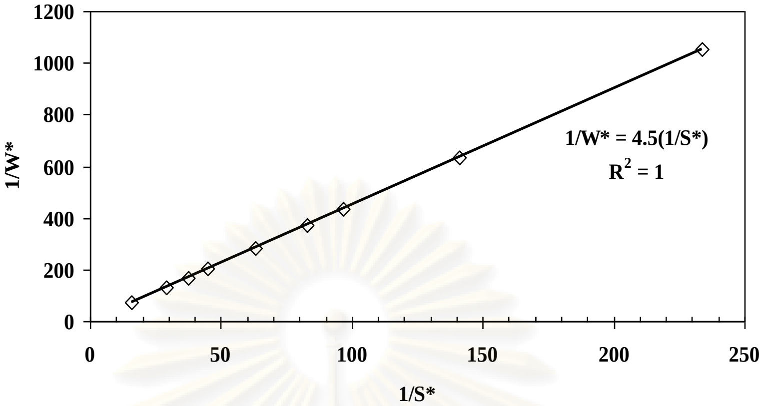

Figure 4.23 Relationship between 1/S* and 1/W* of soaked particles in 1.0% NaCl solution

Figure 4.24 presents the settling velocity calculated with Dietrich settling curve. The concentration of SS observed in the effluent was lower than the control experiment that was 0.04 mg/L. The constant *n* in a complicating factor was 4.62. The settling velocity obtained using Dietrich settling curve was closed to the one yielded from Stokes' law and the R^2 was 0.91. This could suggest that the 1% NaCl solution did not much affect to the roughness of particles.

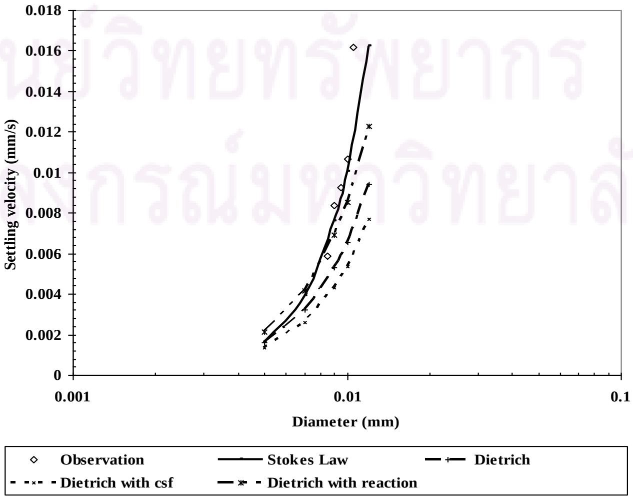

Figure 4.24 Measured and simulated settling velocity of particles in 1.0% NaCl solution fitted with Dietrich Settling Curve

Besides, it was found that there was oscillation on evaluating the settling velocity of particles between using original Dietrich and Dietrich coupling *csf*. Dietrich equation with and without *csf* had presented the same R^2 was 0.91. The shape of particle may slightly change when the particles were swelled. However, the Dietrich equation with reaction referred that the finest particles could sink into NaCl solution more quickly than the ones predicted by Stokes' law. On the other hand, the bigger particles could sink down more slowly than the ones predicted by Stokes' law and was same R^2 value. This was according to the fact that Na^+ ion could adhere and fill into the pore of particles. In case of finer particles, the Na^+ could difficultly fill and slightly increase the particle density, so the finer particles could quickly settle down. For the larger particles, the adhered Na^+ ions were much more than the finer ones. Thus, the particles may less stable and they could disperse into NaCl solution with a longer time than the finer ones.

The 2% NaCl solution was introduced to justify the suitable way to define the complicating factor, which could reflect the interaction between ionic salt constituents and particles. The contour lines of % SS removal are provided in Figure 4.25.

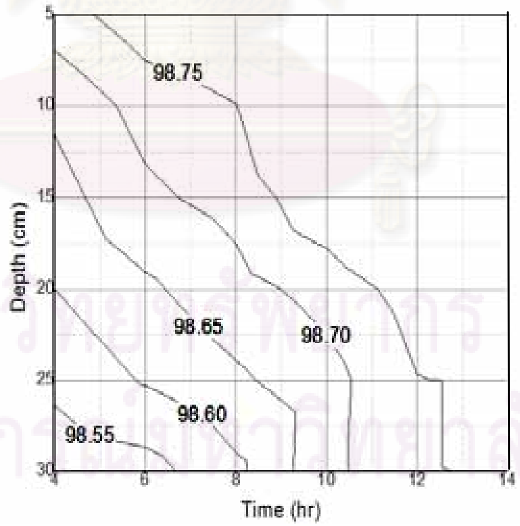

Figure 4.25 Contour of SS removals obtained from sediment settling column with 2.0% NaCl solution

The size of particle observed in this test was 0.013-0.015 mm. It was bigger than the particles observed in 1% NaCl settling column test. This could be a result of swelling of particles, dealing with the accumulation of Na^+ on the particles surface.

The density and dynamic viscosity of 2% NaCl solution were 997.167 kg/m^3 and 0.00116 kg/m-s. These values were higher than the solution of NaCl at concentration of 1%. Stokes' law was applied to evaluate the settling velocity of particles in this column test. The result is presented in Figure 4.26.

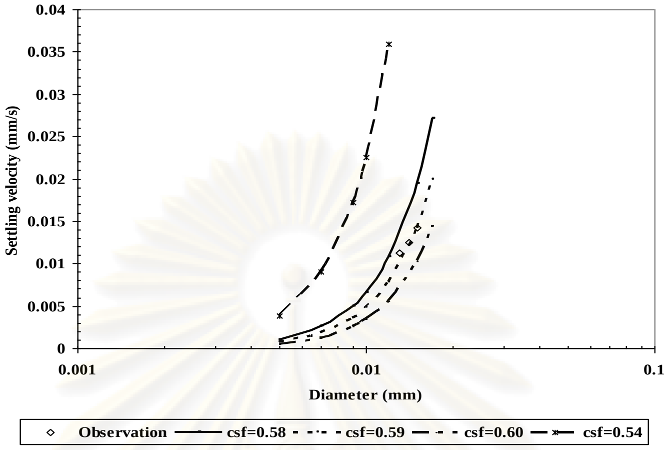

Figure 4.26 Measured and simulated settling velocity of particles in 2.0% NaCl solution fitted with Stokes' law coupled *csf* factor

The suitable values of *csf* factor for this settling column test was 0.59. Stokes' law with *csf* could show the high R^2 value that was 0.99. This revealed that the particles may increase the size due to swelling. The surface roughness might be changed and the impact of this parameter on the settling process was estimated using Dietrich settling curve. The relationship between 1/W* and 1/S* is shown in Figure 4.27. This was the same as previous tests. Dietrich settling curve with and without *csf* had presented the same R^2 was 0.99.

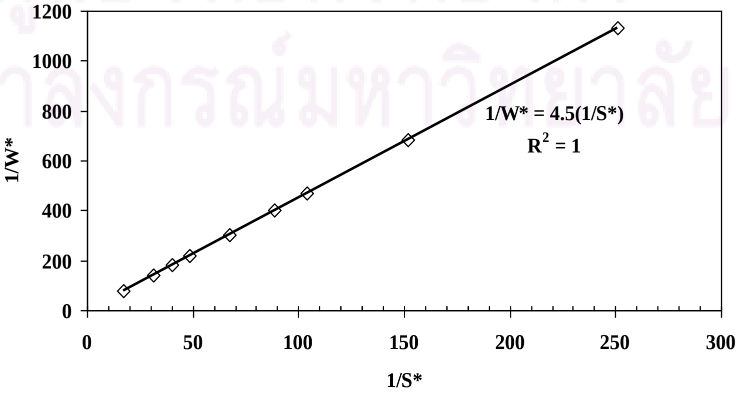

Figure 4.27 Relationship between 1/S* and 1/W* of soaked particles in 2.0% NaCl solution

The settling velocity calculated using the Dietrich settling curve is given in Figure 4.28.

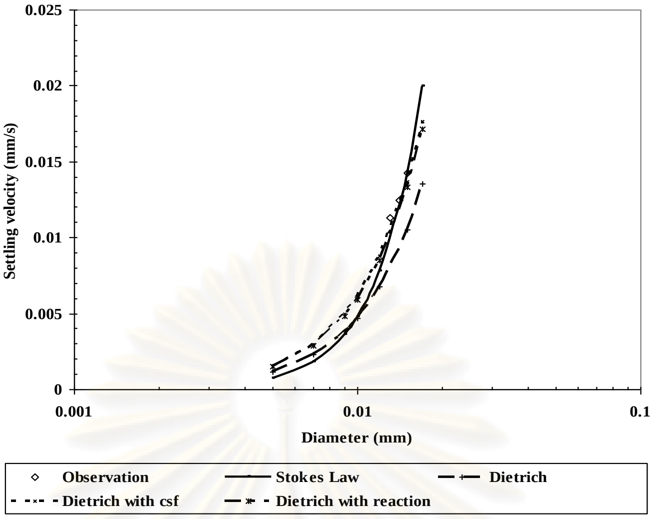

Figure 4.28 Measured and simulated settling velocity of particles in 2.0% NaCl solution fitted with Dietrich Settling Curve

The complicating factor was added to Dietrich settling curve, the SS concentration in effluent was 0.08 mg/L that was lower than the control experiment. The value of *n* was 4.62. It was found that the complicating factor could estimate the influence of reaction between NaCl and particles on the settling velocity. When the concentration of NaCl increased, the settling velocity was decreased. This indicated that the ions of Na^+ might be attached on the surface of particles and the particles may swell. Since the particles size was enlarged and density was reduced resulting in lower settling velocity. Dietrich equation with reaction had presented the R^2 was 0.99. The conventional Dietrich and modified Dietrich involving *csf* factor did not generate the different value of settling velocity comparing to Stokes' law. This might confirm the change of roughness and shape of particles were not affected by the saline solution.

The settling velocity of lead contaminated particles was relied on the particles shape and size rather than the change of solution density and dynamic viscosity. However, the reaction between particles and ions contained in the solution could disturb the size of particles, which directly affect the settling velocity of particles. The summary of findings is given in Table 4.3. The settling velocity of particles tended to be influenced by particle size, rather than the electronegativity force.

Table 4.3 Summary of key parameters in settling column test

Parameter	Order
Particle size	acid < deionised water < 1%NaCl < alkaline < 2%NaCl
Electrical conductivity	deionised water < 1%NaCl < 2%NaCl <alkaline <acid
Settling velocity	acid < deionised water < 1%NaCl < alkaline < 2%NaCl

4.4 Pb content in suspended particles

The lead contaminated sediments utilised in this study were also examined the properties after settlement. The concentration of lead may change due to the reaction between dissolved lead and ionic species in solutions. The observation data were provided in Appendix D.

4.4.1 Natural condition

The particles were soaked in deionised water to examine the background concentration lead that could either escape from sediments or suspend into water. The vertical distribution of lead concentration profiles and mass of particle remained in the deionised water are presented in Figures 4.29 and 4.30, respectively. The 3% SS slurry had totally contained the Pb at the concentration of 60.8 mg/L. The highest SS remained in the slurry was only 1.1% of initial SS. The estimated total lead concentration was 0.67 mg/L. Base on the fraction of lead in sediment, the exchangeable lead was 0.004 mg/L. The highest concentration of soluble lead in deionised water was presented at 0.15 mg/L. The observation of soluble Pb concentration was higher than the calculation of soluble Pb. This finding could be suggested that there was some amount of Pb releasing from the settled or suspended sediments due to molecular and mechanical diffusion. The soluble Pb remained in the deionised water near the surface. The concentration of soluble P was reduced over depth. This was according to the fact that Pb was mainly accumulated or bounded with silt and clay particles. If these fine particles suspended into the deionised water, they could be the source of Pb. The very fine particles were observed near the surface of water, hence the concentration of soluble Pb was high at this location. When the settling time increased, these tiny particles could be settled down. The mass of SS remained in deionised water was slightly reduced. The settlement of suspended solids reversely differed from the profile of soluble Pb. The assumption was made based on the fact that ionic Pb could not be rebounded into sediments and the remaining particles were almost silt, which could be the source of Pb in deionised water.

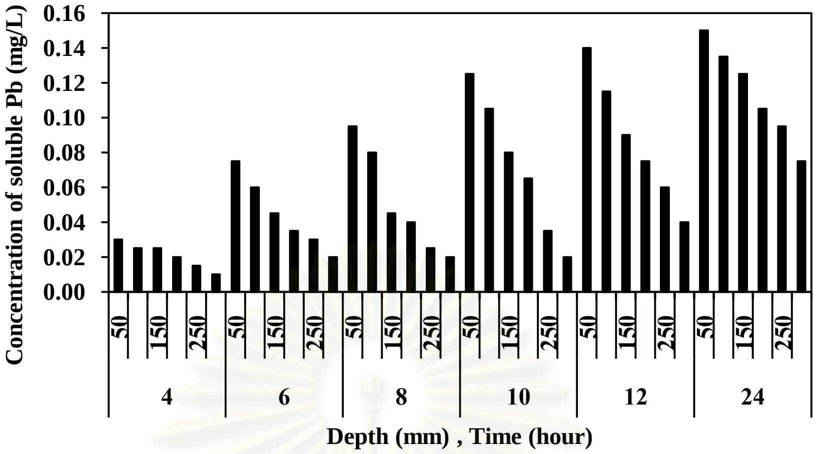

Figure 4.29 Vertical distribution of lead concentration in deionised water

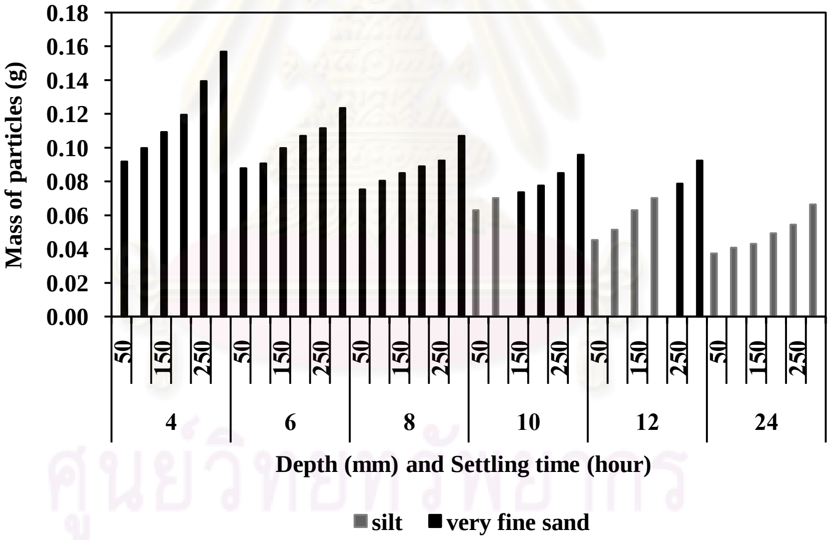

Figure 4.30 Mass of particle remained in deionised water

4.4.2 Acidic condition

Since the sediments were input to the 3.6% HCl solution, the particles and soluble lead were highly remained in the solution. The results of Pb releasing and mass of particles remained in the system are provided in Figures 4.31 and 4.32, respectively. The soluble Pb concentration observed at 24 hours was the highest one that was at 0.41 mg/L. The concentration of soluble Pb was relatively higher than the previous experiment. The acid solution might stimulate the solubility of Pb bound to carbonate and other bounded Pb compounds. However, the concentration profiles of soluble Pb in acid solution had shown the same behaviour as the previous experiment. The soluble Pb was remained into acid solution at the portion near the surface of column and the longer period presented the higher soluble Pb concentration. Besides, the mass of suspended particles was reduced over time.

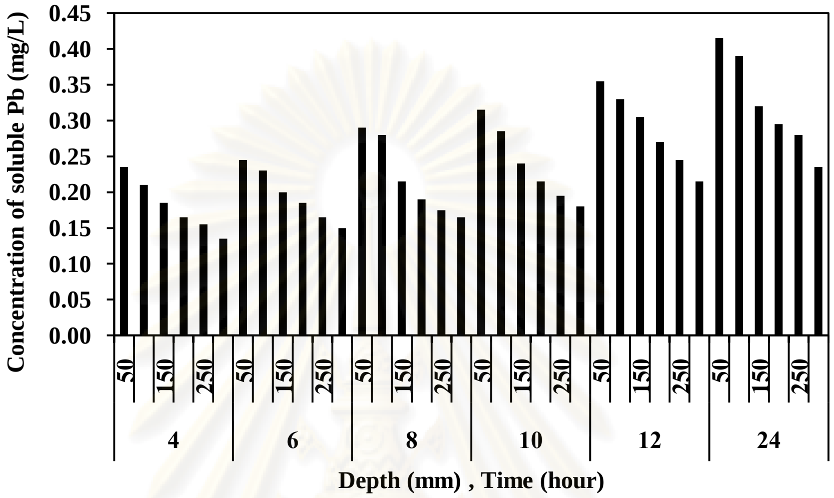

Figure 4.31 Vertical distribution of lead concentration in acidic solution

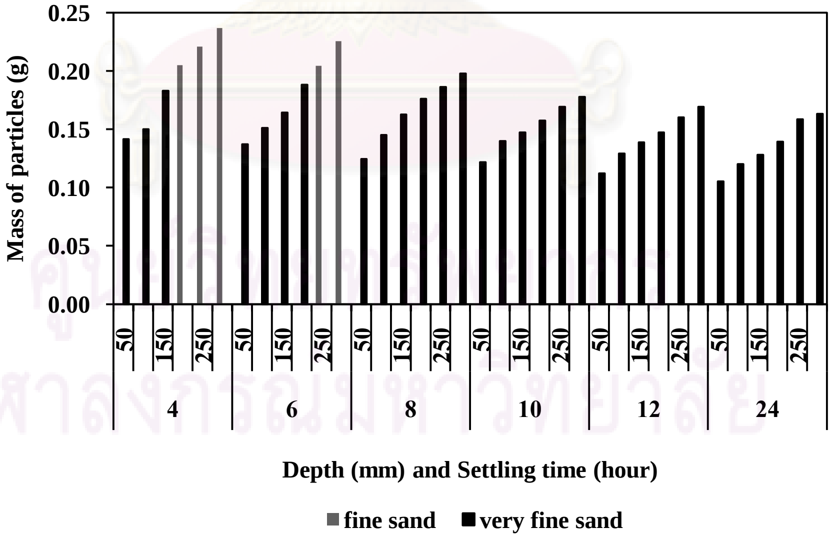

Figure 4.32 Mass of particle remained in acidic solution

When the suspended particles were soaked into solution in a longer time, the size of particles was reduced. The reaction between proton (H^+) in acidic solution and Pb could be occurred. The higher releasing rate of Pb may be a result of ion exchange.

The particles remained in the solution could be fractured and they could be highly suspended due to electromotive forces. These very tiny fractured particles could be able to dissolve into the acid solution. Only the bigger particles that were very fine sand remained in the solution as these particles could tolerate the erosion of acid. Hence, the mass of particles were still high, even the test had been operated for a day.

4.4.3 Alkaline condition

The particles were soaked in alkaline solution to examine the releasing of Pb. The vertical distribution of lead concentration and mass of particle remained in the alkaline solution are presented in Figures 4.33 and 4.34, respectively. The soluble Pb could release from the sediment and the highest concentration of soluble lead was 0.23 mg/L. The concentration of soluble lead in alkaline solution was lower than the system with acid solution. The concentration profiles of soluble Pb and mass of suspended solids remained in the solution acted the same manner presented in both previous experiments. The lowest portion of soluble Pb was observed near the surface of column and size of particles remained in solution became bigger than both previous cases. The slow releasing of Pb might be a result of the reaction between hydroxide group (OH^-) in alkaline solution and Pb. The hydroxide species could bring the lead precipitation in a form of $Pb(OH)_2$. This precipitated lead hydroxide was less soluble. In accordance with the molecular weight of $Pb(OH)_2$, it could increase the settleability of sediment. Only the bigger particles were still suspended into alkaline solution.

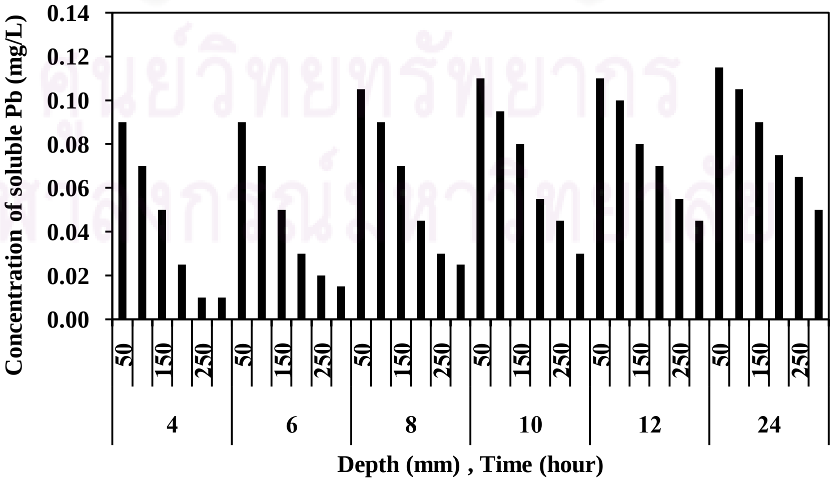

Figure 4.33 Vertical distribution of lead concentration in alkaline solution

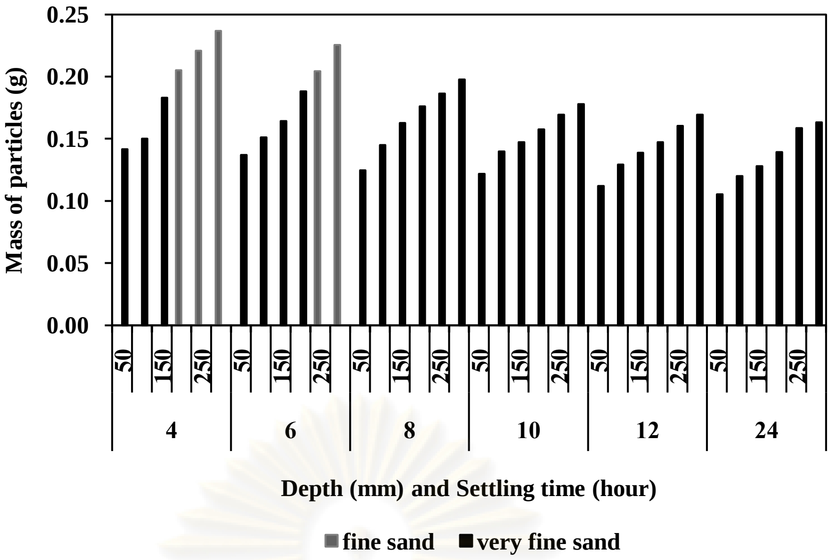

Figure 4.34 Mass of particle remained in alkaline solution

4.4.4 Saline condition

As same as the previous tests, the particles were soaked in saline solution to determine the influence of EC on releasing of soluble Pb. With 1% NaCl solution, the concentration profiles of soluble lead and mass of suspended particles remained in the solution are provided in Figures 4.35 and 4.36, respectively. The Pb could be dissolved into a 1% NaCl solution with the highest concentration of 0.18 mg/L at 24 hours soaking. The releasing of Pb was little higher than the control experiment. The pattern of Pb releasing and the remaining of suspended solids in 1%NaCl solution were similar to the previous tests. The Pb could be highly release and they suspended near the surface of the column that was the same location of accumulation of very fine particles contaminated with Pb. The particles presented in the solution were relatively larger than the previous experiments. The reason for this finding was involved with the fact that the particles may swell due to the accumulation of Na^+ ions. However, the accumulation mass of suspended particles was slightly higher that the control one. This revealed that the mass of Na^+ accumulated surrounded the particle surface could increase the weight of particles. However, the density of solution was increased, this could delay the settling of Na^+ bounded particles, and even its size was increased.

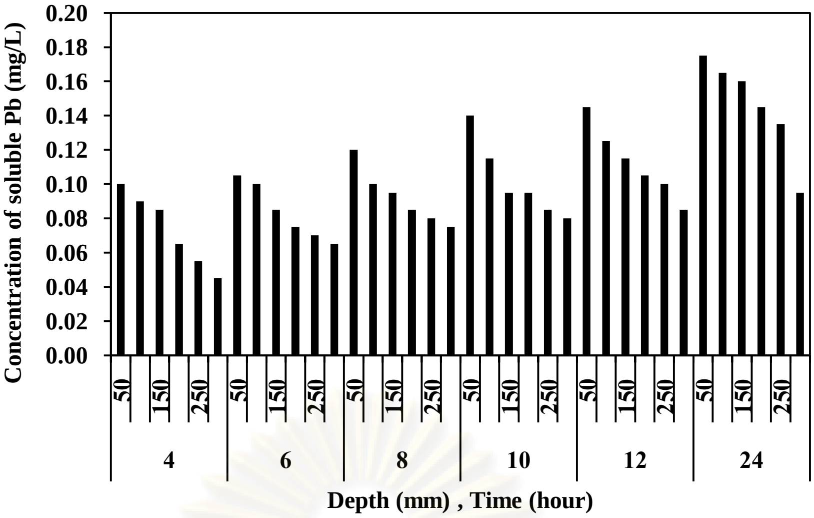

Figure 4.35 Vertical distribution of lead concentration in 1% NaCl solution

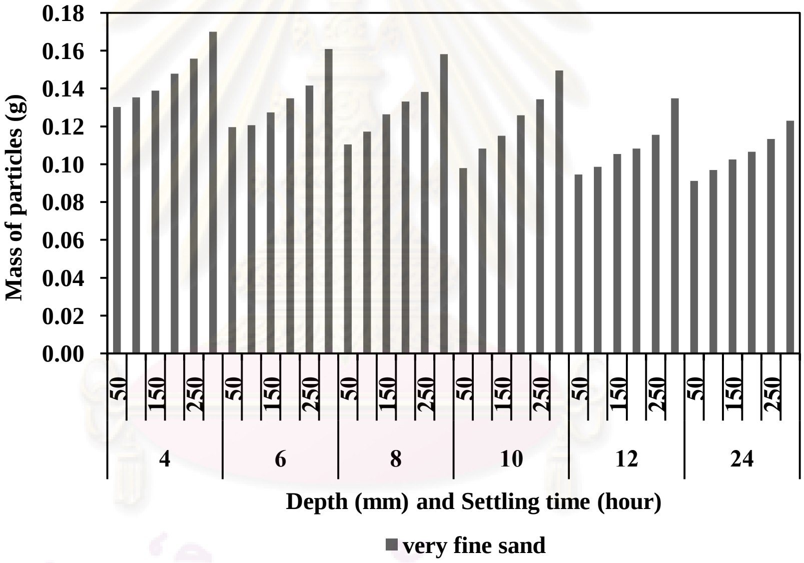

Figure 4.36 Mass of particle remained in 1% NaCl solution

When the NaCl content in the solution was increased to be 2%, the observation of soluble Pb distribution and the accumulation of suspended particles were investigated. The results are presented in Figures 4.37 and 4.38. The soluble Pb remained in the solution was 0.23 mg/L. This was higher than the one with 1%NaCl solution and it was closed to another with 1.2% NaOH solution. The releasing of Pb and accumulation of suspended particles was still presented the same behaviour as the previous experiments. The accumulations of suspended particles were at the top portion of column and these suspended particles may be a source of Pb that could be further released and get dissolved into the solution.

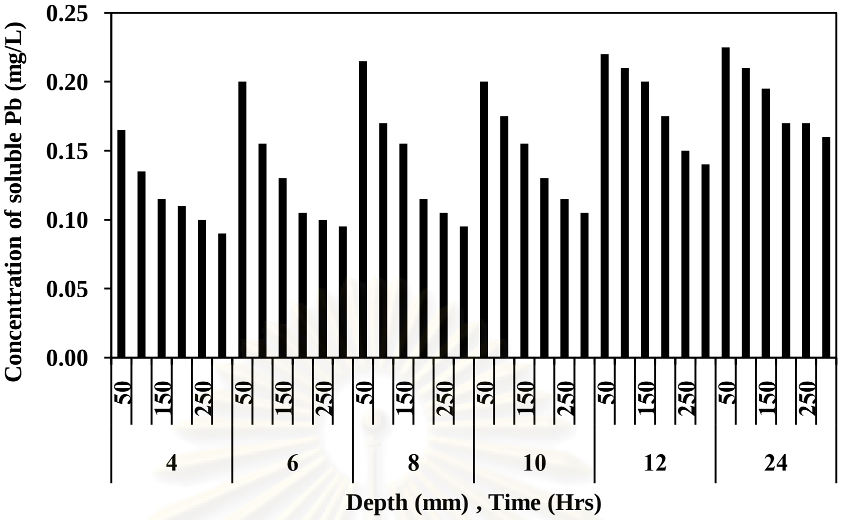

Figure 4.37 Vertical distribution of lead concentration in 2% NaCl solution

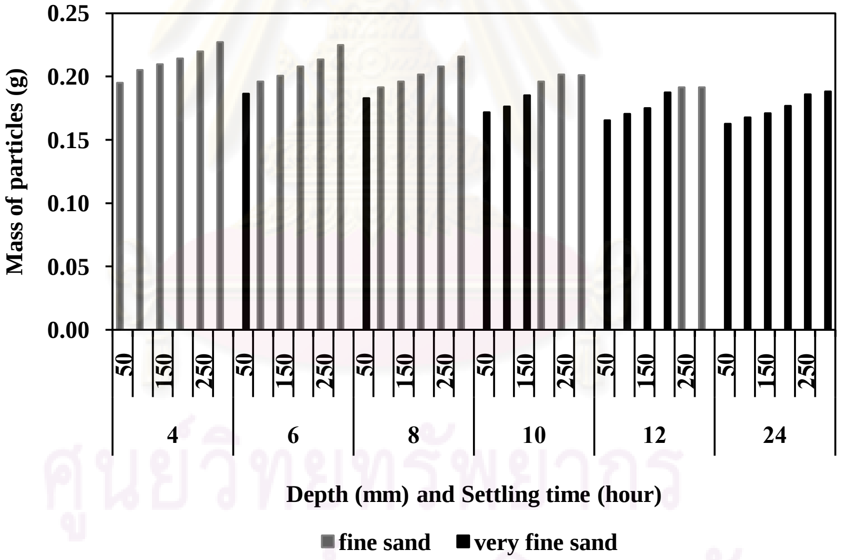

Figure 4.36 Mass of particle remained in 2% NaCl solution

The most of Pb was accumulated in the finer particles. If there was any reactions occurred with these finer particles, Pb and the particles could be dissolved. By comparison, the H^+ or OH^- ions could influence the releasing of Pb rather than the Na^+ ion. The accumulation of the tiny particles could affect the releasing of active Pb. The Pb remained in solution may originate from the active Pb compounds bound to sediments. The releasing of Pb may deal with molecular and mechanical diffusion and other interactions. As these tiny particles could highly store the active Pb, it could be defined as the mobile source of soluble Pb. The orders of lead releasing and mass accumulation of suspended particles were summarised as given in Table 4.4. The releasing of Pb had shown the same order as mass of remaining SS and electrical conductivity of solution. This referred that the reaction and properties of water could affect the releasing of Pb.

Table 4.4 Order of lead releasing, mass of remaining suspended particles, settling velocity and electrical conductivity

Parameter	**Order**
Settling velocity	acid < deionised water < 1%NaCl < alkaline < 2%NaCl
Electrical conductivity	deionised water < 1%NaCl < 2%NaCl < alkaline < acid
Releasing of Pb	deionised water < 1%NaCl < 2%NaCl < alkaline < acid
Mass of remaining SS	deionised water < 1%NaCl < 2%NaCl < alkaline < acid

4.5 Summary

This result showed the pattern of settling and the settling velocity of lead contaminated sediment examined in the various solutions. The settling velocity of sediment was highly depended on the particle size of sediment. The electrical conductivity and pH could affect the reactions between sediments and ions in the solution. The particles suspended in highly electrical conductivity solution could be dissolved and accumulate into the solution. Under natural condition, the small particle could be settled slower than large particle. In case of particles migration under acid condition, the particles were eroded and their size was reduced, resulting in highly dispersion. Under alkaline condition, the particles were bound to hydroxide. The size and density of particles were increased, which could stimulate the settling velocity of particles. On the other hand, the large particles soaked into saline solution could be settled down slower that the small ones. As the particle swelled, the size of particles was increased. Dealing with electromotive force generated from the highly charged particles, this could stimulate the upward drag force conducting the suspending of particles.

Under neutral condition, free Pb could release from suspended particles and bottom sediment. The fine particles were accumulated near the surface. Coincidently, the Pb ions were also accumulated at the same location as particles. In case of particles suspended into acid solution, the fine particle was highly dissolved, resulting in high releasing of Pb. The high mass of particles was observed at the same location as the high Pb releasing was presented. If the particles were mixed into alkaline solution, the particles had lost the lowest amount of Pb. As Pb could react with hydroxide ion and these precipitants were highly stable. The releasing of Pb could be presented at the lowest level. When particles were soaked into saline solution, the ion exchange could enhance the Pb releasing. The higher saline solution could generate the higher Pb releasing. These experiments had shown that the accumulation of finer particles was located at the same location as the highest Pb releasing was yielded. This could be concluded that the fine particles were the source of Pb. If the particles could be settled down and the Pb could be stabilised, the migration of Pb was reduced. The alkaline condition could reduce the movement of sediments and Pb bound sediments. The change of pH and EC could influence the settlement and release of Pb from the contaminated sediment.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 General aspects

This research focused on the influence of pH and EC on the movement of lead contaminated sediment in aqueous solution. The agricultural sediment sample was collected from downstream of the Klity stream, Kanchanaburi province, Thailand. Soil classification of this sample was sand. The concentration of lead that contaminated in sediment sample was 20,250 mg/kg. Lead observed in sediment was mostly bounded onto carbonate compounds.

Two measuring techniques were introduced to examine the settling velocity of particles. First image processing technique was valid to the modified chalk particles settling in solution. However, this technique could not measure settling velocity in sediment solution because the contrast between sediments and water was not clearly observed in this study. By observation via the image processing techniques, it revealed that the particles were not sphere. Secondly, the settling column technique was employed. Sediments had mix grained particles, there were sand, silt and clay. The fine particles with the particle size of 0.004-0.008 mm were still dispersed in deionised water, these particles were classified as silt and clay particles. The settling velocity obtained from Stokes' law was totally different from the observation. The Corey shape factor (*csf*) of these fine particles was 0.54. The *csf* was close to the 2-D observation from image processing technique. The settling velocity obtained from Dietrich settling curve was slightly lower than the one calculated using Stokes' law. It shown that the impact of roughness might not significantly affect the settling velocity of particles in deionised water as the particles might not be eroded or swell after soaking with deionised water. Almost free Pb was adhered onto the fine particles of silt and clay. The accumulation zone of these particles was near the column surface and the Pb releasing was highly observed at this zone. It could be concluded that the fine particles of silt and clay were source of Pb that could input to the water sources.

In acidic condition, the remaining sediment had a particle size in range of 0.001-0.003 mm. The smaller particles size was related to the fracture of particles due to either the corrosivity or reaction between the acidic solution and sediments. The suitable values of *csf* factor was between 0.43-0.44. The settling velocity of particles estimated using the Dietrich settling curve with and without *csf* was given the lower settling velocity than the calculated ones using Stokes' law. This was associated with the fact that the rough particles could be slowly settled down. In acidic solution could react to the particles, therefore the velocity of particles seemed to be lower than the others. The settling velocity was decreased because the ions adhered on the particle might create the upward drag and electromotive forces on adjacent particles. The apparent settling velocity seemed to be reduced comparing with to the settling velocity of discrete particles. The high Pb concentration was obtained at the accumulation zone. The highest Pb concentration was yielded due to the increase of Pb dissolubility. The fine particles could also be dissolved and they were disappeared from the system.

In alkaline condition, the remaining particle with size of 0.011-0.014 mm was observed. The particle was relatively larger than the ones soaked into deionised water. The suitable values of *csf* factor were 0.58. The roughness of particles could little reduce the settling velocity of particles. Where the sediment could form the compound of hydroxide, the roughness of particles was reduced, the calculated settling velocity was higher than the apparent settling velocity. The formation of hydroxide precipitate could increase the size of particles, resulting in high settling velocity. Besides, the reaction could stabilise the Pb contaminated sediments, the releasing of Pb from the zone of accumulation was reduced.

In saline condition, the sizes of particles remained in 1% NaCl solution were 0.008-0.01 mm. The suitable *csf* factor was 0.57. The settling velocity obtained from Dietrich settling curve was closed to the one obtained from Stokes' law. The reaction between NaCl and sediment could increase the size of particles dealing with swelling. The positive charges were sorbed onto particles surface. The larger size of particles could give the higher positive charges. The bigger particles that were highly positive charge particles had the lower settling velocity as a result of upwards electromotive forces. The zone of particles accumulation that was near the column surface had presented the high Pb releasing. Moreover, the higher NaCl concentration had shown the same behaviour with the higher magnitude. Using the 2% NaCl solution, the size of particle observed in this test was 0.013-0.015 mm. The suitable values of *csf* factor for this settling column test was 0.59. When the concentration of NaCl increased, the settling velocity decreased. The conventional Dietrich and modified Dietrich involving *csf* factor did not generate the different values of settling velocity comparing the one obtained from Stokes’ law. This might confirm that the change of roughness and shape of particles were not affected by the saline solution.

5.2 Specific aspect

The settling velocity of particles tended to be influenced by particle size. The Pb releasing and mass of Pb remaining was influenced reactions among Pb, sediments and ionic constituent in the solution and the reaction was related to the EC and pH of the system. The order can be given as follows Table 5.1.

Table 5.1 Summary order of particle size, settling velocity, electrical conductivity, lead releasing and mass of remaining suspended particles

Parameter	**Order**
Particle size	acid < deionised water < 1%NaCl < alkaline < 2%NaCl
Settling velocity	acid < deionised water < 1%NaCl < alkaline < 2%NaCl
Electrical conductivity	deionised water < 1%NaCl < 2%NaCl < alkaline < acid
Releasing of Pb	deionised water < 1%NaCl < 2%NaCl < alkaline < acid
Mass of remaining SS	deionised water < 1%NaCl < 2%NaCl < alkaline < acid

Based on the specific findings, it could be suggested that the Pb could be highly accumulated in the finer particles, which could be able slowly settled down. The alkaline condition could enhance the settlement of particles and to stabilise the Pb in the particles.

5.3 Recommendations

This study could provide the basic information on the influence of EC and pH on settling and releasing of Pb from sediments. The research could be further improved in some issues including of:

- Types of acid and alkaline solution should be varied as the reaction between sediment and ionic substances might be presented the different behaviour.

- The dimension of settling velocity need to be extended to 2D and 3D to model the settling velocity of sediment in real field condition.

- The settling velocity of particles and the releasing of Pb from contaminated sediments under turbulence flow could be further undertaken to be a useful information for the remediation of Pb contaminated sediments.

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APPENDICES

APPENDIX A

Characteristics of sediment samples

1. Particles size of sediment

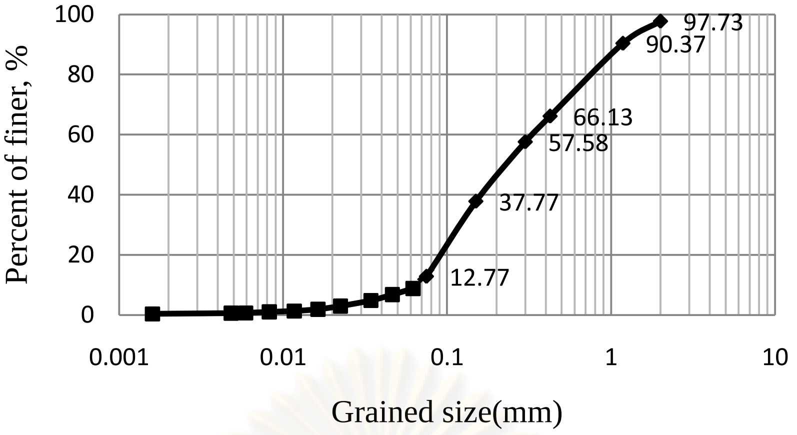

Figure A.1 Particle size of sediment

2. Classification of soil

Table A.1 Percent of sediment texture

Type sediment	**Sediment Texture (%)**			**Sediment classification**
	Clay	**Sand**	**Silt**	
Sediment sample	6.73	89.12	4.15	Sand

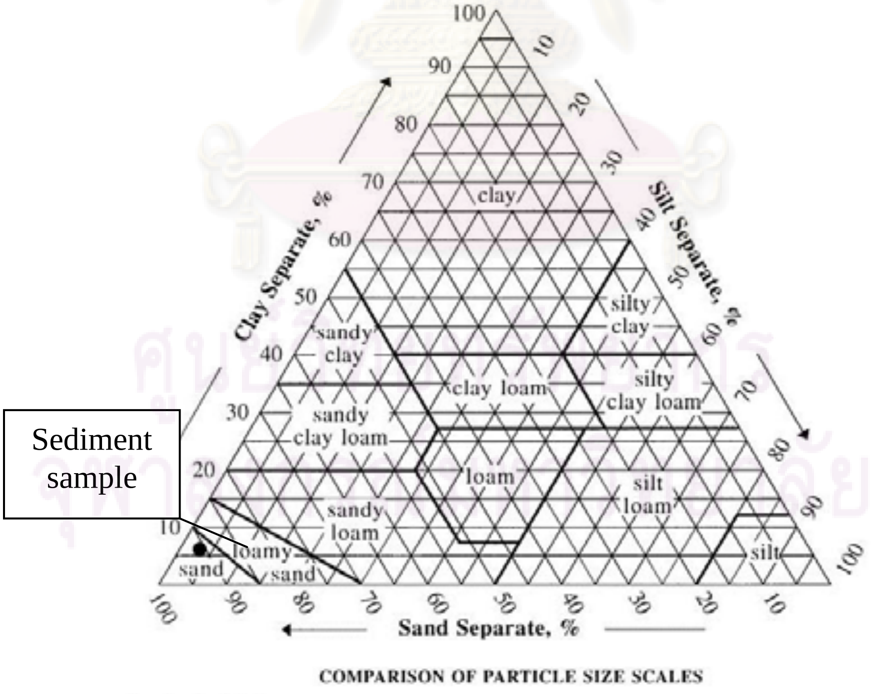

Figure A.3 Classification of sediment

3. Water content of sediment

Table A.2 Water content of sediment

Type soil	Duplicate	Weight before drying (g)	Weight after drying (g)	Water content	Average
Sediment sample	1	22.0708	21.9428	0.5833	0.5898
	2	27.7583	27.5924	0.6013	
	3	25.4666	25.3242	0.5623	
	4	25.5619	25.4104	0.5962	
	5	26.5805	26.4202	0.6067	
	6	26.7446	26.5872	0.5920	
	7	29.9154	29.7408	0.5871	

4. Bulk density of sediment

Table A.3 Bulk density of sediment

Type soil	Duplicate	Weight (g)	Volume (cm^3)	Bulk density (g/cm^3)	Average
Sediment sample	1	404.6	330	1.226	1.214
	2	399.8	330	1.212	
	3	397.9	330	1.206	

5. Hydraulic conductivity of sediment

Table A.4 Hydraulic conductivity of sediment

Type soil	High (cm)	Duplicate	Time (min)	Q (cm3)	A (cm2)	Lc (cm)	k (cm/s) = QLc/ΔHAt
Sediment sample	123.5	1	60	7.0	28.51	12.51	0.000415
		2	60	7.0	28.51		
		3	60	7.0	28.51		
		4	60	7.0	28.51		
		Average	60	7.0	28.51		

6. Specific Gravity

Table A.5 Specific gravity of sediment

Type sediment	Duplicate	Dry Sediment + Container (g)	Flask + Water + Sediment (g)	Specific gravity	Average
Sediment sample	1	496.6	728.7	2.67	2.61
	2	512.7	726.7	2.64	
	3	506.9	784.1	2.52	

7. Organic Matter of sediment (OM)

Table A.6 Organic matter of sediment

Type sediment	Duplicate	Weight (g)	Blank (mL)	Volume of 0.5N FAS (ml)	% OM	Average
Sediment sample	1	0.5002	32.53	23.70	10.1962	10.1370
	2	0.5045	32.53	23.55	10.2811	
	3	0.5020	32.53	24.10	9.6992	
	4	0.5001	32.53	23.55	10.3716	

8. pH (Sediment : water)

Table A.7 pH of sediment

Type soil	Duplicate	pH (1:5)	Average
Sediment sample	1	7.38	7.31
	2	7.48	
	3	7.21	
	4	7.17	

9. Electrical Conductivity of sediment (Sediment : water)

Table A.8 Electrical conductivity of sediment

Type sediment	Duplicate	pH (1:5)	Average
Sediment sample	1	45.3	41.2
	2	40.2	
	3	38.0	

10. Cation Exchange Capacity (CEC)

Table A.9 Cation exchange capacity of sediment

Type sediment	Duplicate	Weight (g)	Volume of HCl (ml)	Blank (mL)	CEC (meq/100g sediment)	Average
Sediment sample	1	5.0412	26.00	0.1	12.3799	12.3168
	2	5.0600	25.30	0.1	12.0010	
	3	5.0800	26.60	0.1	12.5700	

11. Total Phosphorus (TP)

Table A.10 Total Phosphorus of sediment

Type sediment	Duplicate	Weight (g)	Absorbance (690 nm)	µg P from curve	mg P/kg	Average
Sediment sample	1	0.5020	0.284	27.3790	54.5398	62.6475
	2	0.5066	0.362	36.1750	71.4075	
	3	0.5094	0.278	26.7024	52.4192	
	4	0.5040	0.364	36.4006	72.2234	

12. Soluble Phosphorus (SP)

Table A.11 Soluble Phosphorus of sediment

Type sediment	Duplicate	Weight (g)	Absorbance (690 nm)	µg P from curve	mg P/kg	Average
Sediment sample	1	5.0055	0.045	3.9805	0.7952	0.8137
	2	5.0099	0.046	4.12208	0.8228	
	3	5.0076	0.046	4.12208	0.8232	

13. Total Kjeldahl Nitrogen (TKN)

Table A.12 Total Nitrogen of sediment

Type sediment	Duplicate	Weight of sediment (g)	Volume of H_2SO_4 (ml)	Total Nitrogen (%)	Average
Sediment sample	1	1.0036	6.3	0.2085	0.2281
	2	1.0002	6.6	0.2193	
	3	0.5000	3.9	0.2565	

14. Alkalinity

Table A.13 Alkalinity

Type sediment	Duplicate	Volume of sample (ml)	Volume of H_2SO_4 (ml)	Alkalinity (mgCaCo$_3$/kgsoil)	Average
Sediment sample	1	50	1.30	31.20	29.60
	2	50	1.15	27.60	
	3	100	2.50	30.00	

15. Concentration of lead in sediment sample

Table A.14 Concentration of lead in sediment sample

Type sediment	Duplicate	Value from ICP (mg/l)	Dilution factor	Weight of sediment (g)	Concentration of lead in sediment (mg/kg)	Average
Sediment sample	1	0.16	1000	0.1	16,000	20,250
	2	0.18	1000	0.1	18,000	
	3	0.25	1000	0.1	25,000	
	4	0.22	1000	0.1	22,000	

APPENDIX B

Image processing technique

1. Settling velocity of chalk particle

Table B.1 Settling velocity of chalk particle in deionised water

Diameter (m)	**Settling Velocity (Stokes' law)**	**Settling Velocity (image processing)**
0.000016	0.000203	0.000204
0.000018	0.000253	0.000258
0.000020	0.000318	0.000320
0.000022	0.000383	0.000386
0.000022	0.000412	0.000419
0.000024	0.000459	0.000460
0.000029	0.000669	0.000691
0.000035	0.001007	0.000854
0.000050	0.002029	0.001650
0.000055	0.002474	0.001975
0.000063	0.003287	0.002430
0.000071	0.004122	0.003500

Table B.2 Settling velocity of chalk particle in Sea water 10 ppt

Diameter (m.)	**Settling Velocity (Stokes' law)**	**Settling Velocity (image processing)**
0.000013	0.000130	0.000129
0.000018	0.000254	0.000247
0.000020	0.000326	0.000321
0.000021	0.000355	0.000350
0.000022	0.000393	0.000373
0.000023	0.000410	0.000380
0.000026	0.000517	0.000440
0.000030	0.000700	0.000620
0.000034	0.000911	0.000800
0.000043	0.001422	0.001200
0.000056	0.002457	0.002030
0.000069	0.003730	0.003100

Table B.3 Settling velocity of chalk particle in Sea water 20 ppt

Diameter (m.)	**Settling Velocity (Stokes' law)**	**Settling Velocity (Image processing)**
0.000016	0.000207	0.000212
0.000021	0.000327	0.000314
0.000022	0.000391	0.000350
0.000023	0.000408	0.000380
0.000024	0.000437	0.000402
0.000029	0.000672	0.000640
0.000035	0.000934	0.000767
0.000048	0.001791	0.001480
0.000060	0.002790	0.002130
0.000068	0.003616	0.002820
0.000072	0.003986	0.003250

Table B.4 Settling velocity of chalk particle in Sea water 35 ppt

Diameter (m)	**Settling Velocity (Stokes' law)**	**Settling Velocity (Image processing)**
0.000015	0.000182	0.000182
0.000018	0.000235	0.000205
0.000019	0.000277	0.000242
0.000021	0.000352	0.000310
0.000022	0.000387	0.000339
0.000023	0.000418	0.000390
0.000028	0.000604	0.000571
0.000037	0.001057	0.000909
0.000046	0.001625	0.001305
0.000057	0.002486	0.001826
0.000066	0.003315	0.002542
0.000072	0.003981	0.002910

2. Settling velocity of sediment particle

Table B.4 Settling velocity of chalk particle in deionised water

Diameter (mm)	Velocity from image processing (mm/s)
0.111	0.750
0.088	0.469
0.088	0.313
0.130	0.594
0.111	1.188
0.203	0.906
0.124	1.375
0.103	1.500
0.075	0.531
0.111	1.313
0.088	1.469
0.088	1.156
0.130	0.406
0.111	1.625
0.203	0.594

APPENDIX C

Settling velocity

1. Suspended solids removal (%) at natural condition

Table C.1 Suspended solids removal at natural condition duplicate1

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3017	30003.33	73.33	99.76
	10	25	15.3017	30003.33	56.67	99.81
	15	20	15.3017	30003.33	43.33	99.86
	20	15	15.3017	30003.33	36.67	99.88
	25	10	15.3017	30003.33	30.00	99.90
	30	5	15.3017	30003.33	26.67	99.91
12	5	30	15.3025	30004.90	70.00	99.77
	10	25	15.3025	30004.90	60.00	99.80
	15	20	15.3025	30004.90	53.33	99.82
	20	15	15.3025	30004.90	46.67	99.84
	25	10	15.3025	30004.90	43.33	99.86
	30	5	15.3033	30006.90	33.33	99.89
10	5	30	15.3074	30014.51	66.67	99.78
	10	25	15.3074	30014.51	63.33	99.79
	15	20	15.3074	30014.51	56.67	99.81
	20	15	15.3074	30014.51	53.33	99.82
	25	10	15.3074	30014.51	46.67	99.84
	30	5	15.3074	30014.51	40.00	99.87
8	5	30	15.3035	30006.86	86.67	99.71
	10	25	15.3035	30006.86	80.00	99.73
	15	20	15.3035	30006.86	76.67	99.74
	20	15	15.3035	30006.86	70.00	99.77
	25	10	15.3035	30006.86	60.00	99.80
	30	5	15.3035	30006.86	43.33	99.86
6	5	30	15.3076	30014.90	93.33	99.69
	10	25	15.3076	30014.90	90.00	99.70
	15	20	15.3076	30014.90	83.33	99.72
	20	15	15.3076	30014.90	73.33	99.76
	25	10	15.3076	30014.90	66.67	99.78
	30	5	15.3076	30014.90	50.00	99.83
4	5	30	15.3089	30017.45	116.67	99.61
	10	25	15.3089	30017.45	110.00	99.63
	15	20	15.3089	30017.45	93.33	99.69
	20	15	15.3089	30017.45	83.33	99.72
	25	10	15.3089	30017.45	76.67	99.74
	30	5	15.3089	30017.45	70.00	99.77

Table C.2 Suspended solids removal at natural condition duplicate2

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3049	30009.61	73.33	99.76
	10	25	15.3049	30009.61	60.00	99.80
	15	20	15.3049	30009.61	53.33	99.82
	20	15	15.3049	30009.61	43.33	99.86
	25	10	15.3049	30009.61	33.33	99.89
	30	5	15.3049	30009.61	26.67	99.91
12	5	30	15.3063	30012.35	73.33	99.76
	10	25	15.3063	30012.35	70.00	99.77
	15	20	15.3063	30012.35	66.67	99.78
	20	15	15.3063	30012.35	60.00	99.80
	25	10	15.3063	30012.35	53.33	99.82
	30	5	15.3063	30012.35	36.67	99.88
10	5	30	15.3022	30004.31	80.00	99.73
	10	25	15.3022	30004.31	73.33	99.76
	15	20	15.3022	30004.31	66.67	99.78
	20	15	15.3022	30004.31	63.33	99.79
	25	10	15.3022	30004.31	58.33	99.81
	30	5	15.3022	30004.31	43.33	99.86
8	5	30	15.3072	30014.12	93.33	99.69
	10	25	15.3072	30014.12	86.67	99.71
	15	20	15.3072	30014.12	80.00	99.73
	20	15	15.3072	30014.12	73.33	99.76
	25	10	15.3072	30014.12	63.33	99.79
	30	5	15.3072	30014.12	50.00	99.83
6	5	30	15.3054	30010.59	96.67	99.68
	10	25	15.3054	30010.59	90.00	99.70
	15	20	15.3054	30010.59	83.33	99.72
	20	15	15.3054	30010.59	76.67	99.74
	25	10	15.3054	30010.59	60.00	99.80
	30	5	15.3054	30010.59	53.33	99.82
4	5	30	15.3046	30009.02	120.00	99.60
	10	25	15.3046	30009.02	113.33	99.62
	15	20	15.3046	30009.02	86.67	99.71
	20	15	15.3046	30009.02	90.00	99.70
	25	10	15.3046	30009.02	80.00	99.73
	30	5	15.3046	30009.02	83.33	99.72

Table C.3 Suspended solids removal at natural condition duplicate3

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3020	30003.92	76.67	99.74
	10	25	15.3020	30003.92	63.33	99.79
	15	20	15.3020	30003.92	56.67	99.81
	20	15	15.3020	30003.92	53.33	99.82
	25	10	15.3020	30003.92	46.67	99.84
	30	5	15.3020	30003.92	36.67	99.88
12	5	30	15.3032	30006.27	80.00	99.73
	10	25	15.3032	30006.27	70.00	99.77
	15	20	15.3032	30006.27	60.00	99.80
	20	15	15.3032	30006.27	53.33	99.82
	25	10	15.3032	30006.27	50.00	99.83
	30	5	15.3032	30006.27	43.33	99.86
10	5	30	15.3075	30014.71	86.67	99.71
	10	25	15.3075	30014.71	73.33	99.76
	15	20	15.3075	30014.71	66.67	99.78
	20	15	15.3075	30014.71	60.00	99.80
	25	10	15.3075	30014.71	53.33	99.82
	30	5	15.3075	30014.71	46.67	99.84
8	5	30	15.3038	30007.45	93.33	99.69
	10	25	15.3038	30007.45	86.67	99.71
	15	20	15.3038	30007.45	83.33	99.72
	20	15	15.3038	30007.45	76.67	99.74
	25	10	15.3038	30007.45	66.67	99.78
	30	5	15.3038	30007.45	50.00	99.83
6	5	30	15.3079	30015.49	100.00	99.67
	10	25	15.3079	30015.49	96.67	99.68
	15	20	15.3079	30015.49	90.00	99.70
	20	15	15.3079	30015.49	80.00	99.73
	25	10	15.3079	30015.49	69.67	99.77
	30	5	15.3079	30015.49	56.67	99.81
4	5	30	15.3054	30010.59	123.33	99.59
	10	25	15.3054	30010.59	116.67	99.61
	15	20	15.3054	30010.59	100.00	99.67
	20	15	15.3054	30010.59	90.00	99.70
	25	10	15.3054	30010.59	83.33	99.72
	30	5	15.3054	30010.59	76.67	99.74

Table C.4 Suspended solids removal at natural condition average

Time (hr)	Elevation (cm)	Depth (cm)	Duplicate			Average	Stdev.	%RSD
			1	2	3			
24	5	30	99.76	99.76	99.74	99.75	0.0064	0.0064
	10	25	99.81	99.80	99.79	99.80	0.0111	0.0111
	15	20	99.86	99.82	99.81	99.83	0.0231	0.0232
	20	15	99.88	99.86	99.82	99.85	0.0280	0.0280
	25	10	99.90	99.89	99.84	99.88	0.0294	0.0294
	30	5	99.91	99.91	99.88	99.90	0.0192	0.0193
12	5	30	99.77	99.76	99.73	99.75	0.0170	0.0170
	10	25	99.80	99.77	99.77	99.78	0.0192	0.0193
	15	20	99.82	99.78	99.80	99.80	0.0222	0.0222
	20	15	99.84	99.80	99.82	99.82	0.0222	0.0222
	25	10	99.86	99.82	99.83	99.84	0.0170	0.0170
	30	5	99.89	99.88	99.86	99.87	0.0170	0.0170
10	5	30	99.78	99.73	99.71	99.74	0.0340	0.0340
	10	25	99.79	99.76	99.76	99.77	0.0192	0.0193
	15	20	99.81	99.78	99.78	99.79	0.0192	0.0192
	20	15	99.82	99.79	99.80	99.80	0.0170	0.0170
	25	10	99.84	99.81	99.82	99.82	0.0195	0.0196
	30	5	99.87	99.86	99.84	99.86	0.0111	0.0111
8	5	30	99.71	99.69	99.69	99.70	0.0128	0.0128
	10	25	99.73	99.71	99.71	99.72	0.0128	0.0128
	15	20	99.74	99.73	99.72	99.73	0.0111	0.0111
	20	15	99.77	99.76	99.74	99.76	0.0111	0.0111
	25	10	99.80	99.79	99.78	99.79	0.0111	0.0111
	30	5	99.86	99.83	99.83	99.84	0.0128	0.0128
6	5	30	99.69	99.68	99.67	99.68	0.0111	0.0111
	10	25	99.70	99.70	99.68	99.69	0.0128	0.0128
	15	20	99.72	99.72	99.70	99.71	0.0128	0.0128
	20	15	99.76	99.74	99.73	99.74	0.0111	0.0111
	25	10	99.78	99.80	99.77	99.78	0.0165	0.0165
	30	5	99.83	99.82	99.81	99.82	0.0111	0.0111
4	5	30	99.61	99.60	99.59	99.60	0.0112	0.0111
	10	25	99.63	99.62	99.61	99.62	0.0111	0.0111
	15	20	99.69	99.71	99.67	99.69	0.0222	0.0222
	20	15	99.72	99.70	99.70	99.71	0.0129	0.0129
	25	10	99.74	99.73	99.72	99.73	0.0111	0.0111
	30	5	99.77	99.72	99.74	99.74	0.0222	0.0223

2. Suspended solids removal (%) at acidic condition

Table C.5 Suspended solids removal at acidic condition duplicate1

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3030	30005.88	53.33	99.82
	10	25	15.3030	30005.88	33.33	99.89
	15	20	15.3030	30005.88	30.00	99.90
	20	15	15.3030	30005.88	26.67	99.91
	25	10	15.3030	30005.88	23.33	99.92
	30	5	15.3030	30005.88	16.67	99.94
12	5	30	15.3033	30006.47	80.00	99.73
	10	25	15.3033	30006.47	66.67	99.78
	15	20	15.3033	30006.47	63.33	99.79
	20	15	15.3033	30006.47	60.00	99.80
	25	10	15.3033	30006.47	56.67	99.81
	30	5	15.3033	30006.47	23.33	99.92
10	5	30	15.3028	30005.49	110.00	99.63
	10	25	15.3028	30005.49	83.33	99.72
	15	20	15.3028	30005.49	63.33	99.79
	20	15	15.3028	30005.49	63.33	99.79
	25	10	15.3028	30005.49	53.33	99.82
	30	5	15.3028	30005.49	46.67	99.84
8	5	30	15.3029	30005.69	116.67	99.61
	10	25	15.3029	30005.69	90.00	99.70
	15	20	15.3029	30005.69	76.67	99.74
	20	15	15.3029	30005.69	63.33	99.79
	25	10	15.3029	30005.69	60.00	99.80
	30	5	15.3029	30005.69	50.00	99.83
6	5	30	15.3028	30005.49	120.00	99.60
	10	25	15.3028	30005.49	100.00	99.67
	15	20	15.3028	30005.49	86.67	99.71
	20	15	15.3028	30005.49	73.33	99.76
	25	10	15.3028	30005.49	70.00	99.77
	30	5	15.3028	30005.49	56.67	99.81
4	5	30	15.3028	30005.49	120.00	99.60
	10	25	15.3028	30005.49	110.00	99.63
	15	20	15.3028	30005.49	96.67	99.68
	20	15	15.3028	30005.49	76.67	99.74
	25	10	15.3028	30005.49	73.33	99.76
	30	5	15.3028	30005.49	60.00	99.80

Table C.6 Suspended solids removal at acidic condition duplicate2

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3043	30008.43	106.67	99.64
	10	25	15.3043	30008.43	83.33	99.72
	15	20	15.3043	30008.43	80.00	99.73
	20	15	15.3043	30008.43	63.33	99.79
	25	10	15.3043	30008.43	50.00	99.83
	30	5	15.3043	30008.43	40.00	99.87
12	5	30	15.3044	30008.63	110.00	99.63
	10	25	15.3044	30008.63	90.00	99.70
	15	20	15.3044	30008.63	83.33	99.72
	20	15	15.3044	30008.63	66.67	99.78
	25	10	15.3044	30008.63	53.33	99.82
	30	5	15.3044	30008.63	46.67	99.84
10	5	30	15.3085	30016.67	113.33	99.62
	10	25	15.3085	30016.67	96.67	99.68
	15	20	15.3085	30016.67	86.67	99.71
	20	15	15.3085	30016.67	83.33	99.72
	25	10	15.3085	30016.67	70.00	99.77
	30	5	15.3085	30016.67	63.33	99.79
8	5	30	15.3067	30013.14	116.67	99.61
	10	25	15.3067	30013.14	100.00	99.67
	15	20	15.3067	30013.14	90.00	99.70
	20	15	15.3067	30013.14	86.67	99.71
	25	10	15.3067	30013.14	73.33	99.76
	30	5	15.3067	30013.14	70.00	99.77
6	5	30	15.3028	30005.49	123.33	99.59
	10	25	15.3028	30005.49	113.33	99.62
	15	20	15.3028	30005.49	106.67	99.64
	20	15	15.3028	30005.49	96.67	99.68
	25	10	15.3028	30005.49	86.67	99.71
	30	5	15.3028	30005.49	73.33	99.76
4	5	30	15.3041	30008.04	136.67	99.54
	10	25	15.3041	30008.04	126.67	99.58
	15	20	15.3041	30008.04	110.00	99.63
	20	15	15.3041	30008.04	103.33	99.66
	25	10	15.3041	30008.04	96.67	99.68
	30	5	15.3041	30008.04	86.67	99.71

Table C.7 Suspended solids removal at acidic condition duplicate3

Time (hr)	Elevation (cm)	Depth (cm)	Weight of soil (g)	Concentration of soil at C_0 (mg/L)	Concentration of soil at C_t (mg/L)	Suspended solids removal (%)
24	5	30	15.3043	30008.43	90.00	99.70
	10	25	15.3043	30008.43	73.33	99.76
	15	20	15.3043	30008.43	70.00	99.77
	20	15	15.3043	30008.43	56.67	99.81
	25	10	15.3043	30008.43	43.33	99.86
	30	5	15.3043	30008.43	30.00	99.90
12	5	30	15.3044	30008.63	100.00	99.67
	10	25	15.3044	30008.63	83.33	99.72
	15	20	15.3044	30008.63	73.33	99.76
	20	15	15.3044	30008.63	60.00	99.80
	25	10	15.3044	30008.63	46.67	99.84
	30	5	15.3044	30008.63	36.67	99.88
10	5	30	15.3085	30016.67	106.67	99.64
	10	25	15.3085	30016.67	90.00	99.70
	15	20	15.3085	30016.67	80.00	99.73
	20	15	15.3085	30016.67	70.00	99.77
	25	10	15.3085	30016.67	60.00	99.80
	30	5	15.3085	30016.67	50.00	99.83
8	5	30	15.3067	30013.14	110.00	99.63
	10	25	15.3067	30013.14	93.33	99.69
	15	20	15.3067	30013.14	83.33	99.72
	20	15	15.3067	30013.14	80.00	99.73
	25	10	15.3067	30013.14	66.67	99.78
	30	5	15.3067	30013.14	60.00	99.80
6	5	30	15.3028	30005.49	116.67	99.61
	10	25	15.3028	30005.49	106.67	99.64
	15	20	15.3028	30005.49	100.00	99.67
	20	15	15.3028	30005.49	90.00	99.70
	25	10	15.3028	30005.49	80.00	99.73
	30	5	15.3028	30005.49	66.67	99.78
4	5	30	15.3041	30008.04	130.00	99.57
	10	25	15.3041	30008.04	120.00	99.60
	15	20	15.3041	30008.04	103.33	99.66
	20	15	15.3041	30008.04	96.67	99.68
	25	10	15.3041	30008.04	90.00	99.70
	30	5	15.3041	30008.04	76.67	99.74

Table C.8 Suspended solids removal at acidic condition average

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Duplicate**			**Average**	**Stdev.**	**%RSD**
			1	**2**	**3**			
24	5	30	99.82	99.64	99.70	99.72	0.0909	0.0912
	10	25	99.89	99.72	99.76	99.79	0.0882	0.0883
	15	20	99.90	99.73	99.77	99.80	0.0882	0.0883
	20	15	99.91	99.79	99.81	99.84	0.0651	0.0652
	25	10	99.92	99.83	99.86	99.87	0.0462	0.0463
	30	5	99.94	99.87	99.90	99.90	0.0390	0.0390
12	5	30	99.73	99.63	99.67	99.68	0.0509	0.0511
	10	25	99.78	99.70	99.72	99.73	0.0400	0.0401
	15	20	99.79	99.72	99.76	99.76	0.0333	0.0334
	20	15	99.80	99.78	99.80	99.79	0.0128	0.0128
	25	10	99.81	99.82	99.84	99.83	0.0170	0.0170
	30	5	99.92	99.84	99.88	99.88	0.0390	0.0391
10	5	30	99.63	99.62	99.64	99.63	0.0111	0.0111
	10	25	99.72	99.68	99.70	99.70	0.0222	0.0222
	15	20	99.79	99.71	99.73	99.74	0.0400	0.0401
	20	15	99.79	99.72	99.77	99.76	0.0339	0.0340
	25	10	99.82	99.77	99.80	99.80	0.0279	0.0280
	30	5	99.84	99.79	99.83	99.82	0.0294	0.0294
8	5	30	99.61	99.61	99.63	99.62	0.0129	0.0129
	10	25	99.70	99.67	99.69	99.69	0.0169	0.0170
	15	20	99.74	99.70	99.72	99.72	0.0222	0.0222
	20	15	99.79	99.71	99.73	99.74	0.0400	0.0401
	25	10	99.80	99.76	99.78	99.78	0.0222	0.0222
	30	5	99.83	99.77	99.80	99.80	0.0333	0.0334
6	5	30	99.60	99.59	99.61	99.60	0.0111	0.0112
	10	25	99.67	99.62	99.64	99.64	0.0222	0.0223
	15	20	99.71	99.64	99.67	99.67	0.0339	0.0340
	20	15	99.76	99.68	99.70	99.71	0.0401	0.0402
	25	10	99.77	99.71	99.73	99.74	0.0280	0.0280
	30	5	99.81	99.76	99.78	99.78	0.0280	0.0280
4	5	30	99.60	99.54	99.57	99.57	0.0279	0.0281
	10	25	99.63	99.58	99.60	99.60	0.0279	0.0280
	15	20	99.68	99.63	99.66	99.66	0.0222	0.0223
	20	15	99.74	99.66	99.68	99.69	0.0462	0.0464
	25	10	99.76	99.68	99.70	99.71	0.0400	0.0402
	30	5	99.80	99.71	99.74	99.75	0.0449	0.0450

3. Suspended solids removal (%) at alkali condition

Table C.9 Suspended solids removal at alkali condition duplicate1

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3031	30006.08	346.67	98.84
	10	25	15.3031	30006.08	340.00	98.87
	15	20	15.3031	30006.08	296.67	99.01
	20	15	15.3031	30006.08	266.67	99.11
	25	10	15.3031	30006.08	260.00	99.13
	30	5	15.3031	30006.08	230.00	99.23
12	5	30	15.3026	30005.10	356.67	98.81
	10	25	15.3026	30005.10	336.67	98.88
	15	20	15.3026	30005.10	326.67	98.91
	20	15	15.3026	30005.10	323.33	98.92
	25	10	15.3026	30005.10	306.67	98.98
	30	5	15.3026	30005.10	243.33	99.19
10	5	30	15.3020	30003.92	383.33	98.72
	10	25	15.3020	30003.92	363.33	98.79
	15	20	15.3020	30003.92	336.67	98.88
	20	15	15.3020	30003.92	326.67	98.91
	25	10	15.3020	30003.92	316.67	98.94
	30	5	15.3020	30003.92	260.00	99.13
8	5	30	15.3060	30011.76	480.00	98.40
	10	25	15.3060	30011.76	450.00	98.50
	15	20	15.3060	30011.76	436.67	98.55
	20	15	15.3060	30011.76	386.67	98.71
	25	10	15.3060	30011.76	336.67	98.88
	30	5	15.3060	30011.76	263.33	99.12
6	5	30	15.3032	30006.27	623.33	97.92
	10	25	15.3032	30006.27	545.67	98.18
	15	20	15.3032	30006.27	493.33	98.36
	20	15	15.3032	30006.27	390.00	98.70
	25	10	15.3032	30006.27	340.00	98.87
	30	5	15.3032	30006.27	316.67	98.94
4	5	30	15.3038	30007.45	680.00	97.73
	10	25	15.3038	30007.45	616.67	97.94
	15	20	15.3038	30007.45	560.00	98.13
	20	15	15.3038	30007.45	486.67	98.38
	25	10	15.3038	30007.45	346.67	98.84
	30	5	15.3038	30007.45	326.67	98.91

Table C.10 Suspended solids removal at alkali condition duplicate2

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3062	30012.16	286.67	99.04
	10	25	15.3062	30012.16	273.33	99.09
	15	20	15.3062	30012.16	253.33	99.16
	20	15	15.3062	30012.16	240.00	99.20
	25	10	15.3062	30012.16	213.33	99.29
	30	5	15.3062	30012.16	183.33	99.39
12	5	30	15.3045	30008.82	296.67	99.01
	10	25	15.3045	30008.82	283.33	99.06
	15	20	15.3045	30008.82	260.00	99.13
	20	15	15.3045	30008.82	243.33	99.19
	25	10	15.3045	30008.82	223.33	99.26
	30	5	15.3045	30008.82	193.33	99.36
10	5	30	15.3073	30014.31	303.33	98.99
	10	25	15.3073	30014.31	286.67	99.04
	15	20	15.3073	30014.31	266.67	99.11
	20	15	15.3073	30014.31	246.67	99.18
	25	10	15.3073	30014.31	233.33	99.22
	30	5	15.3073	30014.31	213.33	99.29
8	5	30	15.3004	30000.78	316.67	98.94
	10	25	15.3004	30000.78	290.00	99.03
	15	20	15.3004	30000.78	270.00	99.10
	20	15	15.3004	30000.78	253.33	99.16
	25	10	15.3004	30000.78	243.33	99.19
	30	5	15.3004	30000.78	220.00	99.27
6	5	30	15.3035	30006.86	330.00	98.90
	10	25	15.3035	30006.86	296.67	99.01
	15	20	15.3035	30006.86	273.33	99.09
	20	15	15.3035	30006.86	256.67	99.14
	25	10	15.3035	30006.86	253.33	99.16
	30	5	15.3035	30006.86	223.33	99.26
4	5	30	15.3067	30013.14	336.67	98.88
	10	25	15.3067	30013.14	316.67	98.94
	15	20	15.3067	30013.14	290.00	99.03
	20	15	15.3067	30013.14	260.00	99.13
	25	10	15.3067	30013.14	236.67	99.21
	30	5	15.3067	30013.14	226.67	99.24

Table C.11 Suspended solids removal at alkali condition duplicate3

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3029	30005.69	326.67	98.91
	10	25	15.3029	30005.69	320.00	98.93
	15	20	15.3029	30005.69	270.00	99.10
	20	15	15.3029	30005.69	246.67	99.18
	25	10	15.3029	30005.69	233.33	99.22
	30	5	15.3029	30005.69	206.67	99.31
12	5	30	15.3024	30004.71	343.33	98.86
	10	25	15.3024	30004.71	323.33	98.92
	15	20	15.3024	30004.71	280.00	99.07
	20	15	15.3024	30004.71	250.00	99.17
	25	10	15.3024	30004.71	230.00	99.23
	30	5	15.3024	30004.71	223.33	99.26
10	5	30	15.3026	30005.10	360.00	98.80
	10	25	15.3026	30005.10	346.67	98.84
	15	20	15.3026	30005.10	323.33	98.92
	20	15	15.3026	30005.10	293.33	99.02
	25	10	15.3026	30005.10	273.33	99.09
	30	5	15.3026	30005.10	243.33	99.19
8	5	30	15.3063	30012.35	366.67	98.78
	10	25	15.3063	30012.35	356.67	98.81
	15	20	15.3063	30012.35	330.00	98.90
	20	15	15.3063	30012.35	316.67	98.94
	25	10	15.3063	30012.35	273.33	99.09
	30	5	15.3063	30012.35	250.00	99.17
6	5	30	15.3037	30007.25	373.33	98.76
	10	25	15.3037	30007.25	360.00	98.80
	15	20	15.3037	30007.25	340.00	98.87
	20	15	15.3037	30007.25	320.00	98.93
	25	10	15.3037	30007.25	296.67	99.01
	30	5	15.3037	30007.25	266.67	99.11
4	5	30	15.3034	30006.67	376.67	98.74
	10	25	15.3034	30006.67	366.67	98.78
	15	20	15.3034	30006.67	356.67	98.81
	20	15	15.3034	30006.67	330.00	98.90
	25	10	15.3034	30006.67	300.00	99.00
	30	5	15.3034	30006.67	280.00	99.07

Table C.12 Suspended solids removal at alkali condition average

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Duplicate**			**Average**	**Stdev.**	**%RSD**
			1	**2**	**3**			
24	5	30	98.84	99.04	98.91	98.93	0.1019	0.1030
	10	25	98.87	99.09	98.93	98.96	0.1141	0.1153
	15	20	99.01	99.16	99.10	99.09	0.0729	0.0736
	20	15	99.11	99.20	99.18	99.16	0.0463	0.0467
	25	10	99.13	99.29	99.22	99.22	0.0781	0.0787
	30	5	99.23	99.39	99.31	99.31	0.0778	0.0784
12	5	30	98.81	99.01	98.86	98.89	0.1051	0.1062
	10	25	98.88	99.06	98.92	98.95	0.0926	0.0936
	15	20	98.91	99.13	99.07	99.04	0.1141	0.1152
	20	15	98.92	99.19	99.17	99.09	0.1480	0.1493
	25	10	98.98	99.26	99.23	99.16	0.1544	0.1557
	30	5	99.19	99.36	99.26	99.27	0.0839	0.0845
10	5	30	98.72	98.99	98.80	98.84	0.1373	0.1389
	10	25	98.79	99.04	98.84	98.89	0.1346	0.1361
	15	20	98.88	99.11	98.92	98.97	0.1240	0.1253
	20	15	98.91	99.18	99.02	99.04	0.1341	0.1354
	25	10	98.94	99.22	99.09	99.09	0.1390	0.1403
	30	5	99.13	99.29	99.19	99.20	0.0789	0.0796
8	5	30	98.40	98.94	98.78	98.71	0.2787	0.2823
	10	25	98.50	99.03	98.81	98.78	0.2676	0.2709
	15	20	98.55	99.10	98.90	98.85	0.2811	0.2844
	20	15	98.71	99.16	98.94	98.94	0.2221	0.2245
	25	10	98.88	99.19	99.09	99.05	0.1586	0.1602
	30	5	99.12	99.27	99.17	99.19	0.0738	0.0744
6	5	30	97.92	98.90	98.76	98.53	0.5277	0.5356
	10	25	98.18	99.01	98.80	98.66	0.4313	0.4371
	15	20	98.36	99.09	98.87	98.77	0.3760	0.3806
	20	15	98.70	99.14	98.93	98.93	0.2223	0.2247
	25	10	98.87	99.16	99.01	99.01	0.1444	0.1459
	30	5	98.94	99.26	99.11	99.10	0.1557	0.1571
4	5	30	97.73	98.88	98.74	98.45	0.6257	0.6356
	10	25	97.94	98.94	98.78	98.56	0.5357	0.5435
	15	20	98.13	99.03	98.81	98.66	0.4688	0.4751
	20	15	98.38	99.13	98.90	98.80	0.3868	0.3915
	25	10	98.84	99.21	99.00	99.02	0.1841	0.1859
	30	5	98.91	99.24	99.07	99.07	0.1668	0.1684

4. Suspended solids removal (%) at low salinity condition (1% NaCl)

Table C.13 Suspended solids removal at low salinity condition (1% NaCl) duplicate1

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3024	30004.71	253.33	99.16
	10	25	15.3024	30004.71	246.67	99.18
	15	20	15.3024	30004.71	233.33	99.22
	20	15	15.3024	30004.71	230.00	99.23
	25	10	15.3024	30004.71	216.67	99.28
	30	5	15.3024	30004.71	203.33	99.32
12	5	30	15.3019	30003.73	300.00	99.00
	10	25	15.3019	30003.73	250.00	99.17
	15	20	15.3019	30003.73	236.67	99.21
	20	15	15.3019	30003.73	233.33	99.22
	25	10	15.3019	30003.73	220.00	99.27
	30	5	15.3019	30003.73	210.00	99.30
10	5	30	15.3018	30003.53	310.00	98.97
	10	25	15.3018	30003.53	276.67	99.08
	15	20	15.3018	30003.53	273.33	99.09
	20	15	15.3018	30003.53	263.33	99.12
	25	10	15.3018	30003.53	230.00	99.23
	30	5	15.3018	30003.53	216.67	99.28
8	5	30	15.3007	30001.37	313.33	98.96
	10	25	15.3007	30001.37	283.33	99.06
	15	20	15.3007	30001.37	280.00	99.07
	20	15	15.3007	30001.37	266.67	99.11
	25	10	15.3007	30001.37	260.00	99.13
	30	5	15.3007	30001.37	246.67	99.18
6	5	30	15.3020	30003.92	316.67	98.94
	10	25	15.3020	30003.92	286.67	99.04
	15	20	15.3020	30003.92	283.33	99.06
	20	15	15.3020	30003.92	270.00	99.10
	25	10	15.3020	30003.92	263.33	99.12
	30	5	15.3020	30003.92	276.67	99.08
4	5	30	15.3039	30007.65	353.33	98.82
	10	25	15.3039	30007.65	343.33	98.86
	15	20	15.3039	30007.65	336.67	98.88
	20	15	15.3039	30007.65	306.67	98.98
	25	10	15.3039	30007.65	300.00	99.00
	30	5	15.3039	30007.65	286.67	99.04

Table C.14 Suspended solids removal at low salinity condition (1% NaCl) duplicate2

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3038	30007.45	230.00	99.23
	10	25	15.3038	30007.45	203.33	99.32
	15	20	15.3038	30007.45	193.33	99.36
	20	15	15.3038	30007.45	183.33	99.39
	25	10	15.3038	30007.45	173.33	99.42
	30	5	15.3038	30007.45	163.33	99.46
12	5	30	15.3068	30013.33	243.33	99.19
	10	25	15.3068	30013.33	210.00	99.30
	15	20	15.3068	30013.33	193.33	99.36
	20	15	15.3068	30013.33	190.00	99.37
	25	10	15.3068	30013.33	176.67	99.41
	30	5	15.3068	30013.33	170.00	99.43
10	5	30	15.3036	30007.06	283.33	99.06
	10	25	15.3036	30007.06	253.33	99.16
	15	20	15.3036	30007.06	230.00	99.23
	20	15	15.3036	30007.06	203.33	99.32
	25	10	15.3036	30007.06	200.00	99.33
	30	5	15.3036	30007.06	176.67	99.41
8	5	30	15.3007	30001.37	303.33	98.99
	10	25	15.3007	30001.37	256.67	99.14
	15	20	15.3007	30001.37	246.67	99.18
	20	15	15.3007	30001.37	233.33	99.22
	25	10	15.3007	30001.37	210.00	99.30
	30	5	15.3007	30001.37	196.67	99.34
6	5	30	15.3092	30018.04	310.00	98.97
	10	25	15.3092	30018.04	270.00	99.10
	15	20	15.3092	30018.04	250.00	99.17
	20	15	15.3092	30018.04	233.33	99.22
	25	10	15.3092	30018.04	220.00	99.27
	30	5	15.3092	30018.04	206.67	99.31
4	5	30	15.3057	30011.18	316.67	98.94
	10	25	15.3057	30011.18	283.33	99.06
	15	20	15.3057	30011.18	260.00	99.13
	20	15	15.3057	30011.18	246.67	99.18
	25	10	15.3057	30011.18	240.00	99.20
	30	5	15.3057	30011.18	233.33	99.22

Table C.15 Suspended solids removal at low salinity condition (1% NaCl) duplicate3

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3040	30007.84	240.00	99.20
	10	25	15.3040	30007.84	216.67	99.28
	15	20	15.3040	30007.84	200.00	99.33
	20	15	15.3040	30007.84	190.00	99.37
	25	10	15.3040	30007.84	180.00	99.40
	30	5	15.3040	30007.84	170.00	99.43
12	5	30	15.3059	30011.57	250.00	99.17
	10	25	15.3059	30011.57	220.00	99.27
	15	20	15.3059	30011.57	206.67	99.31
	20	15	15.3059	30011.57	196.67	99.34
	25	10	15.3059	30011.57	183.33	99.39
	30	5	15.3059	30011.57	176.67	99.41
10	5	30	15.3035	30006.86	286.67	99.04
	10	25	15.3035	30006.86	260.00	99.13
	15	20	15.3035	30006.86	236.67	99.21
	20	15	15.3035	30006.86	210.00	99.30
	25	10	15.3035	30006.86	206.67	99.31
	30	5	15.3035	30006.86	183.33	99.39
8	5	30	15.3010	30001.96	313.33	98.96
	10	25	15.3010	30001.96	273.33	99.09
	15	20	15.3010	30001.96	256.67	99.14
	20	15	15.3010	30001.96	243.33	99.19
	25	10	15.3010	30001.96	220.00	99.27
	30	5	15.3010	30001.96	206.67	99.31
6	5	30	15.3085	30016.67	320.00	98.93
	10	25	15.3085	30016.67	276.67	99.08
	15	20	15.3085	30016.67	260.00	99.13
	20	15	15.3085	30016.67	246.67	99.18
	25	10	15.3085	30016.67	226.67	99.24
	30	5	15.3085	30016.67	220.00	99.27
4	5	30	15.3061	30011.96	330.00	98.90
	10	25	15.3061	30011.96	290.00	99.03
	15	20	15.3061	30011.96	273.33	99.09
	20	15	15.3061	30011.96	263.33	99.12
	25	10	15.3061	30011.96	256.67	99.14
	30	5	15.3061	30011.96	246.67	99.18

Table C.16 Suspended solids removal at low salinity condition (1% NaCl) average

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Duplicate**			**Average**	**Stdev.**	**%RSD**
			1	**2**	**3**			
24	5	30	99.16	99.23	99.20	99.20	0.0391	0.0394
	10	25	99.18	99.32	99.28	99.26	0.0740	0.0746
	15	20	99.22	99.36	99.33	99.30	0.0715	0.0720
	20	15	99.23	99.39	99.37	99.33	0.0842	0.0847
	25	10	99.28	99.42	99.40	99.37	0.0778	0.0783
	30	5	99.32	99.46	99.43	99.40	0.0715	0.0719
12	5	30	99.00	99.19	99.17	99.12	0.1034	0.1043
	10	25	99.17	99.30	99.27	99.24	0.0695	0.0700
	15	20	99.21	99.36	99.31	99.29	0.0741	0.0746
	20	15	99.22	99.37	99.34	99.31	0.0779	0.0784
	25	10	99.27	99.41	99.39	99.36	0.0779	0.0784
	30	5	99.30	99.43	99.41	99.38	0.0715	0.0720
10	5	30	98.97	99.06	99.04	99.02	0.0485	0.0490
	10	25	99.08	99.16	99.13	99.12	0.0401	0.0405
	15	20	99.09	99.23	99.21	99.18	0.0778	0.0785
	20	15	99.12	99.32	99.30	99.25	0.1097	0.1105
	25	10	99.23	99.33	99.31	99.29	0.0525	0.0529
	30	5	99.28	99.41	99.39	99.36	0.0715	0.0719
8	5	30	98.96	98.99	98.96	98.97	0.0192	0.0194
	10	25	99.06	99.14	99.09	99.10	0.0449	0.0453
	15	20	99.07	99.18	99.14	99.13	0.0570	0.0575
	20	15	99.11	99.22	99.19	99.17	0.0570	0.0575
	25	10	99.13	99.30	99.27	99.23	0.0882	0.0889
	30	5	99.18	99.34	99.31	99.28	0.0882	0.0888
6	5	30	98.94	98.97	98.93	98.95	0.0170	0.0172
	10	25	99.04	99.10	99.08	99.07	0.0282	0.0284
	15	20	99.06	99.17	99.13	99.12	0.0572	0.0577
	20	15	99.10	99.22	99.18	99.17	0.0621	0.0626
	25	10	99.12	99.27	99.24	99.21	0.0780	0.0786
	30	5	99.08	99.31	99.27	99.22	0.1241	0.1250
4	5	30	98.82	98.94	98.90	98.89	0.0619	0.0626
	10	25	98.86	99.06	99.03	98.98	0.1097	0.1108
	15	20	98.88	99.13	99.09	99.03	0.1366	0.1379
	20	15	98.98	99.18	99.12	99.09	0.1033	0.1042
	25	10	99.00	99.20	99.14	99.12	0.1033	0.1042
	30	5	99.04	99.22	99.18	99.15	0.0926	0.0933

5. Suspended solids removal (%) at high salinity condition (2% NaCl)

Table C.17 Suspended solids removal at high salinity condition (2% NaCl) duplicate1

Time (hr)	Elevation (cm)	Depth (cm)	Weight of soil (g)	Concentration of soil at C_0 (mg/L)	Concentration of soil at C_t (mg/L)	Suspended solids removal (%)
24	5	30	15.3013	30002.55	400.00	98.67
	10	25	15.3013	30002.55	396.67	98.68
	15	20	15.3013	30002.55	366.67	98.78
	20	15	15.3013	30002.55	350.00	98.83
	25	10	15.3013	30002.55	346.67	98.84
	30	5	15.3013	30002.55	333.33	98.89
12	5	30	15.3013	30002.55	396.67	98.68
	10	25	15.3013	30002.55	406.67	98.64
	15	20	15.3013	30002.55	396.67	98.68
	20	15	15.3013	30002.55	353.33	98.82
	25	10	15.3013	30002.55	350.00	98.83
	30	5	15.3013	30002.55	340.00	98.87
10	5	30	15.3022	30004.31	400.00	98.67
	10	25	15.3022	30004.31	410.00	98.63
	15	20	15.3022	30004.31	400.00	98.67
	20	15	15.3022	30004.31	363.33	98.79
	25	10	15.3022	30004.31	356.67	98.81
	30	5	15.3022	30004.31	346.67	98.84
8	5	30	15.3030	30005.88	450.00	98.50
	10	25	15.3030	30005.88	440.00	98.53
	15	20	15.3030	30005.88	420.00	98.60
	20	15	15.3030	30005.88	413.33	98.62
	25	10	15.3030	30005.88	403.33	98.66
	30	5	15.3030	30005.88	393.33	98.69
6	5	30	15.3032	30006.27	486.67	98.38
	10	25	15.3032	30006.27	443.33	98.52
	15	20	15.3032	30006.27	433.33	98.56
	20	15	15.3032	30006.27	416.67	98.61
	25	10	15.3032	30006.27	406.67	98.64
	30	5	15.3032	30006.27	390.00	98.70
4	5	30	15.3012	30002.35	496.67	98.34
	10	25	15.3012	30002.35	470.00	98.43
	15	20	15.3012	30002.35	463.33	98.46
	20	15	15.3012	30002.35	456.67	98.48
	25	10	15.3012	30002.35	446.67	98.51
	30	5	15.3012	30002.35	426.67	98.58

Table C.18 Suspended solids removal at high salinity condition (2% NaCl) duplicate2

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3082	30016.08	343.33	98.86
	10	25	15.3082	30016.08	340.00	98.87
	15	20	15.3082	30016.08	330.00	98.90
	20	15	15.3082	30016.08	323.33	98.92
	25	10	15.3082	30016.08	316.67	98.95
	30	5	15.3082	30016.08	306.67	98.98
12	5	30	15.3034	30006.67	346.67	98.84
	10	25	15.3034	30006.67	343.33	98.86
	15	20	15.3034	30006.67	336.67	98.88
	20	15	15.3034	30006.67	333.33	98.89
	25	10	15.3034	30006.67	323.33	98.92
	30	5	15.3034	30006.67	313.33	98.96
10	5	30	15.3015	30002.94	390.00	98.70
	10	25	15.3015	30002.94	386.67	98.71
	15	20	15.3015	30002.94	373.33	98.76
	20	15	15.3015	30002.94	360.00	98.80
	25	10	15.3015	30002.94	326.67	98.91
	30	5	15.3015	30002.94	320.00	98.93
8	5	30	15.3006	30001.18	403.33	98.66
	10	25	15.3006	30001.18	390.00	98.70
	15	20	15.3006	30001.18	376.67	98.74
	20	15	15.3006	30001.18	363.33	98.79
	25	10	15.3006	30001.18	350.00	98.83
	30	5	15.3006	30001.18	323.33	98.92
6	5	30	15.3068	30013.33	406.67	98.65
	10	25	15.3068	30013.33	393.33	98.69
	15	20	15.3068	30013.33	380.00	98.73
	20	15	15.3068	30013.33	366.67	98.78
	25	10	15.3068	30013.33	356.67	98.81
	30	5	15.3068	30013.33	330.00	98.90
4	5	30	15.3038	30007.45	406.67	98.64
	10	25	15.3038	30007.45	400.00	98.67
	15	20	15.3038	30007.45	383.33	98.72
	20	15	15.3038	30007.45	370.00	98.77
	25	10	15.3038	30007.45	360.00	98.80
	30	5	15.3038	30007.45	336.67	98.88

Table C.19 Suspended solids removal at high salinity condition (2% NaCl) duplicate3

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Weight of soil (g)**	**Concentration of soil at C_0 (mg/L)**	**Concentration of soil at C_t (mg/L)**	**Suspended solids removal (%)**
24	5	30	15.3010	30001.96	363.33	98.79
	10	25	15.3010	30001.96	356.67	98.81
	15	20	15.3010	30001.96	343.33	98.86
	20	15	15.3010	30001.96	333.33	98.89
	25	10	15.3010	30001.96	323.33	98.92
	30	5	15.3010	30001.96	316.67	98.94
12	5	30	15.3021	30004.12	383.33	98.72
	10	25	15.3021	30004.12	376.67	98.74
	15	20	15.3021	30004.12	370.00	98.77
	20	15	15.3021	30004.12	343.33	98.86
	25	10	15.3021	30004.12	330.00	98.90
	30	5	15.3021	30004.12	320.00	98.93
10	5	30	15.3025	30004.90	393.33	98.69
	10	25	15.3025	30004.90	390.00	98.70
	15	20	15.3025	30004.90	380.00	98.73
	20	15	15.3025	30004.90	366.67	98.78
	25	10	15.3025	30004.90	353.33	98.82
	30	5	15.3025	30004.90	343.33	98.86
8	5	30	15.3032	30006.27	416.67	98.61
	10	25	15.3032	30006.27	393.33	98.69
	15	20	15.3032	30006.27	390.00	98.70
	20	15	15.3032	30006.27	376.67	98.74
	25	10	15.3032	30006.27	373.33	98.76
	30	5	15.3032	30006.27	360.00	98.80
6	5	30	15.3035	30006.86	430.00	98.57
	10	25	15.3035	30006.86	420.00	98.60
	15	20	15.3035	30006.86	410.00	98.63
	20	15	15.3035	30006.86	396.67	98.68
	25	10	15.3035	30006.86	390.00	98.70
	30	5	15.3035	30006.86	376.67	98.74
4	5	30	15.3018	30003.53	433.33	98.56
	10	25	15.3018	30003.53	423.33	98.59
	15	20	15.3018	30003.53	413.33	98.62
	20	15	15.3018	30003.53	406.67	98.64
	25	10	15.3018	30003.53	400.00	98.67
	30	5	15.3018	30003.53	383.33	98.72

Table C.20 Suspended solids removal at high salinity condition (2% NaCl) average

Time (hr)	**Elevation (cm)**	**Depth (cm)**	**Duplicate**			**Average**	**Stdev.**	**%RSD**
			1	2	3			
24	5	30	98.67	98.86	98.79	98.77	0.0960	0.0972
	10	25	98.68	98.87	98.81	98.79	0.0973	0.0985
	15	20	98.78	98.90	98.86	98.84	0.0621	0.0628
	20	15	98.83	98.92	98.89	98.88	0.0451	0.0456
	25	10	98.84	98.95	98.92	98.90	0.0527	0.0533
	30	5	98.89	98.98	98.94	98.94	0.0451	0.0456
12	5	30	98.68	98.84	98.72	98.75	0.0864	0.0875
	10	25	98.64	98.86	98.74	98.75	0.1057	0.1070
	15	20	98.68	98.88	98.77	98.77	0.1003	0.1015
	20	15	98.82	98.89	98.86	98.86	0.0334	0.0338
	25	10	98.83	98.92	98.90	98.89	0.0463	0.0468
	30	5	98.87	98.96	98.93	98.92	0.0463	0.0468
10	5	30	98.67	98.70	98.69	98.69	0.0169	0.0172
	10	25	98.63	98.71	98.70	98.68	0.0420	0.0426
	15	20	98.67	98.76	98.73	98.72	0.0462	0.0468
	20	15	98.79	98.80	98.78	98.79	0.0111	0.0112
	25	10	98.81	98.91	98.82	98.85	0.0548	0.0554
	30	5	98.84	98.93	98.86	98.88	0.0484	0.0489
8	5	30	98.50	98.66	98.61	98.59	0.0800	0.0812
	10	25	98.53	98.70	98.69	98.64	0.0931	0.0944
	15	20	98.60	98.74	98.70	98.68	0.0739	0.0749
	20	15	98.62	98.79	98.74	98.72	0.0862	0.0873
	25	10	98.66	98.83	98.76	98.75	0.0890	0.0901
	30	5	98.69	98.92	98.80	98.80	0.1166	0.1180
6	5	30	98.38	98.65	98.57	98.53	0.1372	0.1393
	10	25	98.52	98.69	98.60	98.60	0.0835	0.0847
	15	20	98.56	98.73	98.63	98.64	0.0893	0.0905
	20	15	98.61	98.78	98.68	98.69	0.0840	0.0851
	25	10	98.64	98.81	98.70	98.72	0.0850	0.0861
	30	5	98.70	98.90	98.74	98.78	0.1051	0.1064
4	5	30	98.34	98.64	98.56	98.52	0.1542	0.1565
	10	25	98.43	98.67	98.59	98.56	0.1189	0.1206
	15	20	98.46	98.72	98.62	98.60	0.1348	0.1367
	20	15	98.48	98.77	98.64	98.63	0.1451	0.1471
	25	10	98.51	98.80	98.67	98.66	0.1447	0.1466
	30	5	98.58	98.88	98.72	98.73	0.1501	0.1521

6. Calculation V_C by Stokes' law

Table C.21 Calculation V_C by Stokes' law in Natural condition

%finer	Reynold number	diameter(cm)	V_C (cm/s)
99.70	0.0000015	0.00010	0.0001
99.60	0.0000250	0.00028	0.0008
99.50	0.0001000	0.00044	0.0020
99.45	0.0001400	0.00050	0.0025
99.40	0.0001900	0.00056	0.0031
99.30	0.0003200	0.00067	0.0043
99.20	0.0005500	0.00080	0.0062
99.10	0.0007900	0.00090	0.0079
99.00	0.0010900	0.00100	0.0098
98.90	0.0014400	0.00110	0.0118
98.80	0.0018500	0.00120	0.0139

Table C.22 Calculation V_C by Stokes' law in Acidic condition

%finer	Reynold number	Diameter (cm)	V_C (cm/s)
99.70	0.000001	0.00001	0.00007
99.65	0.000003	0.00017	0.00021
99.60	0.000012	0.00028	0.00054
99.50	0.000047	0.00044	0.00133

Table C.23 Calculation V_C by Stokes' law in Alkaline condition

%finer	Reynold number	Diameter (cm)	V_C (cm/s)
99.2	0.007650	0.00080	0.02944
99.1	0.012215	0.00090	0.04178
99.0	0.018560	0.00100	0.05714
98.9	0.027073	0.00110	0.07577
98.8	0.038190	0.00120	0.09798
98.7	0.052383	0.00130	0.12405
98.6	0.070130	0.00140	0.15422
98.5	0.091970	0.00150	0.18876
98.4	0.112740	0.00158	0.21967
98.3	0.150090	0.00170	0.27180
98.1	0.168050	0.00175	0.29563
98.0	0.187530	0.00180	0.32074
97.9	0.208610	0.00185	0.34715
97.8	0.231360	0.00190	0.37488
97.7	0.266175	0.00197	0.41596

Table C.24 Calculation V_C by Stokes' law in 1%NaCl condition

%finer	**Reynold number**	**Diameter (cm)**	**V_C (cm/s)**
99.40	0.000185	0.00056	0.0030
99.30	0.000310	0.00067	0.0042
99.20	0.000530	0.00080	0.0061
99.15	0.000630	0.00085	0.0068
99.10	0.000770	0.00090	0.0078
99.05	0.000890	0.00095	0.0086
99.00	0.001040	0.00100	0.0095
98.50	0.001190	0.00105	0.0104
98.90	0.001800	0.00120	0.0137
98.80	0.002910	0.00140	0.0190

Table C.25 Calculation V_C by Stokes' law in 2%NaCl condition

%finer	**Reynold number**	**Diameter (cm)**	**V_C (cm/s)**
98.9	0.001350	0.00110	0.0113
98.8	0.001740	0.00120	0.0134
98.7	0.002195	0.00130	0.0156
98.6	0.002760	0.00140	0.0182
98.5	0.003400	0.00150	0.0209
98.4	0.003960	0.00158	0.0231
98.3	0.004500	0.00165	0.0251

7. Calculation V_C by Dietrich equation

Table C.26 Calculation V_C by Dietrich equation in Natural condition

%finer	**D (cm)**	**S***	**V***	**Re**	**C_D**	**V_C (cm/s)**
99.70	0.00010	0.00152	0.0003383	2.06044E-06	11935867.31	0.000133
99.60	0.00028	0.00713	0.0015851	4.52308E-05	543918.9187	0.001044
99.50	0.00044	0.01405	0.0031226	0.000175517	140252.8366	0.002577
99.45	0.00050	0.01702	0.0037826	0.000257555	95603.12043	0.003327
99.40	0.00056	0.02018	0.0044835	0.000361847	68067.13504	0.004173
99.30	0.00067	0.02640	0.0058675	0.000619705	39766.13435	0.005970
99.20	0.00080	0.03445	0.0076555	0.001054946	23376.18792	0.008510
99.10	0.00090	0.04111	0.0091349	0.001502062	16427.43471	0.010770
99.00	0.00100	0.04815	0.0106990	0.002060442	11983.01129	0.013290
98.90	0.00110	0.05555	0.0123433	0.002742448	9008.884249	0.016070
98.80	0.00120	0.06329	0.0140642	0.003560443	6943.880933	0.019120

Table C.27 Calculation V_C by Dietrich equation in Acidic condition

%finer	**D (cm)**	**S***	**V***	**Re**	**C_D**	**V_C (cm/s)**
99.70	0.001528	0.001528	0.000339	2.0751E-06	11850117.66	0.00013
99.65	0.003387	0.003387	0.000752	1.0195E-05	2412381.326	0.00038
99.60	0.007159	0.007159	0.001590	4.5552E-05	540083.5207	0.00103
99.50	0.014102	0.014102	0.003133	0.00017676	139264.1538	0.00255

Table C.28 Calculation V_C by Dietrich equation in Alkaline condition

%finer	**D (cm)**	**S***	**V***	**Re**	**C_D**	**V_C (cm/s)**
99.2	0.00080	0.03456	0.00768	0.00106142	23233.91408	0.00841
99.1	0.00090	0.04123	0.00916	0.00151127	16327.48239	0.01063
99.0	0.00100	0.04829	0.01073	0.00207308	11910.12382	0.01313
98.9	0.00110	0.05572	0.01238	0.00275927	8954.105256	0.01588
98.8	0.00120	0.06348	0.01411	0.00358228	6901.673005	0.01889
98.7	0.00130	0.07158	0.01591	0.00455455	5432.244917	0.02216
98.6	0.00140	0.08000	0.01778	0.00568853	4352.608226	0.02569
98.5	0.00150	0.08872	0.01972	0.00699664	3541.578242	0.02948
98.4	0.00158	0.09591	0.02131	0.00817687	3032.33931	0.03270
98.3	0.00165	0.10236	0.02275	0.00931253	2664.079735	0.03565
98.2	0.00170	0.10704	0.02379	0.01018503	2436.881653	0.03783
98.1	0.00175	0.11180	0.02484	0.0111104	2234.86945	0.04008
98.0	0.00180	0.11663	0.02592	0.01209019	2054.645098	0.04240
97.9	0.00185	0.12152	0.02700	0.01312595	1893.346366	0.04477
97.8	0.00190	0.12648	0.02811	0.01421924	1748.550779	0.04722
97.7	0.00197	0.13353	0.02967	0.01584946	1569.699315	0.05074

Table C.29 Calculation V_C by Dietrich equation in 1% NaCl condition

%finer	**D (cm)**	**S***	**V***	**Re**	**C_D**	**V_C (cm/s)**
99.4	0.00056	0.02021	0.00449	0.000362981	67854.50086	0.004151
99.3	0.00067	0.02645	0.00588	0.000621648	39641.94338	0.005940
99.2	0.00080	0.03450	0.00767	0.001058255	23303.20926	0.008466
99.1	0.00080	0.04117	0.00915	0.001506773	16376.16467	0.010712
99.0	0.00100	0.04822	0.01072	0.002066904	11945.62404	0.013220
98.9	0.00120	0.06339	0.01409	0.003571611	6922.230605	0.019025
98.8	0.00140	0.07988	0.01775	0.005671585	4365.563357	0.025876

Table C.30 Calculation V_C by Dietrich equation in 2% NaCl condition

%finer	**D (cm)**	**S***	**V***	**Re**	**C_D**	**V_C (cm/s)**
99.4	0.00110	0.02021	0.00449	0.00036298	67854.50086	0.00415
99.3	0.00120	0.02645	0.00588	0.00062164	39641.94338	0.00594
99.2	0.00130	0.03450	0.00767	0.00105825	23303.20926	0.00847
99.1	0.00140	0.04117	0.00915	0.00150677	16376.16467	0.01071
99.0	0.00150	0.04822	0.01072	0.00206690	11945.62404	0.01322
98.9	0.00158	0.06339	0.01409	0.00357161	6922.230605	0.01902
98.8	0.00165	0.07988	0.01775	0.00567158	4365.563357	0.02588

APPENDIX D

Pb content in clarified effluent

Table D.1 Concentration of lead at natural condition

Detention time (hr)	**Depth (mm)**	**Concentration of lead (ppm)**		**Average (ppm)**	**std**
		#1	**#2**		
24	300	0.07	0.08	0.075	0.024954
	250	0.09	0.10	0.095	0.035422
	200	0.10	0.11	0.105	0.037159
	150	0.12	0.13	0.125	0.047700
	100	0.13	0.14	0.135	0.039484
	50	0.15	0.15	0.150	0.045422
12	300	0.04	0.04	0.040	0.012522
	250	0.06	0.06	0.060	0.019740
	200	0.07	0.08	0.075	0.027108
	150	0.09	0.09	0.090	0.034332
	100	0.11	0.12	0.115	0.046576
	50	0.14	0.14	0.140	0.056438
10	300	0.02	0.02	0.020	0.002698
	250	0.04	0.03	0.035	0.012069
	200	0.06	0.07	0.065	0.026203
	150	0.08	0.08	0.080	0.033173
	100	0.11	0.10	0.105	0.043282
	50	0.12	0.13	0.125	0.049548
8	300	0.02	0.02	0.020	0.007050
	250	0.03	0.02	0.025	0.010285
	200	0.05	0.03	0.040	0.019941
	150	0.06	0.03	0.045	0.024643
	100	0.09	0.07	0.080	0.038366
	50	0.10	0.09	0.095	0.044147
6	300	0.02	0.02	0.020	0.008731
	250	0.03	0.03	0.030	0.013171
	200	0.04	0.03	0.035	0.017505
	150	0.05	0.04	0.045	0.022698
	100	0.07	0.05	0.060	0.032089
	50	0.08	0.07	0.075	0.039170
4	300	0.01	0.01	0.010	0.003512
	250	0.01	0.02	0.015	0.007724
	200	0.02	0.02	0.020	0.008447
	150	0.02	0.03	0.025	0.012313
	100	0.02	0.03	0.025	0.012143
	50	0.03	0.03	0.030	0.013426

Table D.2 Concentration of lead at acidic condition

Detention time (hr)	Depth (mm)	Concentration of lead (ppm)			Std
		#1	#2	Average	
24	300	0.24	0.23	0.235	0.0139
	250	0.28	0.28	0.280	0.0219
	200	0.29	0.30	0.295	0.0179
	150	0.31	0.33	0.320	0.0230
	100	0.40	0.38	0.390	0.0547
	50	0.42	0.41	0.415	0.0577
12	300	0.21	0.22	0.215	0.0217
	250	0.25	0.24	0.245	0.0056
	200	0.27	0.27	0.270	0.0122
	150	0.30	0.31	0.305	0.0222
	100	0.34	0.32	0.330	0.0228
	50	0.36	0.35	0.355	0.0243
10	300	0.18	0.18	0.180	0.0040
	250	0.19	0.20	0.195	0.0100
	200	0.22	0.21	0.215	0.0183
	150	0.25	0.23	0.240	0.0160
	100	0.29	0.28	0.285	0.0098
	50	0.32	0.31	0.315	0.0051
8	300	0.16	0.17	0.165	0.0069
	250	0.17	0.18	0.175	0.0071
	200	0.18	0.20	0.190	0.0116
	150	0.21	0.22	0.215	0.0191
	100	0.29	0.27	0.280	0.0146
	50	0.30	0.28	0.290	0.0151
6	300	0.15	0.15	0.150	0.0062
	250	0.16	0.17	0.165	0.0059
	200	0.18	0.19	0.185	0.0120
	150	0.20	0.20	0.200	0.0116
	100	0.24	0.22	0.230	0.0134
	50	0.25	0.24	0.245	0.0055
4	300	0.13	0.14	0.135	0.0050
	250	0.15	0.16	0.155	0.0051
	200	0.16	0.17	0.165	0.0050
	150	0.18	0.19	0.185	0.0062
	100	0.22	0.20	0.210	0.0153
	50	0.24	0.23	0.235	0.0057

Table D.3 Concentration of lead at alkaline condition

Detention time (hr)	**Depth (mm)**	**Concentration of lead (ppm)**			**Std**
		#1	**#2**	**Average**	
24	300	0.05	0.05	0.050	0.0138
	250	0.07	0.06	0.065	0.0268
	200	0.08	0.07	0.075	0.0290
	150	0.09	0.09	0.090	0.0350
	100	0.11	0.10	0.105	0.0306
	50	0.12	0.11	0.115	0.0368
12	300	0.05	0.04	0.045	0.0223
	250	0.07	0.04	0.055	0.0327
	200	0.09	0.05	0.070	0.0420
	150	0.10	0.06	0.080	0.0459
	100	0.12	0.08	0.100	0.0583
	50	0.12	0.10	0.110	0.0581
10	300	0.03	0.03	0.030	0.0102
	250	0.05	0.04	0.045	0.0241
	200	0.06	0.05	0.055	0.0286
	150	0.08	0.08	0.080	0.0398
	100	0.10	0.09	0.095	0.0497
	50	0.11	0.11	0.110	0.0495
8	300	0.03	0.02	0.025	0.0156
	250	0.04	0.02	0.030	0.0213
	200	0.06	0.03	0.045	0.0349
	150	0.08	0.06	0.070	0.0469
	100	0.10	0.08	0.090	0.0597
	50	0.11	0.10	0.105	0.0590
6	300	0.02	0.01	0.015	0.0091
	250	0.02	0.02	0.020	0.0089
	200	0.03	0.03	0.030	0.0157
	150	0.04	0.06	0.050	0.0205
	100	0.06	0.08	0.070	0.0332
	50	0.08	0.10	0.090	0.0394
4	300	0.01	0.01	0.010	0.0037
	250	0.01	0.01	0.010	0.0029
	200	0.03	0.02	0.025	0.0152
	150	0.05	0.05	0.050	0.0287
	100	0.07	0.07	0.070	0.0409
	50	0.09	0.09	0.090	0.0520

Table D.4 Concentration of lead at 1% NaCl condition

Detention time (hr)	Depth (mm)	Concentration of lead (ppm)			Std
		#1	#2	Average	
24	300	0.09	0.10	0.095	0.0396
	250	0.12	0.15	0.135	0.0619
	200	0.14	0.15	0.145	0.0657
	150	0.15	0.17	0.160	0.0745
	100	0.16	0.17	0.165	0.0747
	50	0.17	0.18	0.175	0.0739
12	300	0.08	0.09	0.085	0.0433
	250	0.10	0.10	0.100	0.0514
	200	0.11	0.10	0.105	0.0531
	150	0.12	0.11	0.115	0.0570
	100	0.12	0.13	0.125	0.0600
	50	0.15	0.14	0.145	0.0709
10	300	0.08	0.08	0.080	0.0419
	250	0.09	0.08	0.085	0.0444
	200	0.10	0.09	0.095	0.0487
	150	0.10	0.09	0.095	0.0463
	100	0.12	0.11	0.115	0.0576
	50	0.15	0.13	0.140	0.0722
8	300	0.08	0.07	0.075	0.0407
	250	0.08	0.08	0.080	0.0416
	200	0.09	0.08	0.085	0.0442
	150	0.10	0.09	0.095	0.0494
	100	0.10	0.10	0.100	0.0505
	50	0.12	0.12	0.120	0.0616
6	300	0.07	0.06	0.065	0.0363
	250	0.07	0.07	0.070	0.0381
	200	0.08	0.07	0.075	0.0407
	150	0.09	0.08	0.085	0.0442
	100	0.11	0.09	0.100	0.0523
	50	0.11	0.10	0.105	0.0533
4	300	0.05	0.04	0.045	0.0265
	250	0.06	0.05	0.055	0.0321
	200	0.07	0.06	0.065	0.0373
	150	0.09	0.08	0.085	0.0486
	100	0.09	0.09	0.090	0.0503
	50	0.10	0.10	0.100	0.0559

Table D.5 Concentration of lead at 2% NaCl condition

Detention time (hr)	**Depth (mm)**	**Concentration of lead (ppm)**			**Std**
		#1	**#2**	**Average**	
24	300	0.17	0.15	0.160	0.074670
	250	0.18	0.16	0.170	0.077941
	200	0.18	0.16	0.170	0.075199
	150	0.21	0.18	0.195	0.087974
	100	0.22	0.20	0.210	0.085211
	50	0.23	0.22	0.225	0.038299
12	300	0.15	0.13	0.140	0.065110
	250	0.15	0.15	0.150	0.068239
	200	0.18	0.17	0.175	0.080524
	150	0.21	0.19	0.200	0.092394
	100	0.22	0.20	0.210	0.087925
	50	0.23	0.21	0.220	0.075664
10	300	0.11	0.10	0.105	0.048539
	250	0.12	0.11	0.115	0.051517
	200	0.14	0.12	0.130	0.058145
	150	0.17	0.14	0.155	0.071567
	100	0.19	0.16	0.175	0.078857
	50	0.22	0.18	0.200	0.069969
8	300	0.10	0.09	0.095	0.049339
	250	0.11	0.10	0.105	0.053100
	200	0.12	0.11	0.115	0.055992
	150	0.16	0.15	0.155	0.075674
	100	0.18	0.16	0.170	0.079304
	50	0.23	0.20	0.215	0.101851
6	300	0.10	0.09	0.095	0.051554
	250	0.11	0.09	0.100	0.054115
	200	0.11	0.10	0.105	0.054600
	150	0.15	0.11	0.130	0.068993
	100	0.18	0.13	0.155	0.081674
	50	0.22	0.18	0.200	0.101928
4	300	0.10	0.08	0.090	0.052915
	250	0.11	0.09	0.100	0.057097
	200	0.11	0.11	0.110	0.059676
	150	0.11	0.12	0.115	0.060363
	100	0.14	0.13	0.135	0.070837
	50	0.17	0.16	0.165	0.086000

BIOGRAPHY

Miss Ataya Jongwisuttisun was born on July 22, 1987 in Bangkok, Thailand. She had completed her secondly school (Grade XII) in 2004 from Benjamarachalai School. She had obtained the bachelor degree in B.Sc. (Microbiology) from Department of Microbiology, Faculty of Science, Chulalongkorn University in 2008. She and her colleagues had developed the senior project titled ‘Isolation of phenanthrene-degrading bacteria in seawater’. She had continued the master study in the international program in environmental management, Chulalongkorn University. She had spent a year period to develop this thesis, aiming to describe the behaviour of very tiny particles of silt, clay and lead ions under the change of electrical conductivity and pH water. She had been trained in the National Excellence Centre in Environmental and Hazardous Waste Management-King Mongkut’s University of Technology Satellite Centre and the Centre for Environment Risk Assessment and Remediation (CERAR), University of South Australia. Some part of her research had been published in the proceeding of The International Conference on Solid Waste 2011 Moving Towards Sustainable Resource Management (ICSW 2011).