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**THE PHYSICS AND
SEDIMENT CONTAINMENT PHENOMENON
OF A SILT SCREEN**

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
2013**

THE PHYSICS AND SEDIMENT CONTAINMENT PHENOMENON OF A SILT SCREEN

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ABSTRACT

Silt screens have been considered as the “best management practice” to contain or control the dispersal of sediment during dredging and reclamation. Although silt screens have been widely deployed, the effectiveness of silt screens in containing sediment is variable and uncertain, especially when the screen is deployed in open configuration.

In this study, the working mechanism of silt screens - i.e. how sediment is redistributed or otherwise contained around a silt screen - was investigated. The hydraulics and trajectories of flow and suspended sediment in the vicinity of a silt screen show that the movement of sediment about a silt screen is driven by three specific hydraulics characteristics. In the upstream retarded zone and downstream eddy zone, the dispersal of sediment is delayed. With the submerged jet-like flow formed in the lower water layer in the lee of the screen, entrainment and transport of sediment might take place. The characteristics of these flow patterns - the principle driver of sediment distribution - are governed by the incident flow velocity, screen penetration ratio, screen types, the vertical configuration of the silt screen and screen deflection angle.

Based on the findings of this study, it was deduced that for a silt screen to be effective in sediment containment, the desirable flow conditions must be established. These flow conditions include the following: (1) the upstream flow should be such that settlement takes place readily and (2) as the flow travels through the gap below the screen, the bed materials would not be entrained and transported downstream. Based on the findings of the simulation study on the flow and the trajectories of the tracer particles around the silt screens (using Discrete Particles Module in ANSYS FLUENT (version 11)), four parameters are found to be relevant in the design of a silt screen. They are: (1) the incident flow approaching the silt screen, (2) screen penetration ratio, (3) the length of the screen in the transverse direction, and (4) the distance between the silt screen and

the sediment source. The criteria of sediment containment in the screened area have also been established. The findings also revealed several limitations in the prevailing design practice, notable of which is the lack of consideration of important design parameters that influence flow distribution and sediment distribution around a silt screen. With respect to the performance of a silt screen, this study found that with the prevailing design practice, detention of sediment is limited. The study also found that there is a threshold incident flow velocity above which positive containment efficiency could not be achieved.

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LIST OF FREQUENTLY USED ABBREVIATIONS AND SYMBOLS

ADCP	Acoustic Doppler Current Profiler (<i>abbr.</i>)
SSC	suspended sediment concentration (ML^{-3}) (<i>abbr.</i>)
C	suspended sediment concentration (ML^{-3})
D	particle diameter (L)
d	particle diameter (L)
d_{50}	particle diameter which comprises 50% of the cumulative mass (L)
g	acceleration of gravity ($=9.81 \text{ m/s}^2$)
H	water depth (L)
L_s	length of the silt screen along the transverse direction (L)
L_{ns}	vertical penetration depth of a silt screen (L)
Q	flow rate (L^3T^{-1})
Q_s	sediment mass (MT^{-1})
Q_0	incident flow rate (L^3T^{-1})
q_s	sediment flux transport per unit width ($\text{ML}^{-1}\text{T}^{-1}$)
q_0	rate of the incident flow per metre width (M^2L^{-1})
q_{reverse}	rate of the reverse flow per metre width (M^2L^{-1})
$\text{rms}(u')$	root-mean-square value of horizontal velocity fluctuation
$\text{rms}(v')$	root-mean-square value of vertical velocity fluctuation
SPR	screen penetration ratio
u	horizontal velocity magnitude (LT^{-1})
u'	horizontal velocity fluctuation (LT^{-1})
U_{env}	environmental flow velocity (LT^{-1})
U_{gap}	gap velocity (LT^{-1})
U_0	incident flow velocity (LT^{-1})
v	vertical velocity magnitude (LT^{-1})
v'	vertical velocity fluctuation (LT^{-1})
x	distance from the silt screen along the longitudinal direction (L)
w_s	settling velocity (LT^{-1})
z	water depth (measured from the surface) (L)
α	screen deflection angle (in the vertical plane) ($^\circ$)
μ	dynamic viscosity ($\text{ML}^{-1}\text{T}^{-1}$)
μ_w	dynamic viscosity of water ($\text{ML}^{-1}\text{T}^{-1}$)
ρ	density of fluid (ML^{-3})
ρ_s	density of a sediment particle (ML^{-3})
ρ_w	density of water (ML^{-3})
ν_w	kinematic viscosity of water (L^2T^{-1})

1. Introduction

1.1 Motivation

Dredging and land reclamation activities in an aquatic environment typically generate suspended sediments which may spread and create undesirable impact to the environment. As a mitigation measure, silt screens have been deployed with the intention to contain a sediment cloud and limit the spreading of sediment to other areas, see Figure 1.1. A silt screen typically serves two main objectives: (1) to contain the suspended sediment arising from the dredging/land reclamation activity by completely surrounding the work site with a silt screen, and (2) to protect an environmentally sensitive area from the encroaching suspended sediment plume (Bray, 2008). A successful application of silt screens maintains an acceptable water quality in the area of interest. At the same time, the deployment of a silt screen should be structurally stable and not obstruct navigation traffic or other users (Francingues and Palermo, 2005).

Figure 1.1: An example of a silt screen deployment site. The objective of the silt screen at this specific site was to protect a nearby sensitive area.

Although it has been labeled as the “best management practice” to mitigate environmental impacts of dredging and reclamation activities, the performance of silt screens in sediment control is still debatable. There are reports that cite poor or variable performance of silt screens in containing the spreading of sediment. It is also widely acknowledged that the effectiveness of a silt screen is highly dependent on the deployment conditions, site conditions and the dredging/land reclamation methods used (Bray, 2008; de Wit et al., 2011; Elastec, 2004;

Francingues and Palermo, 2005). In a review on the application of silt screens, Francingues and Palermo (2005) discussed the uncertainty regarding silt screen deployment and recommended that "... silt screens should be selected only after careful evaluation of the intended function and designed based on a detailed knowledge of the site where they will be used ...". In practice, ineffective silt screens deployment not only resulted in wasted financial and manpower resources in maintaining the screens, but could also lead to adverse water quality in the aquatic environments. On the practice of silt screen deployments, several questions have not been addressed fully and they are:

- (1) Are silt screens effective?;
- (2) Under what conditions will silt screens deployment be efficacious?; and
- (3) How to design an effective silt screen system?

To date, the decision on deploying a silt screen is made mainly based on experience of the designers and operators. Although this approach could provide invaluable information, the method is not rigorous scientifically and the effectiveness has not been proven. Furthermore, because field data are not always published, publicly available information is limited and may not be representative. The author believes that the right approach to design an effective silt screen and successful deployment to contain sediment should be established based on the science of hydraulics and sediment transport in the presence of silt screens. Engineering knowledge must be established to address the following questions:

- (1) How does the suspended sediment redistribute around a silt screen?;
- (2) What are the factors controlling sediment movement in the vicinity of a silt screen?; and
- (3) Under what scenarios/ conditions could the hydraulics and sediment transport be modified to achieve the desirable outcome?

Unfortunately, among the publications about silt screens, little has been reported on either sediment movement or the flow patterns. The latter is undoubtedly the

primary driver of sediment dispersal in the aquatic environment. In the current silt screen design procedure, structural stability has been the major consideration while the resulting effects on containing the spreading of suspended sediment has been overlooked (Taiyo Kogyo, 2010). Sadly the science of sediment distribution around a silt screen remains largely unknown.

1.2 Objectives and scope

Recognizing the needs to reduce the uncertainties associated with the application of a silt screen, this study was initiated to tackle the unanswered questions on the science and practice of designing and deployment of silt screens in the aquatic environment.

First, this study aims to develop the knowledge on the physics of sediment movement around a silt screen. The approach taken was to establish the patterns of sediment movement around a silt screen through understanding the hydraulics and flow patterns in the vicinity of a silt screen.

Next, this study aims to address the questions listed earlier on the practice of silt screens deployment.

To achieve the research objectives discussed, the following works were conducted:

- Literature review of the current practice of silt screen design, deployment and monitoring in order to identify the shortcomings of the present design methodology and to determine the possible improvements of the current design methods;
- Analysis of the flow patterns and the respective sediment movement around a silt screen in order to identify the desirable flow environment that promotes successful containment of suspended sediment within the desired water body. The flow analysis was carried out based on laboratory experiments and

numerical hydrodynamic modeling. The sediment distribution patterns were established using numerical approach.

- Review of the current methods in monitoring the performance of silt screens, in particular the assessment criteria and monitoring approach.

1.3 Layout of the thesis

Chapter 2 is a comprehensive literature review on the development of screens over the past few decades and the operation of silt screens. Based on this literature review, the knowledge gaps are identified. In Chapter 3, the methodology adopted in this study is described. Chapter 4 elaborates the findings of the laboratory investigations, numerical simulation and field observations. Chapter 5 is a synthesis of the desirable flow conditions and the corresponding silt-screen configuration that could achieve the objective of containing the suspended sediment. The implications of the results on the research questions about the practice of silt screens deployment are also discussed. The conclusions of this study are presented in Chapter 6, followed by recommendations for further study in Chapter 7.

2. Literature Review

2.1 Introduction

In this section, a review of suspended sediment and its impact on water quality is presented. The mechanics of sediment transport is also reviewed. The physics of a silt screen in modifying the flow environment and in achieving containment of suspended sediment are presented. Based on the literature review, the following questions are addressed and gaps and key issues that have not been addressed comprehensively by the research community to date are identified.

With respect to the application of silt screens in containing the spread of suspended sediment, answers and solutions to the following questions are sought:

- What are the realistic and achievable objectives of deploying silt screens in the aquatic environment and how is the performance of a silt screen monitored?
- What are the challenges and difficulties that would be encountered in the deployment of silt screens?
- What are the known relationships between hydraulic flow conditions and sediment movement in the context of silt screens as a sediment containment structure?; and
- How is the performance/effectiveness of silt screens measured, and what is the achievable effectiveness? – What is the record of silt screens' performance?

2.2 Sediment and water quality

Sediment content is a major concern in water quality assessment (Anchor Environmental, 2001; Bray, 2008; Kuo and Hayes, 1991). Presence of suspended sediment typically implies increase in turbidity, and an increase in turbidity not only impairs the aesthetics of the water but also affects the production of algae and macrophytes as a result of the shallower depth of penetration of sunlight in the water column. Release of chemicals such as nitrogen and phosphorus adsorbed on the surface of sediment could also cause nutrient imbalance in the

water column and disturb the balance of the ecosystems. On the other hand, decreased dissolved oxygen induced by the oxygen demand attributable to sediment may impede healthy development of the habitat. Excessive sediment has been linked to upset of marine ecology (loss of fishing resources, changes in fish migration patterns, and loss of marine habitats such as coral reefs, etc) and social impacts (coastline alteration, loss of livelihood and human health concerns). Dredging operations may expose and release chemicals and metals adsorbed on the surface of sediment particles into the water column which may lead to undesirable consequences.

Knowing the potential environmental hazards related to high suspended sediment concentration, most dredging and reclamation operations require appropriate and adequate countermeasures to limit the spread and minimize the area affected by the operations. Three issues need to be addressed and they include:

- (1) chemical content of the water, i.e. toxicity consideration with respect to the presence of organics, metals and microorganisms content,
- (2) biological effects of the activity with respect to the well-being of the ecosystems, and
- (3) clarity of water.

With regard to clarity of water, U.K. Marine Association (2012) has set the requirement that 95% of the monitored area must reflect a minimum Secchi depth of 2 metres for fresh and saline water. The ASEAN Committee on Science and Technology stipulates a cap of maximum of 10% increase over the seasonal average concentration as the criterion for total suspended sediment (TSS) concentration in marine water (ASEAN, 2012). To assess the effects of dredging in Australia, Northey and van Renterghem (2008) adopted a limit of 50 mg/l of TSS and sediment deposition rate of less than 2 cm/ month. To assess the impact of construction on water quality for recreational purposes, the Australian and New Zealand authorities stipulated that the change in visual turbidity must be less than 20% for the water to be considered suitable for recreational purpose (Australian

Ministerial Councils, 2012). With regards to bio-ecosystems, Doorn-Groen and Foster (2007) considered a limit of exposure to sediment level exceeding 25 mg/l for no more than 20% of the time to preserve the well-being of corals. The limits of acceptable sediment deposition for seagrass and corals are 1.0 kg/m²/day, and 0.5 kg/m²/day, respectively. According to the guidelines for protection of shellfish populations in U.K., discharge to shellfish inhabited waters must not increase the concentration of suspended solids by more than 30% compared to that in unaffected water. These limits were established based on the acute and chronic effects of sediment on the ecosystems.

Typically for a dredging and reclamation work, silt screens are deployed to control sediment movement so as to satisfy the requirements on sediment level described above. Earlier, a decreased turbidity of 50 NTU was considered effective (Johanson, 1976). Today, sediment concentration and sediment flux have been used to assess the performance of a silt screen system. In field monitoring campaigns, suspended sediment concentration level or the sediment flux are measured at both sides of a silt screen. According to Bray (2008), a successful field monitoring campaign should include appropriate sampling techniques, frequency of sampling, sampling locations, number of samples and data analysis that elucidate the spatial and temporal extent of the turbidity cloud released during dredging and reclamation. The monitoring plan adopted in the case study discussed by Vu and Tan (2009) involved daily measurement of sediment distribution using an ADCP (mounted at the base of the hull, downward looking). Jin et al. (2004) deployed optical backscatterance sensors (OBS) to observe real-time suspended sediment concentration. De Wit et al. (2011) assessed the effects of a silt screen by measuring changes in sediment concentration and sedimentation rate over one year. The performance of a silt screen was assessed based on the reduction of a certain sediment parameter across the screen (de Wit et al., 2011; Jin et al., 2004).

In the current practice of monitoring the effectiveness of a silt screen, the distribution of sediment concentration in the stream-wise direction could be established based on measurements conducted at selected distances away from a silt screen. However, the vertical profiles of sediment concentration are typically ignored or not observed, making it difficult to establish a comprehensive picture of the distribution of sediment in the water column.

2.3 Sediment distribution in the vicinity of a silt screen

This section reviews the characteristics of suspended sediment profiles and the mechanics of sediment transport in an aquatic environment.

2.3.1 Characteristics of suspended sediment in a water column and in the vicinity of a silt screen

2.3.1.1 *Sediment released during dredging*

A dredging process, as described by Eisma (2006), includes four stages, starting with the dislodging of the material, where the sediment/ rock was excavated from the seabed. After being excavated, the materials would be transported upwards either mechanically (by backhoe, dipper, clam shell or bucket ladder dredgers) or hydraulically (by cutter-suction, for example). The process would then be followed by transport of the dredged material to an off-site location. In the final phase, the transported dredged material is deposited at the final disposal location. During the dislodging and excavation process, the sediment structure is disturbed and dredged material is released to the water column. The operation of the dredger head could create a “turbidity” plume near the bed while the release of the overflow from the dredger could contribute to the formation of a plume near the upper water layer.

By measuring the amount of sediment released at different dredging sites in the U.S.A., Anchor Environment (2004) estimated an average of 0.77%-2.1% of the dredged sediment being introduced into the water column during dredging. Pennekamp et al. (1996) listed the four most important factors that define the

characteristics of a turbidity plume resulting from sediment release during dredging: (1) the nature and mode of the activity, (2) the dredging equipment, (3) sensitivity of resuspension of the bed material, and (4) condition of the water column (water depth, current, etc.). Sediment released during dredging has been characterized using two parameters, namely: (1) the amount of sediment released, and (2) the distribution of suspended sediment concentration in the water column.

The first parameter, the mass of sediment released during dredging has been quantified using three approaches. Nakai (1978) represented the amount of the sediment released during dredging with the concept of turbidity generation unit (TGU) and suggested the values of TGU for some types of dredgers (see Appendix B). Pennekamp et al. (1996) quantified the sediment mass released from a dredging activity using a “suspension parameter”, which was defined as the mass of bed materials that could be re-suspended in the surface water per cubic metre of dredged bed. Based on field measurement of suspended sediment concentration distribution around a dredger, typical suspension rates for different types of dredgers and dredging techniques were suggested by the authors. These rates are included in Appendix B for easy reference. Using another approach, Hayes and Wu (2001) quantified resuspension of dry matter during dredging in terms of the percentage of the dry weight of the dredged material. The average resuspension rates were approximately 0.77% and 2.1% for hydraulic dredgers and mechanical dredgers accordingly.

In a water column, the released sediment is dispersed and the distribution is not uniform spatially. Figure 2.1 shows the vertical distribution of sediment mass released from a hopper dredger, a cutter-head dredger and a clamshell dredger as reported by Johnson and Pachure (1999). The proposed distributions implied the effects of dredger type and dredging operation on sediment released.

(a)

(b)

Figure 2.1: Proposed distributions of sediment mass for (a) a hopper dredger, (b) a cutterhead dredger, and (c) a clamshell dredger (adapted from Johnson and Pachure, 1999).

Sediment size is another parameter that influences the distribution of sediment in a water column. Both Collins (1995) and Pennekamp (1998) reported higher sediment concentration in the plume formed with silt or clay particles than that with sand or gravels. The spatial distribution of suspended sediment concentration measured at different field sites exhibited certain common features (Anchor

Environment, 2002; Collins, 1995; McLellan, 1989; Tavoraro, 1984), including the followings:

- the sediment profile shows higher sediment concentration near the bed compared to that at upper water layers;
- along the stream-wise direction, the sediment concentration decreases with distance from the dredger; and
- the near bed region typically is composed of suspended sediment of larger particle sizes compared to that in the upper layer.

2.3.1.2 *Sediment released during reclamation*

According to Teeter (2000), suspended materials are released from a sediment cloud during reclamation under the following four scenarios:

- (1) Spreading and/or stripping of materials at the water surface;
- (2) Gas entrained in the materials released during disposal;
- (3) Stripping of materials by the water column during descent; and
- (4) Entrainment of materials by the water column during underflow spreading.

According to the recorded data at several dumping sites, approximately 1%-5% of the dredged materials remained in the water column as suspended sediment (Gensheimer, 2010; Gordon, 1974; Susta and Wakeman, 1977; Tavoraro, 1984; Truitt, 1986). Compared to the literature on dredging, the characteristics of sediment released during dumping are less well known due to the lack of data on the sediment distribution at dumping sites (Pennekamp, 2011). Monitoring of sediment concentration distribution resulting from dumping of dredged materials showed that the sediment profiles observed upon release of dredged materials shared certain common characteristics, such as:

- The mass and concentration of sediment distribution in the water column depend on the type of the dredger used for the disposal. For example, when sediment is released using a mechanical dredger, higher percentage of suspended sediment is recorded near the bed. When a hydraulic dredger is employed, most of the discharged materials reside at the lower water layer

(Gailani, 2011). Compared to other types of dredging operations, the concentrations produced by hopper dredging exceeds that by cutter-head and clamshell operations by more than eight times (Nichols, 1990; Raymond, 1984);

- The magnitude of sediment concentration measured in the water column is related to particles size distribution, water depth, speed of dumping process, and the ambient flow characteristics. For example, lower concentration (approximately 10 mg/l) is observed when gravel makes up the majority of the content of the dumped materials, while when silt and clay are disposed, a concentration of 1000 mg/l could be recorded (Zimmermann, 2011);
- Higher concentration of sediment near the bed than that in the surface layer during a dumping activity (Nichols, 1990).

Using laboratory experiments and numerical simulation of the plume released from reclamation/ dumping operations, the relationship between the amount of suspended sediment and several parameters including the moisture content of the released materials, the location of discharge point, the water depth at the dumping site, volume of the dredged materials, and the fraction of clumps and the fraction of clay have been established (DeLeach and Waring, 1984; Ruggaber, 2000 and Svahnström, 2008). In a recent study on sediment loss in suspension during disposal of dredged materials, Gensheimer (2010) noted a correlation between the amount of sediment released and the magnitude of the velocity in the area - entrainment of sediment was enhanced in stronger flows. However, the current knowledge on sediment distribution provides little information on the temporal and spatial distributions of suspended sediment resulting from disposal of sediment in water. How sediment characteristics, flow parameters, and site specification affect the distribution of suspended sediment profiles have not been addressed. In addition, depending on sediment size and flow condition, the shape of a sediment profile may vary.

Figure 2.2 presents a schematic sketch of the typical sediment concentration profiles that could be observed in natural flows and the reported influence of sediment size on the profile shape. The typical sediment concentration profile of sand in an aquatic environment (shown in profiles 2.2 (a) and (b)) shows increasing sediment concentration with depth (Harris, 2003; Liu et al., 2007). In the presence of high concentration of silt, a more uniform sediment concentration profile (e.g. profile 2.2c) could be observed. Such a sediment distribution profile associated with high silt content was recorded in both laboratory experiments and field measurement of sediment concentration in rivers and estuaries (Fathi-Maghadam et al., 2011; Garcia, 2007; Green, 2000).

Figure 2.2: Typical suspended sediment concentration (SSC) profiles observed in alluvial streams

On the other hand, the shape of a sediment profile is also influenced by wave conditions, in particular wave height and wave period. William et al. (1999) observed larger wave heights yielded steeper suspended sediment concentration (SSC) profiles. Steeper SSC profiles were also noted during wave breaking (Nielsen, 1992; Wang et al., 2002). In an experiment simulating a surf zone, Kos'yan et al. (2006) measured the sediment distribution along a transect at 30 cm above the sea bed and observed four types of instantaneous vertical SSC profiles; these are presented in Figure 2.3.

Figure 2.3: Typical instantaneous SSC profiles recorded in coastal water (adapted from Kos'yan et al., 2006)

Notably, the profile described in Figure 2.3(d) deviates from the conventional profile shape, with lower suspended sediment concentration detected at the bottom. As noted in the literature, such an irregular SSC profile could be formed under three circumstances:

- when high waves are present in the water area, as reported in Kos'yan et al. (2006);
- when there is a heavy load of sediment injected at the upper layer of the water column, as described by Fredsøe and Deigaard (1992) and recorded in the study by Le et al. (2006) (Fredsøe and Deigaard, 1992; Le et al. 2006); and
- when sediment in the lower water layer is flushed under suction effect, as suggested by Fredsøe and Deigaard (1992).

2.3.2 Sediment in a water column

2.3.2.1 Physics of sediment movement in flow

The forces acting on a particle in suspension include drag F_D , lift F_L , buoyancy F_B , and gravity force W_s , as illustrated in Figure 2.4. A particle on the bed also experiences friction force and reaction from the bed on the particle.

Figure 2.4: A schematic sketch of forces exerting on a suspended particle in flow

The magnitudes of the above mentioned forces on a suspended particle could be estimated as:

$$F_D = \frac{1}{2} c_D \rho A U_r^2 \quad (\text{Equation 2.1})$$

$$F_B = V_p \rho g \quad (\text{Equation 2.2})$$

$$W_s = V_p \rho_s g \quad (\text{Equation 2.3})$$

The lift force F_L is a function of the flow regime and the Reynolds number of the flow (van Rijn, 1984). For viscous flow in the low Reynolds number regime, the lift force could be estimated as

$$F_L = \alpha_L \rho \nu^{0.5} D^2 U_r \left(\frac{\partial u}{\partial z} \right)^{0.5} \quad \text{with } \alpha_L = 1.6 \text{ (Saffman, 1937).} \quad (\text{Equation 2.4})$$

When spinning motion is involved, the lift force could be estimated based on the following equation which was suggested by Rubinow and Keller (1972):

$$F_L = 0.4 \rho D^3 U_r \omega_p \quad (\text{Equation 2.5})$$

In the above equations, c_D is the drag coefficient, A is the cross-sectional area of the particle, V_p is the volume of the particle, U_r refers to the relative velocity approaching the particle; u denotes the local velocity, z is the water depth, ρ is the density of the fluid (e.g. water), ρ_s is the density of the sediment particle, g is

the acceleration of gravity (9.81 m/s^2), ν is the kinematic viscosity, D is the sediment grain size and ω_p denotes the angular velocity of the particle (in the case of spinning) (van Rijn, 1984).

2.3.2.2 *Transport of sediment*

The sediment in flow could be transported either as bed load or suspended load. In the bed load mode, the sediment particles roll, slide, or “jump” along the bed (saltation). Yang (1996) estimated that bed load constitutes about 5-25% of the total transport in a river. The actual amount may vary depending on the sediment size and characteristics of the sites.

By definition, the two types of sediment transport - bed load and suspended load - are classified based on the mode of sediment movement during transport. Bagnold (1956) defined bed load as the successive contacts of the particles, which were driven by gravity while the suspended load transport was defined based on the effects of turbulent eddies. In another approach as suggested by Einstein (1944), bed load was defined as the transport of particles in a thin layer of two-particle diameters thickness above the bed through sliding, rolling and saltation. There is an extensive collection of methods that could be used to estimate the sediment transport rate under equilibrium conditions. This equilibrium state, which includes no net erosion or deposition, is termed sediment transport capacity and represents the largest amount of sediment that the flow could carry (Wilcock, 2004). Bed load transport can be represented as a function of the shear stress and sediment and flow characteristics as shown in Equation 2.6.

$$q_{s,b} = f(\tau, H, D, \rho_s, \rho_w, \mu_w, g) \quad (\text{Equation 2.6})$$

where $q_{s,b}$ is the bed load transport, τ is the bed shear stress, H refers to the water depth, D is the particle size, ρ_s is the density of the sediment particle, ρ_w is the density of water, μ_w is the dynamic viscosity of water, and g is the acceleration of gravity.

In another approach, the sediment transport capacity has also been frequently related to flow discharge (Harris, 2003; Wilcock, 2004). Equation 2.7 shows a relationship between sediment mass and flow rate, also known as sediment rating curve (Wilcock, 2004):

$$Q_s = aQ^b \quad (\text{Equation 2.7})$$

In the above equation, Q_s and Q refer to the sediment transport load and the flow rate respectively, while a and b are coefficients that need to be calibrated for different conditions of river geometry, sediment characteristics, etc.

Appendix C contains examples of the established formulae that have been used to estimate suspended sediment transport in the water. Most of the formulae were established based on one or more of the three main approaches: (1) energy approach, (2) diffusion approach, and (3) stochastic approach. In the energy approach, the sediment load in the flow is expressed as a function of energy. This method was first proposed by Bagnold (1966), who estimated the suspended load based on the work done by the fluid to keep the load in suspension. More recently, Celik and Rodi (1991) developed a formula that relates sediment transport rate as a function of turbulent kinetic energy. In their approach, the suspended sediment load per unit width q_s can be estimated from the flow rate per unit width of the channel q according to the relationship

$$q_s = C_T q \quad (\text{Equation 2.8})$$

in which the mean transport coefficient C_T is a function of turbulent kinetic energy. Celik and Rodi (1991) claimed that the approach worked well for flows with small sediment concentration (i.e. less than 10% by volume).

In the diffusion approach, the hypothesis is that suspension would persist if the sediment's settling velocity w_s is not larger than the turbulence fluctuation component of the vertical velocity w' . The vertical distribution of suspended

sediment in the water could be mathematically described by using the following equation:

$$Cw_s + \varepsilon_s \frac{dC}{dz_b} = 0 \quad (\text{Equation 2.9})$$

where C refers to the local suspended sediment concentration recorded at water depth z (from the water surface) or z_b (measured from the mean bed), w_s is the settling velocity of the particle and ε_s is the sediment diffusion coefficient. In high concentration mixture, the settling velocity is also affected by the sediment concentration according to the following equation (Mehta, 1986, Richardson and Zaki, 1954):

$$w_{s,mixture} = w_{s,clear}(1 - k_w C)^\gamma \quad (\text{Equation 2.10})$$

where $w_{s,mixture}$ is the settling velocity of a particle in a mixture, $w_{s,clear}$ is the settling velocity of the particle in clear fluid, k_w is a coefficient that depends on sediment composition, and γ is a coefficient. According to Zhou and Cheng (2009), in turbulent flow, the settling velocity w_s was reduced compared to that in quiescent flow and such reduction was a function of the root-mean-square of the vertical velocity.

From Equation 2.9, if the sediment diffusion coefficient ε_s is estimated according to a parabolic function, the vertical sediment concentration profile at equilibrium in an alluvial flow is described with the well-known Rouse equation:

$$\frac{C(z_b)}{C_a} = \left[\frac{a_r(H - z_b)}{z_b(H - a_r)} \right]^Z \quad (\text{Equation 2.11})$$

where z_b is the height above the mean bed, H is the depth, a_r refers to the reference level which has the reference concentration C_a . The parameter Z is the suspension parameter, and is related to particle fall velocity, shear velocity and particles diffusion coefficient as seen in Equation 2.12:

$$Z = \frac{w_s}{\beta \kappa u_*} \quad (\text{Equation 2.12})$$

In Equation 2.12, κ is the von-Karman constant, u_* denotes the shear velocity and β is a coefficient that describes the difference in the diffusion of a fluid particle and a discrete sediment particle. The suspension number Z , also known as Rouse parameter, is closely related to the shape of the SSC profile (García, 2007; Harris, 2003; van Rijn, 1993). According to van Rijn (1993), the value of Z was related to the distribution of suspended sediment load along the water depth, as seen in Table 2.1.

Table 2.1: Suspension parameter and suspended sediment distribution along the depth (adopted from van Rijn, 1993)

$Z = \frac{w_s}{\beta \kappa u_*}$	$\frac{u_*}{w_s} (\kappa=0.4; \beta=1)$	Suspended sediment distribution along the depth
5	0.5	Most of the suspended sediment is found in near-bed layer ($z_b < 0.1H$)
2	1.25	Most of the suspended sediment concentrated is found up to mid-depth of the water column
1	2.5	Suspended sediment is found along the water depth
0.1	25	Suspended sediment almost uniformly distributed over the depth

Based on the measured sediment and fluid momentum diffusion coefficients reported by Vanoni (1946), for fine particles, $\varepsilon_m \approx \varepsilon_s$ and $\beta \approx 1$. However, for coarse particles, $\varepsilon_m < \varepsilon_s$ and $\beta < 1$. Chien (1954) summarized the variation of β based on measurements in flume experiments and rivers.

According to van Rijn (2007), the reference concentration C_a in Equation 2.11 can be estimated according to the following equation:

$$C_a = 0.015(1 - p_{clay})f_{silt} \frac{d_{50} T_b^{1.5}}{a_r D_*^{0.3}} \text{ with } C_a \leq 0.05 \quad (\text{Equation 2.13})$$

where d_{50} is the median particle size, f_{silt} is the silt factor ($f_{silt} = d_{sand}/d_{50}$ or $f_{silt} = 1$ if $d_{50} < d_{sand} = 62\mu m$), a_r is the reference level, p_{clay} is the clay content in the sediment, T_b is the dimensionless bed shear stress parameter and D_* is the dimensionless particle size parameter. D_* and T_b are determined based on Equation 2.14 and Equation 2.15:

$$D_* = d_{50} \left[\left(\frac{\rho_s}{\rho_w} - 1 \right) \frac{g}{v_w^2} \right]^{1/3} \quad (\text{Equation 2.14})$$

where ρ_s is the density of the sediment particle, ρ_w is the density of water, and v_w is the kinematic viscosity of water.

$$T_b = (\tau'_{b,c} - \tau_{b,c}) / \tau_{b,c} \quad (\text{Equation 2.15})$$

In Equation 2.15, $\tau_{b,c}$ is the critical bed shear stress according to Shields and $\tau'_{b,c}$ is the effective shear stress which can be calculated based on the depth average velocity $\bar{V}$ according to the following equation:

$$\tau'_{b,c} = \rho_w g \left(\frac{\bar{V}}{c'} \right)^2 \quad (\text{Equation 2.16})$$

in which the coefficient c' can be estimated based on the water depth H and the particle size d_{90} according to Equation 2.17:

$$c' = 18 \log(12H / 3d_{90}) \quad (\text{Equation 2.17})$$

The reference level a_r , according to van Rijn (1993), could be estimated as half the bed-form height or the equivalent bed roughness. The minimum value of the reference level should be 0.01 times of the flow depth.

Another commonly used reference concentration relationship was that proposed by Smith and McLean (1977), where the reference concentration is estimated based on Equation 2.18:

$$C_a = 0.65 \frac{\gamma_0 S_{s0}}{1 + \gamma_0 S_{s0}} \quad (\text{Equation 2.18})$$

where $\gamma_0 = 2.4 \times 10^{-3}$ and $S_{s0} = \frac{\tau_b - \tau_{b,c}}{\tau_{b,c}}$ (Equation 2.19). In Equation 2.19, τ_b refers

to the bed shear stress, $\tau_{b,c}$ is the critical bed shear stress for incipient motion of the sediment.

According to Smith and McLean (1977), the reference level a_r could be defined according to the following equation:

$$a_r = 26.3(\tau_b - \tau_{b,c})/[(\rho_s - \rho_w)g] + k_s \quad (\text{Equation 2.20})$$

where ρ_s is the density of the sediment particle, ρ_w is the density of water, g is the acceleration of gravity, τ_b refers to the bed shear stress, $\tau_{b,c}$ is the critical bed shear stress for incipient motion of the sediment and k_s is the bed roughness.

Several other formulae were proposed to estimate the reference concentration, including those published by Garcia and Parker (1991) and Engelund and Fredsøe (1982).

With known C_a and a_r , the suspended sediment profile can be defined according to Equation 2.11. With known concentration distribution, the suspended load per unit width, q_s , could be estimated using the equation:

$$q_s = \rho_s \int_{a_r}^H V(z_b) C(z_b) dz_b \quad (\text{Equation 2.21})$$

In Equation 2.21, H denotes the water depth, ρ_s is the density of the sediment particles, $V(z)$ is the local flow velocity, C refers to the local suspended sediment concentration recorded at water depth z_b (measured from the mean bed), and a_r is the reference level, from which suspended sediment is estimated. In Appendix C, examples of the developed formulae to estimate suspended load are given.

In the case of stochastic approach, the movement of a particle is computed as the sum of an advective deterministic component and an independent random component which represents the random mixing (Dimou and Adams, 1993; Man

and Tsai, 2007). In the random walk analogy developed by Dimou and Adams (1993), the movement of a particle could be determined by using the equations below:

$$\Delta x = \left[u + \frac{\partial D_{xx}}{\partial x} + \frac{D_{xx}}{H} \frac{\partial H}{\partial x} \right] \Delta t + \sqrt{2D_{xx}\Delta t} Z_{n1} \quad (\text{Equation 2.22})$$

$$\Delta y = \left[v + \frac{\partial D_{yy}}{\partial y} + \frac{D_{yy}}{H} \frac{\partial H}{\partial y} \right] \Delta t + \sqrt{2D_{yy}\Delta t} Z_{n2} \quad (\text{Equation 2.23})$$

in which Δx and Δy refer to the change in the position of the particle in x and y directions respectively, D_{xx} and D_{yy} refer to the dispersion coefficients along the longitudinal and vertical directions, Z_{n1} and Z_{n2} are two independent random numbers with zero mean and unit variance, Δt is the time step applied, u and v are the average flow velocities in x and y direction respectively, and H is the water depth (Dimou and Adams, 1993). The stochastic method was also used to determine the transport/erosion of particles as in the study published by Lisle et al. (1998).

The above formulae were developed to estimate sediment transport in current-dominated conditions. Sediment transport under wave and wave-current conditions requires different treatment. To account for the combined effects of waves and currents, Bailard (1981) modified Bagnold's transport equation and proposed a number of formulae for the corresponding transport and shear stress distribution under wave and current. The flow velocity is treated as the sum of both the mean component and the oscillatory component, see Bailard (1981). The inclusion of the instantaneous velocity component was also adopted in the transport formula proposed by Dibajnia and Watanabe (1992). To account for the effects of combined wave and currents, Bijker (1968) and van Rijn (1984, 2007) modified the relevant parameters in the transport formulae developed for alluvial flow. For example, van Rijn (2007) determined the sediment mixing coefficient from two components – wave-related mixing coefficient and current-related mixing coefficient. The effects of wave were also accounted for in the estimation

of bed roughness and the magnitude of time-averaged bed shear stress (van Rijn, 1993, 2007). In another attempt to estimate sediment transport under wave conditions, Ribberink (1993) assumed that the transport rate was quasi-steady, i.e. the instantaneous sediment flux was proportional to the difference between the actual shear stress and the time-average critical shear stress. As observed by Camenen et al. (2003), the applicability of the different sediment transport formulae developed for wave-current conditions depends on sediment size, current and wave condition (velocity, period, asymmetry).

2.4 Flow characteristics – the principle driver of sediment movement

Previous researches showed that the movement of sediment around hydraulic structures was closely related to the distribution of flow patterns. Odgaard and Mosconi (1987) observed that vortical flow in the lee of submerged vanes enhanced local trapping of sediment. Odgaard and Wang (1991a, 1991b) and Ouyang (2009) attributed the capacity of a submerged vane on sediment control to the effects of circulation zones, and the magnitude and direction of the bed shear stress. Tan et al. (2005) observed that the flow structures around a submerged vane consisted of “the interactions among the lower flow, the upper through flow, the helical flows and large eddies”. Such flow structures led to sediment deposition in the immediate frontal zone of the vane, bed scouring around the vane, and divergence of sediment particles (Tan et al., 2005). The effects of vertical flow on sediment trapping was again emphasized by Li and Yu (2009), who observed the influence of circulations on the deposition of sediment in the lee of a submerged curtain used for sediment control.

Lauchlan (2004) examined the effects of flow patterns on the change of bed level around a weir. Her observations suggested that in the presence of a weir, by changing the distribution of slope along the channel, shear stress distribution was altered, resulting in different sediment distribution patterns. Other researchers

also discussed enhanced sediment erosion under the effects of fast flow (e.g. jet flow, dam break flow) (Dey et al., 2000; van Rhee, 2010).

2.4.1 Flow patterns in the vicinity of a silt screen

In the literature, there were only a handful of publications on the hydraulics and flow patterns around a silt screen. Johanson (1976) and JBF Corporation (1978) observed that around a silt screen (shown in Figure 2.5), higher flow velocity was recorded at the lower depth and there was a decrease in the depth-averaged current velocity across the screen. Reduced average velocity downstream of silt screens was also reported by Yasui et al. (1999) and Jin et al. (2003). Nevertheless, from related publications, little could be concluded about the distribution of flow patterns around a silt screen, and of flow velocity and turbulence, which are the principle hydraulics parameters for evaluating the sediment transport phenomenon in the vicinity of the structure.

Figure 2.5: Schematic drawing of the deployment of a silt screen in water

2.4.2 Flow around thin hydraulic structures

As the thickness of a silt screen is negligible compared to the length and width (as can be seen in Figure 2.5), silt screens represent a type of thin hydraulic structures. Flow characteristics around thin hydraulic structures such as oil booms, screen structures, hydraulic gates, etc. have been investigated extensively. Literature on these hydraulic structures, which exhibit different rigidity and permeability (see

Table 2.2), are reviewed to gain an insight into the hydraulics around a silt screen and the determinants of the flow characteristics.

Table 2.2: Some typical thin structures in practice, classified according to porosity and rigidity

		Porosity	
		<i>Impermeable</i>	<i>Permeable</i>
Rigidity	Low	Oil boom Curtains	Fishing nets
	High	Sluice gate Flap gate	Screens

2.4.2.1 Sluice gates

Figure 2.6 shows the typical layout of a sluice gate which is used to control the flow of water in an open channel (Finnemore and Franzini, 2008). As can be seen in the figure, the sluice gate is held normal to the flow. The sluice gate, similar to a silt screen, is also a vertical structure suspended at a certain distance away from the bed. This gap is defined as the opening gap of a sluice gate.

Figure 2.6: Schematic drawing of a sluice gate system

Publications on sluice gates, which typically focused on flow patterns and flow rate distribution, depicted the characteristics of the flow around a hang-down structure and emphasized the role of the opening gap in defining the hydraulics and flow characteristics in the vicinity of the structure.

The flow patterns around a sluice gate are governed primarily by the level of the tailwater as shown in Figure 2.7. Figure 2.7a describes the expected flow patterns when the tailwater level downstream is maintained at shallow depth (supercritical condition), while Figure 2.7b and Figure 2.7c show the flow patterns that occur when the flow downstream is subcritical. In the latter cases, depending on the tailwater depth and the upstream water level, two scenarios of flow patterns could be formed downstream, i.e. free flow with hydraulic jump or submerged hydraulic jump (Swamee, 1992; Yen et al., 2001). Swamee (1992) presented the anticipated flow patterns based on the mathematical expressions that accounted for the relative water depth at both sides of the gate, and the size of the opening gap. Free flow with hydraulic jump (as shown in Figure 2.7b) could be expected when

$$H_1 \geq 0.81H_3 \left(\frac{H_3}{b_g} \right)^{0.72} \text{ and submerged flow (as shown in Figure 2.7c) would be}$$

formed under the condition $H_3 < H_1 < 0.81H_3 \left(\frac{H_3}{b_g} \right)^{0.72}$ (with b_g refers to the gate opening, and H_1 and H_3 are the water depths at upstream and downstream of the sluice gate respectively).

Figure 2.7: Scenarios of flow patterns around a sluice gate - (a) free flow, (b) free flow with hydraulic jump, and (c) submerged hydraulic jump

The flow discharge across a sluice gate is a function of the opening gap as noted in the formulae given in Table 2.3.

Table 2.3: Formulae for estimating the discharge rate from a sluice gate
(adapted from Garde, 2006)

Flow scenario	Discharge rate
Free flow	$q = C_{dg} b_g \sqrt{2gH_1}$ <p>With $C_{dg} = \frac{C_{cg}}{\sqrt{1+C_{cg}(\frac{b_g}{H_1})}}$ with $C_{cg} = 0.6$</p> <p>(C_{dg} and C_{cg} are coefficients, b_g is the gate opening; H_1 is the upstream water depth and $g = 9.81m/s^2$)</p>
Submerged flow	$q = C_{ds} b_g \sqrt{2g(H_1 - H_s)}$ <p>With $\frac{H_s}{H_3} = \sqrt{1 - 2Fr_3^2 \left(\frac{H_3}{C_{cg} b_g} - 1 \right)}$</p> <p>With Froude number $Fr_3 = U_3 / \sqrt{gH_3}$ and C_{ds} and C_{cg} are coefficients.</p> <p>(H_3 is the tailwater depth, H_s is the submerged depth immediate downstream of the sluice gate, and U_3 is the average flow velocity of the tailwater)</p>

2.4.2.2 Flap gates

A flap gate is a type of hydraulic gates that has been used to prevent backflow into pipes and openings (Coldwell-Wilcox, 2012). During operation, the flap gate only covers part of the flow. The vertical shape of the flap gate resembles the shape of a silt screen when the screen skirt is deflected under the effects of the flow. As shown in Figure 2.8, the geometry of a flap gate is defined by the gate inclination angle θ_G , the gate length (for rectangular shapes) or the gate diameter (for circular gates) D_G , level arm L_G from the hinge, the gate thickness t_G , the gate seating angle λ , and the weight W_G .

Figure 2.8: A sketch of the geometry of a flap gate (adapted from Burrows et al., 1997)

Literature on the hydraulics of a flap gate, though limited, highlights the importance of the inclination angle on the flow characteristics of a thin hydraulic structure. Burrows et al. (1997) conducted laboratory experiments on a circular flap gate used for controlling discharge from a sewer system and noted the relationship among the gate inclination angle θ_G , the flow discharge and the surcharge, which was defined by the ratio between the water levels at the sides of the gate.

2.4.2.3 Oil booms

Being made of impermeable canvas, oil booms represent flexible hydraulic structures. Upon deployment in the water, an oil boom could be deflected by the flow, as described analytically and numerically in several studies (Lee and Kang, 1998; Swift et al., 1992).

Lee et al. (2003) captured the flow field around oil booms using the technique of Particle Image Velocimetry (PIV) on systems of single and multiple oil booms. The velocity profiles observed around a single boom showed increasing velocity with water depth. Instantaneous PIV images revealed the formation of a large shear layer downstream of the boom and a vortex structure in the upper water layer. This is the situation of a barrier that spans fully across an open channel. The situation may be different in the case of open water, where the flow may be diverted toward the open ends.

Using numerical simulation, Ertekin and Sundararaghenan (1995) observed the formation of a recirculation zone upstream of the boom. As the upstream flow approaches the screen, the streamlines will be deflected forming two flow zones; the flow at the upper water layer forms a recirculation flow in front of the boom and that at the lower depth flows past the base of the boom in the form of a jet. Oebius (1999) suggested that the location of the separation point between these two flow features was independent of the boom's draft length. The schematic drawing of the flow patterns around an oil boom as depicted by Oebius (1999) is reproduced here in Figure 2.9 which indicates the influence of the deflection angle on the extent of the recirculation zone formed upstream of the boom. As far as the author is aware, little has been published about the flow characteristics of a deflected boom and how the flow develops downstream of the boom.

Figure 2.9: Flow patterns around different forms of barriers: (a) convex skirt, (b) vertical skirt, (c) concave skirt (adapted from Oebius, 1999)

2.4.2.4 Flexible porous structure

Adolphe et al. (1994) studied the characteristics of the flow across porous geotextiles using Laser Doppler Velocimetry. The geotextiles, with typical normal permeability ranging from 10^{-4} to 10^{-3} m/s, were deployed normal to the flow direction in laminar flow condition with the Reynolds number ranging from 6 to 25. The velocity profiles downstream of the geotextiles showed decreasing mean velocity along the longitudinal direction.

The presence of flexible hydraulic structures with high porosity, such as a fish net, also induced a wake region behind the net structure. Løland (1993) expressed the velocity profiles in the turbulent flow region as a function of the screen properties such as permeability and solidarity (which was defined as the percentage of the area of the screen that allows water to flow through freely).

2.4.2.5 Rigid porous structures

Rigid porous structures, also known as screen structures, have been widely used for applications such as fish bypass and grid turbulence generators in a wind tunnel. Screen coverage depth defines the flow patterns around a screen structure. As reported by Yeh (1998), the flow patterns across a screen anchored vertically in water showed two flow features: (1) a drop in the water level immediately behind the screen due to flow contraction (also known as pressure drop across the screen), and (2) flow separation that could be observed near the bottom boundary (see Figure 2.10). On the other hand, Koo and James (1976) described the flow patterns around a screen that was extended to part of the water column. The flow depicted two distinct regions: (1) the flow around the screen that includes the streamlines flow past the screen – so called the region of “flow around the screen”, and (2) the other region enclosing the streamlines passing through the screen – so called the region of “flow through the screen” (see Figure 2.10b). Recirculation zones as observed around impermeable sluice gates or oil booms were not observed in the flow patterns formed around structures of high porosity.

Figure 2.10: (a) Flow patterns observed for a full-depth porous screen (according to Yeh, 1998); and (b) flow through a porous screen that is attached to the bottom and covering part of the water depth (adapted from Koo and James, 1976).

Katopodis et al. (2005) performed laboratory experiments to measure the flow upstream of angled screens in open channels. In the experiments, a wedge-wire screen was mounted vertically and at angles of 10.4° to 26.8° to the approaching flow (1 to 2 m/s). The results obtained showed that the depth-averaged mean velocity, $\bar{V}$, correlated with the ratio of the channel width covered by the screen b_{cs}/b_c according to the following equation:

$$\frac{\bar{V}}{U_0} = 2.14 - 1.24(b_{cs}/b_c) \quad (\text{Equation 2.24})$$

Here, b_{cs} is the channel width covered by the screen, and b_c is the width of the channel, and U_0 is the incident velocity of the flow approaching the screen.

Teitel et al. (2009) simulated the mean velocity downstream of screens covering the full channel depth at three different screen inclination angles (45° , 90° and

135°) and reported the effects of screen inclination angle on the magnitude of the flow velocity.

The presence of screen structures also changes the turbulence distribution in its vicinity. Schubauer et al. (1950) measured the fluid velocity around wire screens in a 19-foot-long test section of a wind tunnel using hot wire anemometry to study the effects of the screens on turbulence distribution. The porosity of the tested screens ranged from 0.190 – 0.603 and the wind speed tested varied from 10 to 30 fps (equivalent to 3.408 m/s to 9.144 m/s). By using the turbulence data collected further away from a screen, the study suggested that the turbulence downstream of the screen appeared to be damped compared to that without the screen. Briassulis et al. (2001) studied the turbulence characteristics downstream of a vertical grid and classified the development of the turbulence downstream of the structure into three regions: (1) the developing region, which is located close to the grid where rod wakes merge and the flow is strongly turbulent, (2) the developed region where turbulent energy cascade is observed, and (3) the region located further downstream of the grid and dominated by cascading eddies. According to Groth and Johansson (1988), the decay rate of turbulence downstream of a screen could be estimated with the homogeneous isotropic turbulence decay equation:

$$\left(\frac{u'}{U_0}\right)^2 = \frac{1}{C_{decay}} \left[\frac{x}{M} - \left(\frac{x}{M}\right)_0 \right]^{-n} \quad (\text{Equation 2.25})$$

in which C_{decay} is the decay coefficient, n is the decay exponent, x refers to the downstream location of interest, $(x/M)_0$ is the virtual turbulence decay origin, M refers to the mesh size, u' is the fluctuation of the stream-wise velocity, and U_0 is the incident velocity of the flow approaching the screen.

The relationship between the value of the decay coefficient C_{decay} presented in Equation 2.25 and parameters such as the mesh size, the dimensions of wires

along the horizontal and vertical directions, and the porosity of the screen were reported in several studies. Table 2.4 shows the suggested values of the coefficients in Equation 2.25 from published studies (adapted from Azizi and Taweel, 2011). In these studies, the screens were installed vertically in the water and normal to the approaching flow. The values of C_{decay} obtained in these studies demonstrate the effects of screen porosity on turbulence around a vertical screen.

Table 2.4: Reported turbulence decay equation constants (adapted from Azizi and Taweel, 2011)

Open area	n	C_{decay}	$(x/M)_0$	References
0.56–0.69	1.15–1.33	7.1–35	2–5	Comte-Bellot and Corrsin, 1966
0.63	1.28–1.32	13.2–15	0	Gad-El-Hak and Corrsin, 1974
0.56–0.71	1–1.34	25.2	0-6	Groth and Johansson, 1988
0.56; 0.66	0.95-1.42	12.7-109.5	0-6	Mohamed and LaRue, 1990
0.64	1.1	28.5	3	Stewart and Huq, 2006
0.27-0.48		1.5-6.1		Azizi and Taweel, 2011

Azizi and Taweel (2011) observed relatively constant value of the decay coefficient C_{decay} with screens with low porosity. When the porosity was 33 % or more, the coefficient was found to be a function of the porosity. As suggested by Azizi and Taweel (2011), for screens with small porosity, high turbulent energy was generated downstream of the screens, and the turbulence dissipated relatively slowly.

While the turbulence downstream of a vertical grid has been well described, research on turbulence around angled vertical screens remains incomplete. Rajaratnam et al. (2010) published one of a handful of recent papers on the turbulence near a vertical angled fish screen. The wedge-wire screens, which were mounted at angles of 10.4° and 17.5° , were placed in a channel with the environmental flows of 0.45 m/s and 0.57 m/s, respectively. Downstream of the

screen, higher turbulent fluctuations, turbulent kinetic energy and Reynolds shear stress were recorded.

2.4.3 Sediment transport estimation around hydraulic structures (weirs and submerged vanes)

The published sediment transport formulae were generally developed based on the knowledge of alluvial flow. De Vriend (2006) pointed out that these formulae could not account for complex flows such as those around hydraulic structures which might involve vertical velocity components, vortical motion, shear layers, vortices, and sand-mud interactions, etc. A number of studies have been carried out to relate the sediment transport around hydraulic structures to the flow characteristics. Marelius and Sinha (2000) correlated the performance of a submerged vane on sediment control to the moment of momentum about the longitudinal (stream-wise) axis and computed at the origin of the vortex core of the recirculation zone formed downstream of the vane. Li and Yu (2009) used the length and width of the primary recirculation in front of a flexible sedimentation curtain to represent the sedimentation around the curtain. The correlation among these factors, if any, has not been verified.

Observing sediment distribution around a weir and the corresponding flow patterns, Lauchlan (2004) suggested the necessity of considering the distribution of critical shear stress and actual shear stress in the presence of hydraulic structures in order to accurately predict the motion of sediment. In an approach to tackle the sediment entrainment at high flow, van Rhee (2010) proposed a formula for the modified Shields parameters for high velocity flow. However, only a limited number of publications that deal with sediment transport in complex flow conditions could be found.

One approach that had been employed to estimate the sediment transport capacity in a complex flow is to relate the transported sediment with the flow rate. In this approach, the sediment distribution is correlated with the flow rate

redistribution as shown in Equation 2.26 (suggested by Wilcock, 2004), and Equation 2.27 (proposed by Harris, 2003):

$$\frac{Q_s}{Q_{sr}} = \left(\frac{Q}{Q_r} \right)^b \quad (\text{Equation 2.26})$$

where Q_s and Q_{sr} refer to the sediment loads being carried in the flow with flow rates Q and Q_r respectively, and b is a coefficient that needs to be determined.

$$\frac{Q_{s2}}{Q_{s1}} = C_s \frac{Q_2}{Q_1} \quad (\text{Equation 2.27})$$

where Q_{s2} and Q_{s1} refer to the sediment loads being carried in the flow with flow rates Q_2 and Q_1 respectively. In Equation 2.27, the coefficient C_s is assumed to be a linear function of the excess shear stress S_T at the toe of the slope (Harris, 2003). S_T is related to the actual Shields parameter θ and the critical Shields parameter θ_{cr} according to Equation 2.28:

$$S_T = \frac{\theta - \theta_{cr}}{\theta_{cr}} \quad (\text{Equation 2.28})$$

Using Equation 2.27, Vuik (2010) “predicted” the sediment movement around a weir and reported reasonably good results.

2.5 Silt screens, their structure and the implications for the flow and sediment

Francingues and Palermo (2005) defined a silt screen as a vertical, flexible structure that extends downward from the water surface to a certain depth and consists of flexible thermoplastic fabric.

Figure 2.11: Silt screen structure (Francingues and Palermo, 2005)

A conventional silt screen system (as depicted in Figure 2.11) consists of four main parts: a screen skirt, a flotation system, a system of anchorage and ballast chain, and a tension support system. Among these design components, the screen skirt is the most important element of a silt screen system and defines the performance

of a silt screen. Upon deployment, the screen skirt is kept suspended from the water surface to a specific water depth with reinforcement from the floating system and the anchorage and ballast chains system. Structurally, silt screen skirts are usually made up of woven polyethylene or polypropylene multi-filament.

2.5.1 Deployment of silt screens at the field

Silt screen systems have been deployed in three configurations: maze, closed and open configurations as depicted in Figure 2.12.

Figure 2.12: Typical layouts of a silt screen deployment at dredging sites: (1) maze configuration, (2) open configuration, and (3) closed configuration, off shore, and (4) closed configuration, on shore (plan view) (Johanson, 1976; JBF Corporation, 1978)

According to Francingues and Palermo (2005), the deployment configuration of a silt screen has always been selected and designed based on the intended objectives of the silt screen, the hydrodynamic regime at the project location, and other factors such as boat traffic. In particular, the closed configuration is mostly deployed to contain turbid water near to the shore. Silt screens are often arranged in U-shape configuration or open configuration in aquatic regions with uni-direction flow. At locations that are under tidal influence, a circular or an elliptical configuration is usually chosen.

2.5.2 Design of a silt screen system

Figure 2.13 summarizes the procedure adopted and the steps undertaken in the design of a silt screen system. This design system is currently being adopted by silt screen manufacturers (Elastec, 2004; Taiyo Kogyo, 2008).

Figure 2.13: Diagram of the currently adopted procedure of the design of silt screens

As can be seen in Figure 2.13, the current design procedure focuses on maintaining the structural stability of the silt screen system. The screen's tensile strength and geometry are designed to sustain the silt screen system under the forces induced by the hydraulics, wind, wave and tides. The one single requirement for the

deployment depth of a silt screen system is that a silt screen must be kept a distance above the bed. This “rule-of-thumb” approach aims to prevent burial of the silt screen system in case of sediment deposition (Bennish, 2008; Eaton, 2008; Johanson, 1976). The desirable effects of silt screens on the hydraulic conditions and sediment redistribution are not considered in the current design.

On the other hand, during the long exposure to outdoor environment, the structural properties of a silt screen may deteriorate under the mechanical, chemical or physical processes in the environment. Mouritz et al. (2004) studied the mechanical performance of polymer composites (geotextiles) submerged in seawater. They suggested that the pH and ionic nature of seawater are potential causes of the degradation of the polymer. Examples of reduction in a geotextile’s tensile strength exposed to the elements have been reported in many studies (Bouazza et al., 2006; Hsieh et al., 2003; Lodi et al., 2009). Such phenomenon raised concerns about the effects of the environment on the properties of silt screens during extended periods of deployment. Nevertheless, information on the effects of environmental factors such as UV light, salinity, and humidity on silt screen properties is scarce.

Sediment clogging on the screen surface could be expected after some time. The process of particles deposition during clogging is governed by filter characteristics, particle characteristics and flow properties (flow rates), see Freshwater and Stenhouse (1972), Sutherland (2008), and Wakeman (2007). The effects of the filter pores, including the pore size, pore shape and pore patterns, on particles deposition have been reported in several studies (Chandler and Zydney, 2006; Hwang et al., 2008; Lin, 2009; Lu et al., 1997; Tung and Chuang, 2002). Lin (2009), in a study on particle deposition onto a micro-sieve, observed that the pore patterns had a certain influence on the location of particles deposition. Considering the potential effects of the additional weight added onto a silt screen system by the clogged sediment and its effects on structural stability, it is

necessary to address the significance of clogging on silt screens and identify the relevant controlling parameters.

2.5.3 Sediment redistribution in the presence of a silt screen

As noted by Francingues and Palermo (2005), an efficient silt screen contains or excludes the suspended sediment within a certain area or from the external sources, depending on the objective. Yasui et al. (1999) designed a silt screen system consisting of a stand-up screen and/or a hang-down silt screen arranged in tandem in a flume. The measured turbidity at 4.5m and 5.5m downstream of the screen showed that the local maximum concentration had been reduced across the silt screens. Compared to the case without a silt screen, the maximum concentration detected decreased by 60-80% when there was a stand-up silt curtain while 25-50% reduction was measured when both the stand-up and hang-down silt screen were deployed. In addition, the variation of the flux of outward sediment at various flow velocities suggested enhanced containment capacity of a silt screen if the flow upstream of the silt curtain was slow.

Johanson (1976) studied various project sites where silt screens were deployed and measured suspended sediment characteristics near the free surface and the bed. Under similar hydraulics conditions, higher turbidity reduction was observed when silt curtains were deployed in a closed configuration. It was observed that turbidity was significantly reduced across a silt screen deployed in low flow condition (0.05 m/s or less). At certain project sites, high sediment content (represented as % solids) was recorded near the bed during both ebb and flood tides. Johanson (1976) attributed such high sediment content at the bottom to a potential turbid layer of material flowing under the curtain.

Jin et al. (2004) examined the sediment distribution along both sides of a silt screen set in an open configuration. The local sediment flux measurement indicated 60% of the sediment flux was reduced across the silt screen at mid

depth. Nevertheless, the depth-averaged suspended sediment concentration measured downstream of the silt screen was 60% higher than that upstream. Such high sediment concentration raised concerns over the representativeness of the reported sediment flux reduction, which was monitored based on measurement at a single location. Shaw et al. (2000) reported negative impacts resulting from the silt screen deployment on sediment containment around a reclamation site.

De Wit et al. (2011) monitored the performance of a silt screen deployed in closed configuration in an area with average flow speed of 0.04 m/s. The objective of the silt screen was to protect nearby zebra mussels from being subjected to high suspended sediment concentration (SSC) and siltation rate. The monitored SSC showed that the peak values were reduced by 25-50% across the silt screen. The suspended sediment values were restored to the background value at 200 metres away from the silt screen.

In general, reported studies showed that the effectiveness of silt screens has been highly variable. Based on the observed sediment concentration distribution and potential structural instability, the present design guidelines do not recommend silt screens deployment at sites where the flow speed is higher than 0.5 m/s.

2.6 Discussion

In an effort to develop a comprehensive approach in design, the author adapted the design procedure introduced by Verhagen (2012) and d'Angremond and van Roode (2004). The proposed design process consists of five stages: (1) analysis, (2) synthesis, (3) design, (4) evaluation, and (5) decision making. As illustrated in Table 2.5, through this five-stage process, a suitable design is selected based on considerations of both engineering requirements and scientific knowledge of the structure.

Table 2.5: Guidelines of issues to be addressed in the design process
(adapted from d'Angremond and van Roode, 2004)

Stage	Issues to address
1. Analysis	<ul style="list-style-type: none"> • What are the general requirements that the design must fulfill in all aspects ? <ul style="list-style-type: none"> ○ Technical requirements ? ○ Cost requirements ? ○ Functionality requirements ?
2. Synthesis	Conceptual ideas and alternatives that broadly meet the outlined requirements
3. Simulation	Develop the details of the concepts and acceptable alternatives
4. Evaluation	Assess the effectiveness of the alternatives, comparison based on a set of criteria
5. Decision making	Selection the best option among the alternatives

Figure 2.14 is a flow diagram that describes the steps and issues to be addressed in a comprehensive design of a silt screen. The issues that are accounted for in the current practice are highlighted in italic style.

Figure 2.14: The proposed approach for a comprehensive design of silt screens (with reference to Verhagen, 2012 and d'Angremond and van Roode, 2004). The issues that are considered in the current design approach are highlighted in italics.

According to the framework described, the current practice of silt screen design includes certain limitations. First, to the best knowledge of the author, a criterion on hydraulics conditions has not been considered in the analysis. Second, in the

current approach of silt screen design, only a vertical screen has been considered, i.e. the silt screen was assumed to be deployed and stayed as a single vertical section. Third, except for the tension criterion, the effects of the other properties of silt screen skirt have not been taken into account. Fourth, the current approach does not consider all the criteria in the evaluation of the effectiveness of the silt screens design.

In the contemporary design of silt screens, structural stability has been well-considered. Silt screens systems have been designed to sustain the physical forces exerted by wind, waves, and tidal conditions. Nevertheless, it has been observed often that while the components of a silt screen system have been designed based on the forces corresponding to the original geometry, thickness and weight of the silt screen, these parameters typically differ under environment degradation and sediment clogging. This has not been considered in the current design procedure.

The current design approach also fails to account for the effectiveness of silt screens on sediment containment. The hydraulic conditions have often been overlooked during the design process (as discussed in section 2.5.2) and are likely to contribute to variable effectiveness of silt screens after deployment. Furthermore, with little information about the science of sediment movement around a silt screen (i.e. the hydraulic characteristics and sediment patterns around a silt screens), the effectiveness of the current design of silt screens is questionable.

In the previous sections of this chapter, the literature on sediment transport mechanism, the hydraulics of structures and the respective sediment movement around thin hydraulics structures have been reviewed. The author summarizes the processes that could be expected in a silt screen system in Figure 2.15. In the lower block of the figure, the parameters of sediment, flow and silt screen that influence these processes are included. The shades of the boxes indicate the status of

knowledge to date. As illustrated in Figure 2.15, several processes remain unknown or not fully understood. Clogging of sediment on silt screens and the effects of environmental degradation on silt screens have not been investigated. Regarding the flow about a silt screen, the literature indicates that the established knowledge on the flow characteristics and flow patterns is limited to the effects of porosity of rigid grid screens. The influence of factors such as the coverage depth, deflection angle and flexibility has not been considered. On the transport of sediment in the vicinity of a silt screen, the literature on sediment transport in complex flows provides only scarce information which may not be comprehensive for the design, deployment and assessment of the performance of a silt screen.

Figure 2.15: Summary of the processes associated with the silt screen, flow and sediment in a silt screen system

To tackle the rigour in the design and science of silt screens, two particular issues need to be addressed urgently:

- (1) Regarding the structural stability of a silt screen system, the effects of environmental factors and clogging of silt screen need to be identified,
- (2) Regarding the evaluation of the efficiency of a silt screen system, the hydraulic and sediment patterns around a silt screen need to be

established. Such information is crucial to evaluate the efficiency of a silt screen system and should be included in the design consideration.

In addition, in consideration of the engineering design process, the required hydraulic conditions that promote/contain the desired sediment movement need to be established.

3. Methodology

3.1 General

The current design practice focuses on the structural stability of silt screens. To improve the design methodology and application of silt screens as an effective sediment containment structure, four issues have been identified, and they are:

1. To determine the influence of the hydraulic and sediment patterns around a silt screen system on the containment of suspended sediment. The hydraulic characteristics and sediment distribution around silt screens set in various deployment configurations need to be investigated.
2. To identify and devise the parameters that control the hydraulic characteristics and the containment of suspended sediment in the vicinity of a silt screen.
3. To identify the most ideal and practical configuration of the deployment of silt screens to create and induce the desired hydraulic flow patterns and suspended sediment profiles within the containment area.

It is the objective of this study to investigate and establish a design methodology based on the flow/sediment patterns that will achieve the containment objective. The approach and procedure to achieve this objective are described in later parts of this thesis.

4. Environmental degradation and clogging of silt screen.

As a complementary study, a series of experiments were designed to determine the effects of environmental degradation and clogging of silt screens. The impacts of environmental factors such as UV light, humidity, and salinity on the permeability of silt screens are investigated. The effects of fibre arrangement and weaves on the clogging of sediment onto the surface of a silt screen are assessed. These experiments are discussed in this chapter.

3.2 Laboratory study of the hydraulics and sediment patterns around a silt screen

The flow patterns, velocity and turbulence distribution around a silt screen based on the prevailing design were investigated through laboratory experiments. The experiments were conducted in a flume (5 m length x 0.45 m height x 0.3 m width). In the experimental setup, which considered the configuration of a hang-down silt screen system, a silt screen model was placed across the span of the channel and ballasted using a cylindrical weight attached to the base of the skirt. The two sides of the silt screen sample were secured to the flume bed to maintain the rectangular shape of the silt screen during the experiments. The flow depth in the channel was controlled using a tail gate/weir and the flow rates were adjusted by changing the rotation speed of the pump which supplied the flow to the channel.

The flow around the silt screen was captured and analyzed using the technique of Particle Image Velocimetry (PIV). During the experiments, planar images of the flow field along the mid-plane of the flume were captured with a 12-bit charge-couple device (CCD) camera (see Figure 3.1). The CCD camera had a resolution of 1600x1200 pixels and a frame rate of 15 Hz. A double cavity Nd:YAG laser light sheet which has a wavelength of 532 nm (Litron model, power of 135 mJ per pulse, duration of 5 ns) was used to illuminate the flow field. In order to obtain images of the entire water depth, the size of the viewing area was chosen as 300mm x 225mm. Sphericel hollow glass spheres produced by Potter Industries¹ were seeded in the flow as tracers. The particles, which had specific weight of 1.1, had diameters in the range of 10-15 μm . The time interval between two consecutive frames was adjusted according to the flow condition.

¹ Potters Industries (<http://www.pottersbead.com>). Accessed March 2012

Figure 3.1: Diagram of the experiment setup

In the experiments, three types of silt screens, namely A, B, and C, were tested. The properties of these three silt screens, which were obtained from different manufacturers in Singapore, are summarized in Table 3.1. The experiments were repeated with two cases of incident flow velocity U_0 (0.05 m/s and 0.1 m/s) and three cases of screen penetration ratio SPR (SPR = 0.5, 0.7 and 0.8). The screen penetration ratio (SPR) is defined as the ratio between the vertical penetration length of the silt screen (L_{ns}), which corresponds to the vertical distance from the top of the screen at the water surface to the base of the skirt, and the water depth (H) (see Figure 3.2).

Figure 3.2: Description of the configuration of a silt screen in the vertical plane. The silt screen is represented as the red solid line in the figure.

Table 3.1: Properties of the three silt screen types used in the experiments

Silt screen	Initial hydraulic conductivity (m/s)	Weaving type
A	3.18×10^{-6}	Plain weave
B	6.55×10^{-6}	Plain weave
C	9.45×10^{-6}	Twill weave

Figure 3.3: Close-up view of the silt screens used in the laboratory study: (a) silt screen A, (b) silt screen B, and (c) silt screen C.

Figure 3.4: Locations of flow measurement in the experiments (the silt screen is represented as the red solid line).

The flow field was plotted based on flow images captured at five locations both upstream and downstream of the silt screen as illustrated in Figure 3.4.

Consider the velocity u of the flow in the vertical plane in the vicinity of a silt screen and at distance x away from the silt screen.

It is assumed that a functional relationship of u can be expressed as:

$$u = f(x, \mu_w, \rho_w, g, H, U_0, L_{ns}) \quad (\text{Equation 3.1})$$

where μ_w is the dynamic viscosity of water, ρ_w is the density of water, g is the acceleration of gravity, H refers to the water depth, U_0 is the incident flow velocity, and L_{ns} refers to the vertical penetration length of the screen in the vertical plane.

Applying Buckingham Pi Theorem, the following relationship was obtained:

$$\frac{u}{U_0} = f\left(\frac{x}{H}, \frac{L_{ns}}{H}, \frac{\mu_w}{\rho_w U_0 H}, \frac{gH}{U_0^2}\right) \quad (\text{Equation 3.2})$$

For geometric similarity, the dimension of the model and the prototype must satisfy the relationships elaborated in Equation 3.3 and Equation 3.4.

$$\left(\frac{L_{ns}}{H}\right)_{prototype} = \left(\frac{L_{ns}}{H}\right)_{model} \quad (\text{Equation 3.3}), \text{ and}$$

$$\left(\frac{x}{H}\right)_{prototype} = \left(\frac{x}{H}\right)_{model} \quad (\text{Equation 3.4})$$

In terms of dynamic similarity, however, it is impossible to satisfy both Reynolds number similarity and Froude number similarity. In this study, because gravitational force is dominant, Froude number similarity was chosen for assessment of dynamic similarity. The parameters must satisfy the condition as described in Equation 3.5:

$$\left(\frac{gH}{U_0^2}\right)_{prototype} = \left(\frac{gH}{U_0^2}\right)_{model} \quad (\text{Equation 3.5})$$

$$\text{or } \frac{U_{0prototype}}{U_{0model}} = \sqrt{\frac{H_{prototype}}{H_{model}}} \quad (\text{Equation 3.6})$$

where $U_{0prototype}$ and U_{0model} are incident flow velocities in the prototype and the model respectively. $H_{prototype}$ and H_{model} are the water depths in the prototype and the model respectively.

Hyun et al. (2003) recommended a minimum of 1000 flow shots to ensure the statistical representativeness of the turbulence characteristics and the convergence of the data in PIV measurement. In this study, with each experiment, the averaged velocity field was plotted based on the analysis of 1050

instantaneous flow shots, with a recording duration over 70 seconds. The cross-correlation technique was used to deduce the flow field from the captured images. The particle displacement was calculated using the cross-correlation algorithm with the standard Gaussian sub-pixel fit structured as an iterative multi-grid method (Scarano and Riethmuller, 1999). The processing procedure included two passes, starting with a grid size of 64x64 pixels, stepping down to 32x32 pixels overlapping by 50%. The uncertainty in the mean velocities (u and v) and the turbulence intensities (u' and v') were estimated to be about 2% for the present setup. A detailed description of this technique is given in Adrian (1991) and Wang and Tan (2008).

The experiments captured the flow in a small region that extended from 40 cm upstream ($x/H \approx 1.6$) of the silt screen to 80 cm downstream ($x/H \approx 3.2$) of the silt screen. To describe the full evolution of the flow around a silt screen, numerical simulation of the flow field was carried out.

3.3 Numerical simulation

3.3.1 Simulation of flow around silt screens

ANSYS FLUENT (version 11, 2010), a commercial fluid dynamics software package, was used to investigate the following two issues regarding the flow around silt screens:

- Flow distribution around a silt screen in the transverse direction; and
- Vertical distribution of flow along the water depth around a silt screen

3.3.1.1 *Flow distribution around a silt screen in the transverse direction*

In order to establish the flow development in the transverse plane, numerical simulation was used to simulate the flow patterns around a line-shaped silt screen (plan view) that is deployed normal to the flow direction (refer to Figure 3.5). It is assumed that the resultant flow velocity u_x at a distance x_u upstream of the

screen and along the axis of symmetry of the screen is governed by five parameters as follows:

- The environmental velocity U_{env}
- The distance x_u to the silt screen of the location where u_x is the flow velocity
- The length of the screen along the transverse direction L_s
- Density of water ρ_w
- The dynamic viscosity of water μ_w

Applying Buckingham Pi Theorem, with L_s , U_{env} and μ_w chosen as the repeating variables, the following relationship was obtained:

$$\frac{u_x}{U_{env}} = f\left(\frac{x_u}{L_s}, \frac{\rho_w U_{env} L_s}{\mu_w}\right) \quad (\text{Equation 3.7})$$

a. Physical domain

The flow was simulated for a domain in plan. A silt screen with the transverse length L_s was placed normal to the direction of the flow and at the centre of the domain, see Figure 3.5. In the simulation, four scenarios of the transverse length of the silt screen L_s (100m, 250 m, 500m, 1000m) were considered. For each length, the size of the domain (L_w) was adjusted accordingly so that the side boundaries do not affect the flow in the vicinity of the screen.

Figure 3.5: Physical domain considered in the simulation of flow in the transverse direction

Table 3.2 summarizes the conditions of the screen length and the environmental flow velocity that were used in the numerical simulations of the flow around a silt screen in the transverse plane.

Table 3.2: Summary of the flow and screen conditions adopted in the simulations of the flow around a silt screen in the transverse plane

Parameter	Unit	Input values
U_{env}	m/s	0.05; 0.1; 0.2; 0.5
L_s	m	100; 250; 500; 1000

b. Turbulence model

The turbulent flow in the domain was simulated using the shear stress transport (SST) $k - \omega$ model. In this turbulent model, the turbulent kinetic energy k and the specific dissipation rate ω are governed by the following two equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}(\Gamma_k \frac{\partial k}{\partial x_j}) + \tilde{G}_k - Y_k + S_k \quad (\text{Equation 3.8})$$

and

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j}(\Gamma_\omega \frac{\partial \omega}{\partial x_j}) + G_\omega - Y_\omega + D_\omega + S_\omega \quad (\text{Equation 3.9})$$

In the above equations $\tilde{G}_k$ denotes the generation of turbulent kinetic energy, G_ω is the generation of ω ; Γ_k and Γ_ω are the effective diffusivity of k and ω respectively. Y_k and Y_ω refer to the dissipation of k and ω due to turbulence; D_ω is the cross-diffusion term and S_k and S_ω are the source terms (FLUENT, 2006). u_i ($i=1,2,3$) refers to the velocity components in x, y, z direction. x_i and x_j ($j=1,2,3$) represent x, y and z directions.

c. Boundary conditions

The boundary conditions applied at the boundaries in the simulations are listed in Table 3.3.

Table 3.3: Boundary conditions applied on the domain in the simulations of the flow in the transverse plane

Boundary	Boundary condition
Inlet	Velocity-inlet
Outlet	Outflow
Side boundary	Symmetry
Silt screen	Wall

d. Mesh generation

A structured mesh was generated to simulate the flow around the silt screen. Finer grids were generated at the zones where large velocity gradient was expected, such as near the silt screen (as seen in Figure F1 of Appendix F). The grids generated were optimized to ensure grid independence and grid resolution requirements in the $k - \omega$ model in FLUENT.

e. Post-processed data

The simulated flow patterns around the silt screen were processed to visualize flow separation around a silt screen and to determine the effects of a silt screen on the flow characteristics in the transverse plane.

3.3.1.2 Simulation domain of the two-dimensional simulation of the flow around a screen in the vertical plane (2DV simulation)

The hydraulic characteristics of silt screens of different configurations were simulated to determine the effects of silt screens on the distribution of flow patterns and velocity distribution.

a. 2DV simulation of flow about the silt screen along the water depth

The numerical simulation study was intended to elucidate the flow patterns of a 2-D flow about a silt screen. In the simulation of the flow in the flume setting, the silt screen was placed in the middle of the simulation domain and at a distance of $20H$ from the upstream and downstream boundaries (H is the water depth of the flow approaching the silt screen). The dimension of the domain was chosen to ensure sufficient length for flow development upstream and downstream of the silt screen.

Figure 3.6: Physical domain applied in the simulations of the flow around a silt screen in the vertical plane (with H refers to the water depth).

The simulation assumed a “rigid-lid” scenario with zero shear stress along the water surface. As seen in Figure 3.7, the boundary condition “symmetry” was applied to the upper boundary of the simulation domain. As noted by van Balen (2010), Demuren and Rodi (1986), and McGuirk and Rodi (1977), compared to free surface simulation, the error induced from this assumption was negligible when the change in elevation is less than 10% of the depth. The sizes of the meshes used in the simulation of the flow in the flume setting and in pilot scale are summarized in Appendix F. Finer grids were generated in the zones where large velocity gradient was expected (as seen in Appendix F). These zones include the area near the channel bed and along the area around the boundary of the silt screens. The grids generated were optimized to ensure grid independence and grid resolution requirements according to the $k - \omega$ model in FLUENT.

Figure 3.7: Boundary conditions applied in the simulations of the flow around a silt screen in the vertical plane in FLUENT

b. 2-D simulation of the flow around a compound screen

It is hypothesized that a compound screen which consists of a number of sections arranged at various angles with the vertical axis could affect the flow characteristics around a silt screen and hence influences the sediment containment efficiency. In this study, two examples of compound screens (2-segment screen and 3-segment screen) in a 2-D flow were tested. The shapes of these compound screens are shown in Figure 3.8 and Figure 3.9.

Figure 3.8: Geometry of a single screen (a) and compound screens, including 2-segment screen (b), and 3-segment screen (c). For the pilot scale, $H=25\text{m}$.

Figure 3.9: Hypothetical configurations of the compound silt screens considered in the simulations

In the simulations, the vertical penetration ratio of the hypothetical screen configurations (see Figure 3.9) is 0.9. The pertinent parameters used are summarized in Table 3.4.

Table 3.4: Geometry of the hypothetical configurations of silt screens studied in the simulation

1-segment screen	Case 1.1	$L_{ns1}=0.9H$	$\alpha_1=90^\circ$
2-segment screen	Case 2.1	$L_{ns1}=0.45H; L_{ns2}=0.45H$	$\alpha_1=90^\circ; \alpha_2=135^\circ$
	Case 2.2	$L_{ns1}=0.45H; L_{ns2}=0.45H$	$\alpha_1=90^\circ; \alpha_2=45^\circ$
	Case 2.3	$L_{ns1}=0.6H; L_{ns2}=0.3H$	$\alpha_1=90^\circ; \alpha_2=135^\circ$
	Case 2.4	$L_{ns1}=0.6H; L_{ns2}=0.3H$	$\alpha_1=90^\circ; \alpha_2=45^\circ$
3-segment screen	Case 3.1	$L_{ns1}=0.3H; L_{ns2}=0.3H; L_{ns3}=0.3H$	$\alpha_1=90^\circ; \alpha_2=120^\circ; \alpha_3=135^\circ$
	Case 3.2	$L_{ns1}=0.3H; L_{ns2}=0.3H; L_{ns3}=0.3H$	$\alpha_1=90^\circ; \alpha_2=60^\circ; \alpha_3=45^\circ$

Based on their vertical shapes, the six configurations were divided into two categories: (1) convex configurations (Case 2.1, 2.3 and 3.1), and (2) concave configurations (Case 2.2, 2.4 and 3.2). The simulations of the flow around the proposed configurations employed similar boundary conditions and simulation steps as those for a vertical silt screen as shown in Figure 3.7.

3.3.2 Simulation of sediment patterns about a silt screen

In this study, the sediment trajectories in the presence of a silt screen were modeled using the module of Discrete Particles Model (DPM) in the commercial software package ANSYS FLUENT. A description of DPM is presented in Section 3.3.2.1. The simulation domain considered a pilot site of 25 metres depth. The domain extended from 150 metres upstream to 450 metres downstream of the screen (see Figure 3.10). A one-way coupled-model, in which the motions of the particles were driven by the flow characteristics, was adopted. In the simulation, the SST k- ω turbulence model was used to solve the flow field. The “rigid-lid” assumption, as described in the previous section, was also adopted to simulate the flow around the silt screen in the pilot scale. Similar boundary conditions to those described in Figure 3.7 were adopted.

Using steady-state discrete phase modeling, the sediment patterns around a silt screen in the vertical plane were analyzed based on the simulated flow field.

Figure 3.10: Physical domain studied in the simulation of the flow about a silt screen in the vertical plane and in the pilot scale (the geometry was not drawn to scale).

3.3.2.1 Discrete Particle Model (DPM) Module

By using the DPM module, the trajectory of a particle was estimated by integrating the force-balance of the particle as described in Equation 3.10, which is a general momentum equation resolved in the direction of the flow:

$$\frac{du_i^p}{dt} = F_D(u_i - u_i^p) + g_i(\rho_p - \rho) / \rho_p + F_i / \rho_p \quad (\text{Equation 3.10})$$

In Equation 3.10, the three components on the right hand side represent the effects of drag force, gravity force and other forces (e.g. Brownian force, etc.). Here, u_i ($i = 1, 2, 3$) represents the fluid phase velocities (u, v, w) along x, y and z direction; u_i^p ($i = 1, 2, 3$) refers to the velocities of the particle in x, y and z direction, g_i ($i = 1, 2, 3$) is the acceleration of gravity in x, y, and z direction; ρ_p is the specific density of the particle; ρ is the specific density of the fluid; F_D is the drag force; and F_i ($i = 1, 2, 3$) refers to the additional acceleration in x, y and z direction. In particular, the drag force F_D was calculated according to Equation 3.11 (FLUENT, 2006):

$$F_D = \frac{18\mu}{\rho_p D^2} \frac{C_D \text{Re}}{24} \quad (\text{Equation 3.11})$$

with C_D representing the drag coefficient, μ is the dynamic viscosity of the fluid, D is the diameter of the particle, ρ_p is the specific density of the particle, and Re is the relative Reynolds number, which is calculated based on the following equation (FLUENT, 2006):

$$\text{Re} = \frac{\rho D |u_i^p - u_i|}{\mu} \quad (\text{Equation 3.12})$$

The estimation of velocity components (u, v and w) along x, y and z direction include the effects due to turbulence fluctuation as noted in Equations 3.13, 3.14 and 3.15.

$$\text{For x direction: } u = \bar{u} + u' \quad (\text{Equation 3.13})$$

$$\text{For y direction: } v = \bar{v} + v' \quad (\text{Equation 3.14})$$

$$\text{For z direction: } w = \bar{w} + w' \quad (\text{Equation 3.15})$$

Dispersion of particles is determined by the turbulence of the flow. Such turbulence fluctuation was estimated based on random walk theory according to the following equations (FLUENT, 2006):

$$u' = \varsigma \sqrt{u'^2} \quad (\text{Equation 3.16})$$

$$v' = \varsigma \sqrt{v'^2} \quad (\text{Equation 3.17})$$

$$w' = \varsigma \sqrt{w'^2} \quad (\text{Equation 3.18})$$

In the above equations, the parameter ς represents the random characteristics of turbulence and was assumed to follow the normal distribution (FLUENT, 2006).

Assuming isotropy, the kinetic energy k is known at each point of the flow, the values of u' , v' , and w' could be approximated according to Equation 3.19:

$$\sqrt{u'^2} = \sqrt{v'^2} = \sqrt{w'^2} = \sqrt{\frac{2k}{3}} \quad (\text{Equation 3.19})$$

The duration of a particle in a turbulent motion along the particle path ds was estimated as in Equation 3.20 (FLUENT, 2006).

$$T = \int_0^\infty \frac{u'_p(t)u'_p(t+s)}{u_p'^2} ds \quad (\text{Equation 3.20})$$

where $u'_p(t)$ and $u'_p(t+s)$ refer to the instantaneous velocity fluctuation u' of the particle at time t and $(t+s)$.

For particles moving with the fluid, T became the fluid Lagrangian integral time T_L which is calculated based on the turbulence characteristics according to the following equation (FLUENT, 2006):

$$T_L = C_L \frac{k}{\varepsilon} \quad (\text{Equation 3.21})$$

Where C_L is a parameter to be determined. C_L is approximated to be 0.15 or 0.30 depending on the turbulence models. ε is the dissipation rate of the turbulent kinetic energy.

The characteristic lifetime of the eddy τ_e is then defined as being proportional to the integral time (FLUENT, 2006) as followed:

$$\tau_e = 2T_L \text{ (Equation 3.22) or } \tau_e = -T_L \log(r) \text{ (Equation 3.23)}$$

where r is a random number between 0 and 1.

The particle eddy crossing time t_{cross} is estimated as described in FLUENT manual (2006) as followed:

$$t_{cross} = -\tau_p \ln \left[1 - \left(\frac{L_e}{\tau_p |u_i - u_i^p|} \right) \right] \quad \text{(Equation 3.24)}$$

Where L_e is the eddy length scale and τ_p is the particle relaxation time and $|u_i - u_i^p|$ refers to the magnitude of the relative velocity.

The particle is assumed to interact with the fluid phase eddy over the time span corresponding to the eddy lifetime, or the eddy crossing time, whichever was smaller. When the duration was equaled or exceeded, a new value of the instantaneous velocity is assigned randomly.

3.3.2.2 *Sediment tracking using FLUENT DPM*

Particle movement about a silt screen was simulated using the Discrete Particles Model in FLUENT. The size distribution of the sediment at a dredging site in Singapore was defined and used as the input for the numerical model (refer to Table 3.5). As can be seen in Table 3.5, the sediment was composed mostly of silt and clay. The simulation runs monitored the number of particles remaining in the simulation domain after a steady state had been reached. To incorporate the effects of turbulent dispersion on particles movement, stochastic tracking with random eddy lifetime was adopted (FLUENT, 2006).

Table 3.5: Specification of the sediment size distribution at the field site

Parameter	Input value
Minimum particle size (μm)	1
Maximum particle size (μm)	361
Mean particle size (μm)	12

a. Initial conditions

The sediment particles were released in a group of 51, and hence 51 streamlines of particles along the water depth of 25 metres were produced. At each run, a total of 1020 particles were injected into the flow domain. The particles released were assumed inert. FLUENT's DPM module provides a preloaded data of materials that could be adopted for particles tracking. The sediment particles were represented as calcium-carbonate, the specific weight of which is 2.71 (the specific weight of natural sediment is 2.65).

b. Boundary conditions

The FLUENT DPM model allows the specification of boundary conditions for certain particles when they arrive at certain boundaries. The stipulated response of the particles at the boundaries includes such properties as "reflect", "trap", or "escape" (FLUENT, 2006). The boundary conditions applied in the simulations are shown in Figure 3.11.

Figure 3.11: Boundary conditions applied in the DPM simulations

Due to the fast flow observed in the lower water layer (as will be discussed in details in chapter 4), the boundary condition at the bed was set as “reflect” condition, assuming that all the particles approaching the bed would be reflected back to the flow. Trapping of particles on the silt screen’s surface was not considered, and hence the “reflect” boundary condition was adopted along the surface of the silt screen.

The temporal locations of the released particles were determined based on the simulated trajectories. The vertical distribution of the particles, on the other hand, was deduced from the histogram of the distribution of particles at specific stream-wise locations.

The effectiveness of the silt screen in containing sediment was assessed by the detention time, which is defined as the duration for which at least 90% of the particles are retained in the upstream zone.

3.4 Field measurements

Field measurements were conducted by DHI Singapore at certain locations in Singapore (DHI Singapore, 2009) where a 400-m length of silt screen of type A (see Section 3.2 for the definition of type A screen) was deployed and laid in open configuration. The silt screen had a submerged depth of 13 metres and was originally placed perpendicular to the ambient current. Detailed properties of the screen as provided by the manufacturer are listed in Table 3.6.

Table 3.6: Properties of silt screen A as deployed at the field site
(as obtained from the manufacturer)

Material	Polyester
Weight	>600 g/m ²
Thickness	>1.2 mm
Mean wide width tensile strength-wet condition	>150kN/m
Mean tensile tension at maximum load – wet condition	<18%
Shrinkage in seawater	<2%
Seawater permeability	<7.5x10 ⁻³ cm/s
UV Resistance (obtained after 60 days of exposure to tropical sunlight)	70%

During the field measurements, the suspended sediment concentration profiles and the velocity profiles were measured using an acoustic Doppler current profiler (ADCP) (Wewetzer et al., 1999). In these field exercises, the ADCP, supplied by Teledyne RD Instruments², was bottom-mounted on the hull of a survey boat (downward looking) and operated at a frequency of 600 kHz. Flow data were collected along six survey lines, so-called transects, at both sides of the silt screen. The transects, which were parallel to the screen, were approximately 10 m, 20 m, and 30 m away from the screen. Communication and control of the ADCP was accomplished using the software VISEA DAS, which was developed by AquaVision BV³. The software was also used to configure and acquire data from the profiler.

Theoretically, the ADCP measures the flow properties along the water depth in a series of specific sized control volumes called bins as illustrated in Figure 3.12. In the measurement, the depth of each bin was assigned to be either 0.5 m or 1 m. The width of the bins, however, varied with transects. The results were presented in the form of backscatter data and flow velocity of the bins in colour bands which were correlated to the range of data acquired (AquaVision BV, 2006a, 2006b).

² Teledyne RD Instrument: <http://www.rdinstruments.com/> (Accessed December 2009)

³ AquaVision BV: <http://www.aquavision.nl/> (Accessed December 2009)

Figure 3.12: Scheme of data collection by an ADCP along a silt screen (a) plan view, and (b) side view along transect AA' with description of the bins arrangements. The flow and sediment data collected by the ADCP present the flow and sediment characteristics of the bins.

The ADCP velocity data contained both the magnitude and direction time series along the water column. By using the VISEA Plume Detection Toolbox, the results of velocity characteristics and suspended sediment concentration of the bins were recorded in ASCII output files. Due to the nature of the ADCP, information on the turbulence characteristics of the flow could not be measured. As a result of the ongoing construction activities on site and vessel availability, only instantaneous

data of the flow and sediment properties in the stipulated area were collected. The flow data obtained at the field were analyzed to verify the flow patterns observed with the laboratory and numerical studies.

To obtain the data on sediment distribution, backscatter data (I) were converted to suspended sediment concentration (C) according to the following relationship as described in AquaVision (2006b):

$$10 \log C = a_1 + b_1 I \quad (\text{Equation 3.25})$$

The coefficients a_1 and b_1 in the above equation were determined through calibration of the backscattered data with SSC measurement (AquaVision BV, 2006b). For each calibration process, a minimum of six water samples were collected at the locations where backscattered data were measured. The samples would then be tested in the laboratory for suspended sediment concentrations. The calibration was then based on the best-fit linear function between $10 \log C$ and I , and was determined using ViSea Plume Detection Toolbox (AquaVision BV). Puckett (1998) and Kostachuk et al. (2005) recommended regular calibration to be carried out during the field exercise. The water quality parameters, including salinity, temperature and density were also measured.

The instantaneous suspended sediment concentration (SSC) profiles measured with the ADCP at the field site were analyzed to elucidate the physical sediment transport process. To avoid the complications of the tidal directions, the data collected during slack tide were excluded from the analysis.

3.5 Study of degradation and clogging of a silt screen system

3.5.1 Environmental degradation of silt screens and its effects on permeability

This experiment was designed to investigate the effects of environmental factors such as UV light, salinity and humidity on the durability of the screen and in particular, the permeability of silt screens.

In this experiment, silt screen samples were prepared in sheets of 100mm x 100mm and stored in transparent plastic containers. Different combinations of salinity, moisture and sunlight conditions (8 scenarios) were simulated. The water quality parameters were measured with YSI⁴ 6600-V2 sonde. The measured water quality results are summarized in Table 3.7.

Table 3.7: Water quality characteristics of the survey site

Parameter	Unit	Measurement result
pH	-	7.9 ± 0.24
Salinity	ppt	29.5± 2.52
Conductivity	mS/cm	49.6± 4.21
Temperature	°C	29.6± 0.05

The environmental conditions adopted in the experiment are listed in Table 3.8. The plastic containers were left exposed to the 8 environmental conditions and were placed in four wire racks outdoors. The dark condition was created in two racks by covering all sides of the racks with thick, heavy-duty canvas (see Figure 3.13). During the planned 24 months of the experiments, silt screen samples were collected at different times of 1, 6, 12, 18, and 24 month from the start. Three silt screen samples were extracted from each experimental scenario, visually inspected for physical degradation, and tested for permeability.

⁴ YSI: <http://www.ysi.com/> (Accessed December 2009)

Table 3.8: Environmental conditions as applied in the experiment on the environmental degradation of silt screens

Condition No.	Description	Moisture condition	pH condition	Salinity condition	Sunlight condition
ATM1	Atmosphere environment	Dry	Atmospheric condition	Atmospheric condition	Dark
ATM2	Atmosphere environment	Dry	Atmospheric condition	Atmospheric condition	Light
FW1	Fresh water	Wet	7	Freshwater condition	Dark
FW2	Fresh water	Wet	7	Freshwater condition	Light
SAL1	Salinity adjusted	Wet	7	29.5± 2.52	Dark
SAL2	Salinity adjusted	Wet	7	29.5± 2.52	Light
SEA1	Seawater	Wet	7.9± 0.24	29.5± 2.52	Dark
SEA2	Seawater	Wet	7.9± 0.24	29.5± 2.52	Light

Figure 3.13: Site layout of the outdoor experiment on the effects of environmental degradation on silt screens' permeability

For the permeability test, the silt screen samples were fitted into a filter and subjected to a constant water head. The setup was carefully checked to ensure there was no leakage. The volume of water permeated across the silt screen and the time taken for it to do so were measured and recorded. The hydraulic conductivity k_{hc} of the sample was determined according to the constant head equation as presented in the following equation (Kasenow, 2002):

$$k_{hc} = \frac{V_w L}{A_f h t} \quad (\text{Equation 3.26})$$

where V_w denotes the volume of water permeated across the screen over a period of time t ; L refers to the thickness of the filter sample, A_f is the cross-sectional area and h represents the head difference across the silt screen.

The permeability K could then be determined based on the estimated hydraulic conductivity k_{hc} according to Equation 3.27 (Kasenow, 2002):

$$K = \frac{k_{hc} \mu_w}{\rho_w g} \quad (\text{Equation 3.27})$$

in which ρ_w (kg/m^3) is the density of water, μ_w is the dynamic viscosity of water (kg/ms) and $g = 9.81 \text{ m}^2/\text{s}$.

3.5.2 Effects of sediment clogging on silt screen's permeability

Section 2.5 highlights the importance of sediment clogging on the performance of a silt screen. In this study, the role of weaving structures on the permeability was investigated by monitoring the change in permeability of three different types of silt screens in flow containing sediment. The three types of silt screens tested - silt screens A, B, and C - were made of woven multi-filament polymer but were of different weaves and porosities (see Figure 3.3, Figure 3.15, and Table 3.9).

Table 3.9: Properties of the silt screens being studied

Silt screen type	Weaving structure	Thickness t_w (mm)	d_{warp} (mm)	d_{weft} (mm)	Initial hydraulic conductivity (m/s)
A	Plain weave	1	1	1.3	3.18×10^{-6}
B	Plain weave	0.5	0.7	1	6.55×10^{-6}
C	Twill weave	1	1	1.3	9.45×10^{-6}

In Table 3.9, d_{warp} and d_{weft} are the centre-to-centre distances between neighboring threads in the warp direction and weft direction of the weaving structure respectively. As illustrated in Figure 3.14, warp direction refers to the longitudinal thread in the roll while weft refers to the transverse thread.

Figure 3.14: Waft and weft directions as defined for plain-weaved structures (adopted from <http://en.wikipedia.org/wiki/Weft>).

Figure 3.15: Schematic illustration of the weaves of the screen samples tested: (a) plain weave; and (b) twill weave

According to Armour and Cannon (1968) and Teitel et al. (2009), the porosity of woven multifilament structures such as silt screens is governed by three factors: (1) thread diameters in the warp and weft directions, (2) weaves, and (3) the arrangement of threads in the warp and weft directions. Of the three silt screens investigated, both silt screens A and B exhibited a plain weave structure. The different arrangement of threads in warp and weft directions resulted in higher porosity in silt screen B. On the other hand, silt screens A and C, which were tightly weaved and designed for stronger current, had the same thread arrangement in both the warp and weft directions (refer to Table 3.9), but differed in weaves (as observed in Figure 3.3 and Figure 3.15).

Figure 3.17 shows the experimental setup used in these experiments. A silt screen sample with diameter of 0.1 m was firmly secured and placed normal to the flow. During the test run, the screen sample was subjected to a continuous influx of water containing 300 mg/L of sediment. The cumulative size distribution of the particles used is shown in Figure 3.16. During the experiment, the water head was maintained constant while the outlet was open to the atmosphere.

Figure 3.16: The size distribution of the particles used in the experiments on the effects of sediment clogging on the permeability of silt screens

During the experiments, the permeability of the silt screen sample was measured at various time intervals after the start of the experiment (the intervals used are

listed in Table 3.10). After each time interval, the permeability of the screen was calculated based on the flow rate of the effluent collected at the collector (refer to Figure 3.17). With the measured volume of collected effluent, the hydraulic conductivity of the sample was estimated according to the constant head permeability equation (Equation 3.26). The results of the experiment show the temporal variation of the permeability of the three types of silt screens tested. The results are used to evaluate the influence of silt screen structures on clogging behaviour.

Table 3.10: Time steps of permeability measurement in the clogging experiments

Time step	Time
0	0 (start time)
1	15 minutes
2	30 minutes
3	45 minutes
4	60 minutes
5	90 minutes
6	2 hours
7	2.5 hours
8	3 hours
9	4 hours
10	6 hours
11	8 hours
12	9 hours

Figure 3.17: Diagram of the setup of the experiment on the effects of clogging on the permeability of a silt screen

4. Results

4.1 General

Flow characteristics play a vital role on how sediment is redistributed around a silt screen. The movement of sediment is strongly influenced by the flow patterns and flow characteristics. Ideally, an effective silt screen is one that creates a flow environment that results in effective sediment containment and minimizes sediment movement/ dispersion outside the silt screen enclosure.

Figure 4.1 illustrates the components and processes that determine the sediment containment around a silt screen and the questions that an effective silt screen design needs to address. The key question remaining is whether a silt screen, based on the current design practice, is able to create a desirable flow environment that results in efficient and effective containment of sediment. The associated issues have been discussed in the literature review in Chapter 2, and methods to investigate the various physical, hydraulics and sediment characteristics have been presented in Chapter 3. This chapter presents the findings of the investigations carried out in this study.

Figure 4.1: Description of the processes involved around a silt screen system, and the context of the research questions set forth

Regarding the structural stability of silt screens under the effects of environmental degradation, a preliminary study was conducted to investigate the potential effects of environmental degradation on silt screen properties, in particular permeability. The results (shown in Appendix J) indicate insignificant changes in the permeability of the silt screens during the 2-year experiments. This suggests that the exposure of silt screens in the tested environments of various conditions of pH, salinity and humidity does not affect the screens' permeability.

On the other hand, the results obtained from the clogging experiments indicated significant decrease in the permeability of the silt screens during the clogging experiments. This suggests that during silt screen deployment, considerable sediment mass could be clogged on the silt screen's surface. However, it is noted that the experimental setup does not completely reflect the field condition. In the experiments, the silt screen samples were subjected to a vertical flow while in the

field, silt screens are normally subjected to a horizontal incident flow. Because of such difference, the results on the effects of clogging on silt screen properties are not conclusive. The roles of flow velocity and screen properties that determine the clogging process have to be further investigated.

In the following sections, the results on the flow characteristics and sediment movement in the vicinity of a silt screen are discussed. The results from the laboratory experiments, numerical simulations and field observations are presented accordingly. The effects of different screen properties and incident flow conditions on the flow distribution and sediment movement around a silt screen are also elucidated.

The experimental results on the flow patterns, velocity profiles and turbulence characteristics around a silt screen are described in section 4.2. This section also discusses the pertinent flow parameters that influence the sediment containment and sediment dispersion around silt screens. In section 4.3, the simulation results on the flow characteristics and sediment redistribution around a silt screen are presented. Field data are discussed in section 4.4.

4.2 Laboratory results

4.2.1 Flow characteristics around silt screens and the effects of screen type

4.2.1.1 *Flow patterns*

Figure 4.2 shows an example of the typical distribution of the flow patterns as observed in the experiments with the three silt screens A, B and C.

Figure 4.2: Typical flow patterns in the immediate vicinity of a silt screen as observed from the experiments with a silt screen with $SPR=0.5$ and $U_0=0.05$ m/s

The streamlines distribution in Figure 4.2 shows that upstream of the silt screen, a vortex or a recirculation zone is formed in the upper water layer. In the lower water layer, the flow is deflected towards the gap formed between the silt screen's lower end and the bed. This deflected flow, upon emerging from below the screen and entering the water in the lee of the screen, forms a region of strong flow in the lower water layer and a large vortex or recirculation zone in the upper water layer (as depicted in Figure 4.2). Such flow arrangement in the lee of the screen is typical of a submerged plane jet (Ead et al., 2004; Dey et al., 2010).

4.2.1.2 Velocity profiles

Figure 4.3 shows the typical velocity profiles obtained from the laboratory experiments with the three types of silt screens. With all the three silt screens, the variations of horizontal and vertical velocities along the water depth exhibit similar patterns (refer to Figure 4.3). Upstream of the screens (Figure 4.3a), the profiles of the horizontal velocity indicate an area of slow velocity in the upper water layer. With silt screen A ($SPR = 0.7$), and for the water column from the surface to $z/H =$

0.17, the magnitude of the measured horizontal velocity component at location $x=-H$ is smaller than that of the incident flow (i.e. $u/U_0 < 1$). In this thesis, the extent of the water depth where $u/U_0 < 1$ (denoted as L_{retarded} in Figure 4.4) is referred to as the extent of the retarded flow region. With silt screens B and C, the retarded flow regions extend to water depth $z/H = 0.23$ and 0.2 , respectively (see Figure 4.3).

Figure 4.3: Profiles of the horizontal velocity component (a&c) and vertical velocity component (b&d) obtained at D1 of three silt screens A, B and C (SPR=0.7; $U_0 = 0.05$ m/s). The profiles shown in a & b were collected upstream and the profiles shown in c & d were collected downstream of the screens (the screen coverage is highlighted with a thick red solid line on the ordinate).

Figure 4.4: Diagrammatic definition of the extent of the upstream retarded region

As the flow moves downstream, two distinct flow regions can be discerned in the profiles of the horizontal velocity component (see Figure 4.3c and the profiles at D1, D2, and D3 in Figure 4.5c). Slow flow is recorded in the upper water layer while fast flow is observed in the lower layer. Figure 4.5 shows an example of the development of the profiles of the horizontal and vertical components of the flow velocity along the stream-wise direction. The data were collected at five locations upstream and downstream of the silt screen in the experiment setup (refer to section 3.2). Upstream of the screen, the velocity profiles show high flow velocity in the lower water layer. Downstream of the screen, reverse flow was observed in the upper water layer. In the lower water layer, the magnitude of the flow indicates a fast flow. At location D1, the magnitude of this flow could reach as high as three times of the original incident velocity. As the flow moves further downstream, this fast flow is weakened. In the example shown in Figure 4.5, as the flow moves from location $x=H$ to $x=3H$ downstream, the largest recorded normalized horizontal velocity drops from 3.04 to 2.01.

Figure 4.5: Mean velocity profiles across a screen – horizontal velocity profiles (a&c), vertical velocity profiles (b&d) at locations upstream (U1 and U2) and downstream (D1, D2, and D3) of the screen (the locations U1, U2, D1, D2 and D3 are as defined in section 3.2).

To examine the distribution of the flow patterns around a silt screen, the following parameters were used:

- (1) The extent of the upstream recirculation zone – defined as the fraction of the water depth occupied by the recirculation zone (L_{reverse}) along the vertical plane across the point where the maximum reverse horizontal flow was recorded. Along this plane, the centre of the recirculation zone, R , is defined at half-length of the water fraction occupied by the reverse flow, as illustrated in Figure 4.6 and Figure 4.7.

- (2) Upstream recirculation rate, which is defined as the percentage of the flow rate per metre width of the reverse flow (q_{reverse}) to the incident flow per metre width (q_0) along the vertical plane across R (refer to Figure 4.6, Figure 4.7 and Appendix D).
- (3) Downstream recirculation rate, which is quantified as the percentage of the reverse flow per metre width (q_{reverse}) at location $x=H$ to the original incident flow (refer to Figure 4.7a). Table 4.1 summarizes the results on the distribution of the flow patterns obtained from the experiment with a silt screen of $\text{SPR}=0.5$. Upstream of the screen, the upstream recirculation zone only accounts for less than 5% of the incident flow. This implies that most of the upstream flow diverts towards the lee side. Downstream of the screen, recirculation contributes more significantly to the flow (see Table 4.1).

Figure 4.6: Schematic illustration of flow patterns around a silt screen, and the centre of the upstream recirculation zone

Figure 4.7: Diagrammatic description of the definitions of the reverse flow rate (per metre width) (a) and the extent of the upstream recirculation zone (b)

Table 4.1: Examples of the estimated flow patterns distribution around silt screens A, B and C (for $U_0=0.05$ m/s and $SPR=0.7$)

Screen type	q_0 (m^3/ms)	Upstream recirculation		Extent of the upstream recirculation zone	Downstream recirculation (at $x=H$)	
		q_{reverse} (m^3/ms)	Recirculation rate		q_{reverse} (m^3/ms)	Recirculation rate
A	0.012	2×10^{-4}	2 %	0.2	2.8×10^{-3}	23 %
B	0.012	4×10^{-5}	0.3 %	0.1	2.5×10^{-3}	21 %
C	0.012	8×10^{-5}	0.7%	0.1	2.6×10^{-3}	22 %

The values of the estimated extent of the upstream recirculation zone and the upstream recirculation rate and the downstream recirculation rate shown in Table 4.1 do not indicate any clear effects of screen type on the flow characteristics.

4.2.1.3 Turbulence characteristics

Figure 4.8 shows the turbulence intensities of the horizontal and vertical flow components observed in the laboratory experiments for the three types of silt screens.

Figure 4.8: Profiles of the normalized turbulence intensity of the horizontal (a) and vertical (b) velocity components at location $x=H$ downstream of the three types of silt screens. The data were collected in experiments with $U_0=0.05$ m/s and $\text{SPR} = 0.7$ (the screen coverage in the water column is highlighted with a thick red solid line on the ordinate).

As can be seen in Figure 4.8, the profiles of turbulence intensity for both velocity components as measured in the laboratory experiments for the three silt screens show increasing turbulence intensity from the surface to a certain water depth. In the case of a screen with $\text{SPR} = 0.7$ and $U_0=0.05$ m/s (as shown in Figure 4.8), the maximum turbulence intensity of the horizontal velocity component was recorded at $z/H = 0.8$. For the turbulence intensity of the vertical velocity component, the largest turbulence intensities for silt screens A, B and C are close. High turbulence in the lower water layer is also observed in the turbulent kinetic energy profiles recorded at location $x=H$ downstream of the three silt screens, see Figure 4.9. The

observed largest turbulent kinetic energy for the three silt screens (of SPR=0.7) are 0.0016, 0.0018 and 0.002 m^2/s^2 and are observed at $z/H = 0.80$, 0.74 and 0.78, respectively.

Figure 4.9: Distribution of the turbulent kinetic energy along the depth at location $x=H$ downstream of silt screens A, B and C (SPR=0.7, $U_0=0.05$ m/s) (the screens' coverage is highlighted with a thick red solid line on the ordinate).

4.2.2 Flow characteristics around silt screens and the effects of screen penetration depth

4.2.2.1 Flow patterns

In Figure 4.10, the streamlines observed around silt screen A (for screen penetration ratio (SPR) of 0.5 and 0.7) are shown. These streamlines help to visualize the distribution of flow around a silt screen and demonstrate the effects of screen penetration ratio on the flow distribution.

Figure 4.10: Distribution of the streamlines around silt screen A of screen penetration ratio (SPR) of 0.5 (a&c) and 0.7 (b&d) in incident flow velocity of 0.05 m/s (a&b) and 0.1 m/s (c&d). In the cases presented, the silt screens were anchored firmly to the bottom of the flume and formed a vertical shape.

As can be seen in Figure 4.10, the flow patterns in the immediate vicinity of the screen are similar for SPR of 0.5 and 0.7. In both cases, the streamlines show a recirculation zone in the upper water layer upstream of the screen. Downstream of the screen, a large recirculation zone is observed in the upper water layer and the lower water layer is dominated by a submerged plane jet-like flow (refer to Figure 4.10).

Table 4.2 summarizes the recirculation rates estimated at locations upstream (across R) and $x=H$ downstream of silt screens of different screen penetration ratios (SPR). The incident flow velocity is 0.05 m/s. The results show that there is little difference in the upstream recirculation rate when the screen penetration ratio changes. The downstream recirculation rate slightly increases as the SPR is increased.

Table 4.2: Estimated upstream and downstream recirculation rates of silt screens of various screen penetration ratios in incident flow velocity of 0.05 m/s

U_0 (m/s)	SPR	q_0 ($m^3/m.s$)	Upstream recirculation (across R)		Downstream recirculation (at $x=H$)	
			$q_{reverse}$ ($m^3/m.s$)	Upstream recirculation rate	$q_{reverse}$ ($m^3/m.s$)	Downstream recirculation rate
0.05	0.5	0.012	2×10^{-4}	2%	0.0029	23%
0.05	0.7	0.012	1.4×10^{-4}	1%	0.0031	26%
0.05	0.8	0.012	3.5×10^{-4}	3%	0.0039	32%

4.2.2.2 Velocity profiles

Figure 4.11 and Figure 4.12 show the development of the velocity profiles around silt screens with SPR of 0.5 and 0.7. In both cases, the incident flow is 0.05 m/s.

Figure 4.11: Velocity profiles measured at upstream locations (U1, U2) and downstream locations (D1, D2 and D3) around a silt screen with SPR=0.5 in incident flow velocity $U_0=0.05$ m/s (the locations are as defined in Chapter 3, the coverage of the screen is highlighted with a thick red line on the ordinate).

Figure 4.12: Velocity profiles measured at upstream locations (U1, U2) and downstream locations (D1, D2 and D3) around a silt screen of SPR=0.7 in incident flow velocity $U_0=0.05$ m/s (the coverage of the screen is highlighted with a thick red line on the ordinate).

As observed in Figure 4.11, Figure 4.12 and Figure 4.13, the effects of screen penetration ratio are most obvious in the increased horizontal velocity in the lower water layer downstream of the screen. As shown in the horizontal velocity profiles observed at $x=H$ downstream of the screens, the largest horizontal velocity increases from 3 to 4.1 (in terms of u/U_0) when the screen penetration ratio is increased from 0.5 to 0.7. This finding is to be expected, as it is anticipated that for conservation of mass, an increase in silt screen length would result in increased velocity of the flow through the smaller gap between the screen and the bed. On

the other hand, the results do not indicate any clear effects of screen penetration ratio on the vertical flow velocity.

Figure 4.13: The variation of horizontal velocity component (a&c) and vertical velocity component (b&d) recorded at locations $x=-H$ upstream (a&b) and $x=H$ downstream (c&d) of silt screens with screen penetration ratios (SPR) of 0.5 and 0.7 in incident flow velocity $U_0=0.05$ m/s.

4.2.2.3 Turbulence characteristics

Figure 4.14 shows the turbulence intensities of the horizontal and vertical components of the flow velocity around silt screens with screen penetration ratios of 0.5; 0.7 and 0.8. In general, higher turbulence intensity is observed downstream of silt screens with larger penetration ratios. The largest turbulence intensities of both horizontal and vertical velocity components recorded at all the three

downstream locations (D1, D2 and D3) increase when the screen penetration ratio increases. For example, the largest turbulence intensity of the horizontal velocity component recorded at D1 increases from 50% to 130% as the screen penetration ratio is lengthened from 0.5 to 0.8. Such an increase is also seen in the turbulent kinetic energy, see Figure 4.15.

Figure 4.14: Profiles of normalized turbulence intensities in the lee of silt screens of different screen penetration ratios (SPR): SPR=0.5 (a&b), SPR=0.7 (c&d), SPR=0.8 (e&f) (the locations D1, D2 and D3 are as defined in Chapter 3; the coverages of the screens are highlighted with a thick red line on the ordinate)

Figure 4.15: Distribution of turbulent kinetic energy upstream and downstream of a silt screen of SPR=0.5 (a&b) and in the lee of screens of SPR = 0.7 (c) and SPR = 0.8 (d) (the coverages of the screens are highlighted with a thick solid red line on the ordinate).

4.2.3 Flow characteristics around silt screens and the effects of incident flow condition

4.2.3.1 Flow patterns

In Figure 4.16, the streamlines observed around silt screens in incident flows of 0.05 m/s and 0.1 m/s are presented. In all these cases the following common characteristics are observed:

- (1) A vortex formation is seen in the upper water layer upstream of the screen. In the streamlines observed with incident flow velocities of 0.05

m/s and 0.10 m/s, this vortex functions as a recirculation zone in the upper water layer;

- (2) A significant amount of flow is diverted towards the gap formed between the screen's lower end and the bed; and
- (3) The formation of two layers of flow downstream of the screen, an upper recirculation zone and a lower submerged plane-jet like flow.

Figure 4.16: Distribution of the streamlines around silt screens as obtained from the PIV experiments with silt screens of SPR=0.5 (a&c) and SPR =0.7 (b&d) in incident flow velocity of 0.05 m/s (a&b) and 0.1 m/s (c&d). The screens were deployed normal to the flow.

The distribution of the flow patterns, however, could slightly vary when the screens are deployed in different incident flow velocities as can be seen in Table 4.3, which summarizes the estimated extents of the upstream recirculation zones for different incident velocities.

Table 4.3: Estimated extents of the upstream recirculation zone in experiments of different flow conditions

U_0 (m/s)	SPR	Extent of the upstream recirculation zone
0.05	0.5	0.2
0.10	0.5	0.23
0.05	0.7	0.27
0.10	0.7	0.21

As described in Chapter 2, a silt screen system is a flexible structure in which a geotextile skirt is deployed vertically and stabilized using a system of tension elements, anchors and ballast, and a floating system. Thus, under the effects of the flow, deflection of the screen skirt away from the vertical plane could take place. To examine the distribution of the flow patterns around silt screens in deflected configurations, the flow characteristics around silt screens which are free to deflect were investigated. The experimental results show that the streamlines around deflected screens exhibit similar flow patterns to those of rigid screens, as seen in Figure 4.17. However, the distribution of flow patterns is affected by the vertical configurations of the screen, as observed in Table 4.4.

Figure 4.17: Distribution of the streamlines around silt screens as obtained from the PIV experiments with silt screens of $SPR=0.5$ (a&c) and $SPR=0.7$ (b&d) in incident flow velocity of 0.05 m/s (a&b) and 0.1 m/s (c&d). The screens were free to deflect by the flow.

Table 4.4 summarizes the estimated extents of the recirculation zone upstream of vertical (rigid) and deflected silt screens for various flow and screen penetration depths. The vertical silt screen was fully secured to the channel and maintained rigid in the vertical direction. In the “free” condition, the screens were free to deflect. Compared to that of a rigid silt screen of similar screen penetration ratio, the extent of the upstream recirculation zone of a deflected silt screen is slightly smaller.

Table 4.4: Estimated extents of the recirculation zone upstream of silt screens deployed in rigid and deflected (free) conditions

U_0 (m/s)	SPR	Screen deployment condition	Extent of the upstream recirculation zone
0.05	0.5	free	0.2
0.05	0.5	rigid	0.2
0.05	0.7	free	0.25
0.05	0.7	rigid	0.27
0.1	0.5	free	0.23
0.1	0.5	rigid	0.23
0.1	0.7	free	0.20
0.1	0.7	rigid	0.21

4.2.3.2 Velocity profiles

Figure 4.18 depicts the characteristics of the flow upstream and downstream of a silt screen for various flow conditions. In the velocity profiles observed at location $x=-H$ upstream of the screen and for $U_0=0.05$ m/s, the lowest normalized horizontal velocity recorded along the water depth is -0.15. This negative value suggests reverse flow in the upper water layer. When the same silt screen is deployed in the flow of 0.1 m/s, the lowest normalized horizontal velocity recorded at location $x=-H$ is 0.53. Reverse flow is not observed in this flow scenario.

The values of the maximum normalized horizontal velocity observed at location $x=H$ downstream of the screens are 4.4 and 4.1 for the incident flow of 0.05 m/s and 0.1 m/s, respectively. The profiles of the horizontal velocity component observed at location $x=H$ downstream of the screen exhibit an almost identical trend in both cases of incident flow velocity (see Figure 4.18).

Figure 4.18: Profiles of the normalized horizontal velocity observed at locations $x=-H$ upstream (a&c) and $x=H$ downstream (b&d) of a silt screen with $SPR=0.7$ and deployed in vertical configuration in incident flow velocities of 0.05 m/s (a&b) and 0.1 m/s (c&d).

Figure 4.19 shows typical flow characteristics observed around a rigid and a deflected silt screens with similar screen penetration ratios. Upstream of the screen, the retardation effects in the upper water layer were less significant in the case of the free-to-deflect silt screen. The lowest normalized horizontal velocity observed is 0.7 compared to 0.5 for a rigid screen. Downstream of the screen, the normalized horizontal velocity profiles of the two silt screen configurations exhibit different shapes of the velocity profile in the upper layer. As seen in Figure 4.19, the range of the normalized horizontal velocity for a rigid silt screen is from -0.8 to 0. In the case of the free-to-deflect screen, the values of the normalized horizontal

velocity range from -0.5 to 0.2. At $x=H$ downstream, the estimated recirculation rate is smaller downstream of the deflected silt screen compared to that of a rigid screen, as shown in Table 4.5 (which shows the estimated rates of the recirculation zones downstream of rigid and free-to-deflect silt screens in the incident flow velocity of 0.05 m/s).

Figure 4.19: Profiles of the normalized horizontal velocity observed at locations $x=-H$ upstream (a&c) and $x=H$ downstream (b&d) of a silt screen (SPR=0.7) deployed in rigid condition (a&b) and deflected condition (c&d) in the incident flow velocity of 0.1 m/s (the vertical coverage of the screens are highlighted with thick red lines on the ordinate).

Table 4.5: Estimated downstream recirculation rates for a rigid and a deflected silt screens with SPR=0.7

U_0 (m/s)	Screen condition	q_0 (m ³ /m.s)	q_{reverse} (m ³ /m.s)	Recirculation rate at $x=H$ downstream of the screen
0.05	Rigid	0.012	0.0029	24.0%
0.05	Free-to-deflect	0.012	8.37×10^{-4}	7%

4.2.3.3 Turbulence characteristics

Figure 4.20: Distribution of turbulence intensity in the horizontal and vertical direction at location $x=H$ downstream of silt screen A with SPR=0.7 and submerged in the incident velocity of 0.05 m/s and 0.10 m/s (the vertical coverage of the screens are highlighted with a thick blue solid line on the ordinate).

Figure 4.20 shows the turbulence intensity profiles observed in the lee of a silt screen in two flow conditions. The profiles of the turbulence intensities do not show significant difference between these two flow conditions. However, as seen in Figure 4.21, in both cases of SPR=0.5 and SPR=0.7, along the entire depth, the turbulent kinetic energy observed for the flow velocity of 0.1 m/s is greater than that for the flow velocity of 0.05 m/s. This observation suggests that higher turbulent kinetic energy is expected in the lee of the screen in faster flows.

Figure 4.21: Turbulent kinetic energy profiles obtained at location $x=H$ downstream of silt screens of $SPR=0.5$ (a) and $SPR=0.7$ (b) in two incident flow velocities of 0.05 m/s and 0.10 m/s (the vertical coverage of the screens are highlighted with a thick blue solid line on the ordinate).

4.2.4 Flow patterns and sediment movement in the vertical plane

In the previous section, the flow characteristics around a silt screen are presented. The results were obtained from experiments on the flow around the silt screens laid out in the vertical plane as per the prevailing design practice. The flow patterns and the velocity profiles observed from the laboratory experiments reveal three notable features of the flow patterns in the vertical plane around a silt screen: (1) a retarded flow formed in the upper water layer upstream of the screen; (2) a large recirculation zone in the upper water layer downstream of the screen, and (3) a strong submerged plane jet-like flow at the lower water layer downstream of the silt screen. These flow patterns influence the movement of sediment in different ways. The transport of sediment could be retarded in the slow flow regions – including the upstream retarded flow region and the downstream recirculation zone. On the contrary, the submerged plane jet is known to have high sediment transport capacity and could entrain and transport sediment.

Because of the potential effects of these flow patterns on sediment containment, it is useful to understand the characteristics of these flow patterns and how design parameters influence such flow characteristics.

In this study, the containment of sediment in the downstream recirculation zone is not considered. It is stipulated that the containment of sediment upstream of a silt screen may be related to the extent of the upstream retarded flow. There, under the effects of the slowed flow velocity, sediment transport would be retarded. To illustrate the (vertical) spatial influence of the silt screen in the upstream region, the extent of the upstream retarded flow is represented by the ratio of the depth of the retarded zone to the original water depth. The depth of the retarded flow is estimated as the vertical distance from the surface to the water depth where the magnitude of the horizontal velocity equals that of the ambient incident flow (refer to Figure 4.4).

On the other hand, sediment transport/ entrainment around a silt screen is correlated to the magnitude of the flow. The maximum (resultant) flow is logically the parameter that may be used to indicate the magnitude of the flow around a silt screen and the potential of sediment entrainment around the screen.

The results presented in the previous section discuss the influence of screen type, screen penetration ratio and incident flow velocity on the distribution of flow patterns and flow characteristics around a silt screen. In the next section, the experimental results regarding the effects of these three parameters (screen type, screen penetration ratio and incident flow velocity) on the parameters of “containment-flow” (i.e. the extent of the upstream retarded flow region and the maximum resultant flow as discussed above) will be elaborated.

For simplicity, the extent of the upstream retarded flow region is defined based on the results of the flow obtained at location $x=-H$ upstream of the silt screen. For the cases of vertical silt screens, the second “containment-flow” parameter, the magnitude of the flow, is defined representatively as the maximum normalized velocity, which is the ratio of the maximum resultant flow measured along the

water depth at location $x=H$ downstream of the screen to the original incident flow.

4.2.4.1 Effects of screen type on “containment-flow”

Table 4.6 presents the results on the “containment-flow” parameters obtained with silt screens A, B and C. As can be seen in Table 4.6, the results on the extent of the retarded flow do not indicate any clear effects of screen type on the extent of the upstream retarded flow. Similarly, the results on the maximum flow velocities at location $x=H$ downstream obtained with different screen types are comparable.

Table 4.6: Estimated characteristics of the “containment-flow” around screens A, B and C (SPR=0.7, $U_0=0.05$ m/s).

U_0 (m/s)	SPR	Screen type	Extent of the upstream retarded flow at $x=-H$	Maximum normalized velocity at $x=H$
0.05	0.7	A	0.17	4.39
0.05	0.7	B	0.23	4.14
0.05	0.7	C	0.20	4.31

4.2.4.2 Effects of screen penetration depth on “containment-flow”

In Table 4.7, the experimental results on the characteristics of the “containment-flow” with silt screens of different screen penetration ratios are presented. As can be seen in Table 4.7, for incident flow velocity of 0.05 and 0.1 m/s and at location $x=-H$ upstream of the screen, the extent of the upstream retarded region is larger with increased screen penetration depth. Of the three screen penetration ratios considered, the largest upstream retarded zone was observed for screens with SPR=0.8. This could be due to the weaker effect of a silt screen in blocking the flow when the screen covers less of the flow depth. On the other hand, increasing screen penetration ratio also results in stronger flow in the lower water layer. As

seen in Table 4.7, higher maximum normalized velocity was recorded at location $x=H$ downstream of screens with higher screen penetration ratios.

Table 4.7: Characteristics of the “containment-flow” obtained from the experiments with silt screens (screen A) of different screen penetration ratios.

U_0 (m/s)	SPR	Extent of the upstream retarded zone	Maximum normalized velocity at $x=H$
0.05	0.5	0.08	3.04
0.05	0.7	0.17	4.39
0.05	0.8	0.25	5.84
0.1	0.5	0.21	3.06
0.1	0.7	0.32	4.11
0.1	0.8	0.41	5.60

4.2.4.3 Effects of incident flow velocity on “containment-flow”

From Table 4.7, it was also observed that the “containment-flow” parameters varied when the silt screens were subjected to different incident flow velocities. With silt screens of the same screen penetration ratio, the results show a trend of larger upstream retarded zone being formed when the screen is deployed in stronger flow. To assess the potential effects of flow velocity on sediment entrainment, the absolute values of the maximum flow velocity at location $x=H$ obtained when the silt screens were submerged in different flow conditions were compared. As seen in Table 4.8, in the cases of stronger incident flow ($U_0=0.1$ m/s), stronger flow was recorded downstream of the screen. For example, with $SPR=0.8$ and $U_0=0.1$ m/s, the maximum resultant flow velocity recorded at $x=H$ was 0.56 m/s (compared to 0.29 m/s when $U_0=0.05$ m/s).

Table 4.8: Variation of the magnitude of the flow around silt screens (of type A) submerged in different incident flow velocities.

U_0 (m/s)	SPR	Maximum normalized velocity at $x=H$	Maximum resultant flow velocity at $x=H$ (m/s)
0.05	0.5	3.04	0.15
0.05	0.7	4.39	0.22
0.05	0.8	5.84	0.29
0.1	0.5	3.06	0.31
0.1	0.7	4.11	0.41
0.1	0.8	5.60	0.56

4.3 Simulation results

4.3.1 Characteristics of the flow in the vertical plane around a silt screen (2DV simulation)

4.3.1.1 *Simulation results of the flow around a silt screen in the flume setting (2DV)*

Figure 4.22 presents the simulated flow patterns around a silt screen with SPR=0.7 in the incident flow velocity $U_0=0.05$ m/s. The development of the flow patterns along the stream-wise direction in the vicinity of a silt screen was simulated using the software package ANSYS FLUENT (version 11, 2010). In general, the simulated flow patterns exhibit most of the features observed in the experimental results. As the flow approaches the screen, the flow is deflected downward towards the gap formed between the lower end of the screen and the bed. In the lee of the silt screen, a recirculation zone is clearly visible in the upper water layer. Meanwhile, a fast flow dominates the lower water layer in the downstream region (see Figure 4.22).

Figure 4.22: An example of the flow patterns distribution around a silt screen along the simulated domain (a) and in the vicinity of the screen (b) (the location of the screen, which is denoted with the blue line, is marked by the arrow) (corresponding to the simulation of a silt screen with $SPR=0.7$ and in the incident velocity $U_0=0.05$ m/s).

The simulation results of the velocity profiles at various locations downstream of a silt screen of $SPR=0.7$ are appended in Appendix G. From the velocity profiles, it was observed that in the presence of a silt screen, the flow along the water column at the location $x=-H$ upstream of the silt screen is affected. As elaborated in Appendix G, the size of the vortex downstream of the screen extends as far as a downstream distance of $x=7H$ when the screen penetration ratio is 0.7. The numerical simulation, however, could not reproduce the recirculation pattern upstream of the silt screen as observed in the PIV experiments (see Figure 4.6). Such limitation in reproducing the recirculation zones is inherent in RANS turbulence models as noted in Vuik (2010).

In Figure 4.23 and Figure 4.24, the results of the numerical simulations of silt screens with $SPR=0.5$ and $SPR=0.7$ and subjected to the incident flow velocity $U_0=0.05$ m/s are compared with the experimental results. The profiles of the horizontal velocity component at $x=-H$ upstream and $x=H$ downstream of the silt screens are compared with the respective profiles that were recorded in the laboratory experiments. In general, the variations of the velocity profiles obtained from the simulation results exhibit similar trend as the corresponding

experimental data. However, as discussed earlier, and shown in Figure 4.23 and Figure 4.24, the simulations could not reproduce the retarded flow region in the upper water layer upstream of the screens. In the lower water depth, the largest difference between the simulated velocity and the experimental results of the two cases are about 25-30% (see Figure 4.23 and Figure 4.24).

The above limitations aside, the simulation results are still useful in predicting the flow development and sediment movement. Based on the experimental results, the upstream recirculation zone contributes to less than 5% of the incident flow. Thus, the simulated flow still reflects the behavior of bulk of the flow. In terms of sediment movement prediction, the simulation results on the maximum flow velocity tend to err on the higher side compared to the corresponding experimental results at the same location. As such, the simulation results can be used as conservative predictions of the flow magnitude around a screen.

Figure 4.23: Comparison of the horizontal velocity profiles obtained at locations $x=-H$ upstream (a) and $x=H$ downstream (b) of a silt screen (SPR=0.5; $U_0=0.05$ m/s) (the coverage of the silt screen is highlighted with a thick red solid line on the ordinate).

Figure 4.24: Comparison of the horizontal velocity profiles obtained at locations $x=-H$ upstream (a) and $x=H$ downstream (b) of a silt screen ($SPR=0.7$; $U_0=0.05$ m/s) (the coverage of the silt screen is highlighted with a thick red solid line on the ordinate).

4.3.1.2 Simulation results of the flow around a silt screen in pilot scale

a. Simulation results of the flow around a silt screen of the prevailing design

The characteristics of the flow in the pilot scale around a silt screen of the prevailing design practice were obtained from the numerical simulation of a single-section vertical silt screen with SPR of 0.9. The simulated velocity profiles are presented in Figure 4.25. According to the simulation, the retarded flow occupies approximately 24% of the depth of the water column. In Figure 4.26, the variation of the downstream recirculation rate along the stream-wise direction of a silt screen designed according to the prevailing design practice is shown. The characteristics of the “containment flow” were drawn from the simulated velocity profiles and presented in Table 4.9.

(a)

(b)

Figure 4.25: Variation of the horizontal flow velocity along the stream-wise direction upstream (a) and downstream (b) of a silt screen based on the prevailing design practice (SPR=0.9; $U_0 = 0.05$ m/s).

Figure 4.26: Spatial variation of the downstream recirculation rate as obtained from the simulation of a silt screen configuration based on the prevailing design practice (SPR=0.9; $U_0=0.05$ m/s).

b. Effects of the vertical configuration of silt screens on “containment-flow”

This section presents the findings on the flow characteristics around screens of various vertical configurations based on numerical simulation. As described in Chapter 3, the effects of the vertical configuration of a screen on “containment-flow” have been examined by studying the flow patterns around six hypothetical compound configurations. In the following section, the characteristics of the “containment-flow” in the vicinity of these six compound configurations are presented and compared with the prevailing design practice of a single-segment silt screen.

In Figure 4.27, Figure 4.28, Figure 4.29, Figure 4.30, Figure 4.31 and Figure 4.32, the simulated velocity profiles upstream and downstream of a silt screen with the six compound configurations are presented. Based on the simulated velocity profiles, the characteristics of the “containment-flow” obtained with the compound configurations are summarized in Table 4.9. In Table 4.9, to assess the effects of the vertical configurations on flow magnitude, the maximum normalized velocity was defined as the maximum normalized resultant velocity obtained along the entire domain.

(a)

(b)

Figure 4.27: Variation of the horizontal flow velocity around a silt screen of configuration 2.1 upstream (a) and downstream (b) of the silt screen (SPR=0.9; $U_0=0.05\text{m/s}$).

(a)

(b)

Figure 4.28: Variation of the horizontal flow velocity around a silt screen of configuration 2.2 upstream (a) and downstream (b) of the silt screen (SPR=0.9; $U_0=0.05\text{m/s}$).

(a)

(b)

Figure 4.29: Variation of the horizontal flow velocity around a silt screen of configuration 2.3 upstream (a) and downstream (b) of the silt screen (SPR=0.9; $U_0=0.05\text{m/s}$).

(a)

(b)

Figure 4.30: Variation of the horizontal flow velocity around a silt screen of configuration 2.4 upstream (a) and downstream (b) of the silt screen (SPR=0.9; $U_0=0.05\text{m/s}$).

(a)

(b)

Figure 4.31: Variation of the horizontal flow velocity around a silt screen of configuration 3.1 upstream (a) and downstream (b) of the silt screen (SPR=0.9; $U_0=0.05\text{m/s}$).

(a)

(b)

Figure 4.32: Variation of the horizontal flow velocity around a silt screen of configuration 3.2 upstream (a) and downstream (b) of the silt screen (SPR=0.9; $U_0=0.05\text{m/s}$).

Table 4.9: Simulation results on the characteristics of the “containment-flow” around silt screens of the six tested compound configurations

Configuration	Extent of the upstream retarded flow region (fraction) (at $x=-H$)	Maximum normalized velocity (along the entire domain)
2.1	0.54	17.2
2.2	0.39	13.4
2.3	0.52	17.3
2.4	0.41	12.6
3.1	0.56	17.6
3.2	0.39	13.6
Prevailing design practice	0.25	14.96

As can be seen from Figure 4.25, Figure 4.27, Figure 4.28, Figure 4.29, Figure 4.30, Figure 4.31, Figure 4.32 and Table 4.9, the characteristics of the flow around a silt screen are affected by its vertical configuration. Compared to a silt screen designed according to the prevailing design practice, the extents of the upstream retarded flow are larger when compound silt screens are used. Meanwhile, the effects of the vertical configuration on the flow magnitude can be clearly discerned from the results shown in Table 4.9. The values of the maximum normalized velocity obtained with silt screens of convex configurations (configurations 2.1, 2.3 and 3.1) are higher than those of silt screens of concave configurations (configurations 2.2, 2.4 and 3.2). The maximum normalized velocities obtained with the concave configurations are also slightly lower than that of the vertical configuration adopted in the prevailing design practice.

4.3.2 Characteristics of the flow in the transverse plane around a silt screen (2DH)

Figure 4.33 shows the development of the flow along the transverse direction when a silt screen is deployed in the open configuration. The flow is from left to right and initially uniform in the span wise direction. In Figure 4.33, the zoom-in

image of the development of the streamlines in the close vicinity of a silt screen is shown. Upon approaching the screen, the flow is deflected to flow around the silt screen. In the case of a screen with short span, the flow generally wraps around the screen as is typically the case of flow around a cylinder. For a silt screen of several hundred metres in length, although the flow still wraps around the screen at the edges, the flow in the mid-plane and along the longitudinal direction decelerates, while the bulk of the flow diverts to flow away from the longitudinal axis as can be seen in Figure 4.33. Such flow arrangement resembles the case of a flow hitting an obstacle with a stagnation point observed at the longitudinal axis. As seen in Figure 4.33, in all cases of environmental flow velocity and transverse length of the screen considered in the simulations, the results of the simulated flow patterns were similar.

(a)

(b)

(c)

(d)

Figure 4.33: Simulation results on the flow development along the transverse plane around a silt screen ($L_s=100\text{m}$) in the environmental flow velocity of (a) 0.05 m/s, (b) 0.1 m/s, (c) 0.2 m/s and (d) 0.5 m/s.

As indicated in the velocity distribution shown in Figure 4.33, as the flow approaches the silt screen, flow separation takes place. At a certain distance upstream of the screen, most of the approaching flow is deflected laterally towards the edges of the screen. Only the flow in the middle plane of the screen maintained the normal direction when approaching the screen. In the lee of the screen, a pair of vortices is formed. As a result, it could be deduced that a long span of silt screen placed across the flow would change the flow hydraulics, slowing the flow and creating a slow flow environment on both sides of the screen. Figure 4.34 shows the velocity distribution around a silt screen in the transverse plane as obtained from the numerical simulation. In terms of its magnitude and flow rate, the flow along the longitudinal axis and in the neighborhood of the silt screen is a fraction of the incident flow (as elaborated in Figure 4.34, Figures H1, H2, H3 and H4 and Table H2 in Appendix H).

(a)

(b)

Figure 4.34: Simulated distribution of the velocity magnitude in the transverse plane around a silt screen of length $L_s=100\text{m}$ subjected to incident flow velocity of 0.05 m/s (a) and 0.2 m/s (b) (along the colour band, the numbers refer to the magnitude of the velocity in terms of m/s).

Dimensional analysis was used to establish the development of the flow in the transverse plane. As elaborated in Chapter 3, considering the 2D flow development along the transverse plane, the flow velocity u_x at any distance x_u upstream of the screen can be expressed according to the following equation:

$$\frac{u_x}{U_{env}} = f\left(\frac{x_u}{L_s}, \frac{\rho_w L_s U_{env}}{\mu_w}\right) \quad (\text{Equation 4.1})$$

where U_{env} is the environmental velocity, L_s is the length of the screen along the transverse direction, ρ_w is the density of water, and μ_w is the dynamic viscosity of water.

Based on the simulation results, the variation of $\frac{u_x}{U_{env}}$ with respect to $\frac{x_u}{L_s}$ was calculated and shown in Figure 4.35.

Figure 4.35: Spatial variation of the velocity magnitude in the upstream zone of a silt screen, along the transverse plane and along the axis of symmetry of the screen.

In Figure 4.35, $Pi3 = \frac{\rho_w L_s U_{env}}{\mu_w}$. From Figure 4.35, in the data range of $\frac{u_x}{U_{env}} < 0.2$, the values of $\frac{u_x}{U_{env}}$ appear to relate to $\frac{x_u}{L_s}$ linearly. Fitting of the simulated data in

the range of $\frac{u_x}{U_{env}} < 0.2$ shows that the data can be roughly estimated based on the

function $\frac{u_x}{U_{env}} = 1.1818 \frac{x_u}{L_s}$ (Equation 4.2).

4.3.3 Simulation results of the sediment movement around a silt screen in pilot scale (2DV)

In the previous section, the flow around a silt screen in both the vertical plane and the transverse plane is addressed. In this section, the simulation results on the distribution of sediment particles are presented in the form of discrete particles and their path lines. The sediment movement patterns around a silt screen and how silt screens affect sediment distribution are discussed.

4.3.3.1 Sediment trajectories

Figure 4.36 shows the simulated particles trajectories recorded in the numerical simulations based on 10 particles released upstream and approaching the silt screens for two cases of SPR=0.6 and SPR=0.9.

Figure 4.36: Examples of the trajectories of 10 particles obtained in a FLUENT simulation of particles of size $10\text{ }\mu\text{m}$ in the environmental velocity of 0.05 m/s and in the presence of a silt screen of $\text{SPR}=0.6$ (a) and 0.9 (b). The colour of the trajectories indicates the position of the particles in the x-direction.

As can be observed in both simulation cases shown in Figure 4.36, all of the particles released upstream were carried past the screen in the steady state. As illustrated in Figure 4.37, which shows examples of the stream-wise movement of the released particles, in the lee of the screen, two patterns of movement could be discerned. The trajectory of particle 1 (red dashed line) shows a particle travelling gradually across the domain while spiraling trajectories are observed for particles 2 and 3.

Figure 4.37: Examples of x-t diagram of the temporal development of the stream-wise location of a particle (the location of the silt screen is marked with the red solid line and the arrow).

According to the simulation results, no particles were detained upstream of the screen in the steady state. The capacity of the silt screen in sediment detention may be expressed in terms of the detention duration of the particles, and this can be determined based on the duration that the sediment particles take to travel from the source to the screen. As introduced in section 3.3.2.2, for each particle tracking simulation, the detention time is defined as the duration for which at least 90% of the number of particles are detained in the upstream zone. From the simulated particle trajectories, the detention times of particles around screens of different configurations were estimated and summarized in Table 4.10 and Appendix K. On the other hand, as noted earlier, as the simulation with RANS model could not reproduce the upstream recirculation zone, the estimated detention times are conservative estimate of the effectiveness of the screen in sediment containment.

Table 4.10: Estimated detention time of particles around silt screens of various vertical configurations (the particles were released at $x=-6H$).

U_0 (m/s)	Configuration						
	original	2.1	2.2	2.3	2.4	3.1	3.2
0.05	1000 s	2000 s	1500 s	1200 s	1500 s	1500 s	1350 s
0.1	300 s	500 s	750 s	600 s	750 s	600 s	670 s
0.2	140 s	300 s	380 s	250 s	340 s	250 s	380 s

4.3.3.2 *Sediment distribution along the water depth*

To illustrate the effects of a silt screen on the distribution of sediment in a water column, the vertical distributions of the particles transported across several sections upstream and downstream of a silt screen are presented in Figure 4.38 and Figure 4.39. Figure 4.38 suggests that upstream of the screen, the particles spread relatively uniformly along the water depth. However, downstream of the screen, as can be seen in Figure 4.39, 68% of the particles which have been transported across location $x=H$ downstream of the screen were transported in the lower 2.5 m of the water depth. At location $x=2H$, the simulation shows that 58% of the particles which have been transported across this section were within the deepest 2.5 m of the water depth. It is noted that the deepest 2.5 m of the water column is also the water depth that is not “obstructed” by the screen. As expected, most of the particles being transport are conveyed in the portion of the water depth that is not “obstructed” by the screen.

(a)

(b)

Figure 4.38: Distribution of transported particles along the water depth at locations $x=-2H$ (a) and $x=-H$ (b) upstream of a silt screen of the current design ($SPR=0.9$) in the incident flow velocity of 0.05 m/s (the coverage of the silt screen is highlighted with the red thick solid line on the ordinate).

(a)

(b)

Figure 4.39: Distribution of transported particles along the water depth at locations $x=H$ (a) and $x=2H$ (b) downstream of a silt screen of the current design ($SPR=0.9$) in the incident flow velocity of 0.05 m/s (the coverage of the silt screen is highlighted with the red thick solid line on the ordinate).

4.4 Field observation

4.4.1 Field data on the flow distribution around a silt screen

4.4.1.1 Flow distribution along the transverse plane

Similar to the simulation results of the flow development along the transverse direction, the data obtained at the field also suggest flow separation around a silt screen in the transverse plane. As observed in the examples presented in Figure

4.40, which shows the flow vectors measured using an ADCP at a certain project location in Singapore (DHI Singapore, 2009), the development of the flow direction around the silt screen shows that in the middle plane, the flow maintains normal to the screen. As the flow stream approaches the silt screen, the streams at the two ends of the transects tend to travel around the ends of the silt screen, as seen in Figure 4.40a. Downstream of the screen, the directions of the flow recorded at the downstream transect located at 30 metres from the screen show a tendency of the flow to re-converge towards the middle plane.

(a)

(b)

(c)

Figure 4.40: Examples of the distribution of the velocity vectors around the silt screen in the field (the silt screen is located at location 0 along x-axis) – (a) data collected at 12.36 m depth on 08 July 2009, (b) data collected at 3.36 m depth on 13 July 2009, and (c) data collected at 11.86 m depth on 24 March 2009 (DHI Singapore, 2010)

4.4.1.2 Flow distribution in the vertical plane

As shown in Figures I1, I2, I3 and I4 in Appendix I, in both upstream and downstream of the screens, majority of the recorded profiles show stronger flow in the lower layer of the water column. In particular, upstream of the screen, as the flow moves nearer to the silt screen, a relatively sharp peak of higher velocity was observed in the lower 5 metres of the water column (as seen in Figure 4.41). This observation suggests the diversion of flow towards the lower water layer as the flow travels nearer to the screen. Such diversion was also observed in the experimental and simulation results (as discussed in section 4.2 and section 4.3).

Figure 4.41: Development of suspended sediment concentration profiles as the flow approaches the screen. Diagram (a) was observed at approximately 30 meter upstream of the screen, while diagram (b) was observed at approximately 10 meter upstream of the screen (data collected on 24 March 2009, DHI Singapore).

4.4.2 Field data on the sediment distribution around a silt screen

4.4.2.1 Distribution of sediment flux

Figure 4.42 and Figure 4.43 show typical distributions of sediment flux along the transects on both sides of the silt screen during flood and ebb tides, respectively. In both cases, a high flux of sediment mass is observed in the water layer that is not “obstructed” by the screen.

Figure 4.42: Vertical sediment flux profiles measured along the transects located at 10 m away from the silt screen on 24 March 2009 during flood tide and East going current (the coverage of the silt screen is highlighted with a thick red solid line on the ordinate). The prevailing current was from the sediment source towards the screen.

Figure 4.43: Vertical sediment flux profiles measured along the transects located at 10 m away from the silt screen on 09 September 2009 during ebb tide and West going current (the coverage of the silt screen is highlighted with a thick red line on the ordinate). The prevailing current was from environmental water towards the screen.

On 24 March 2009, the largest suspended sediment concentration (SSC) flux in the water column was approximately 200 mg per metre width at the depth of 20 metres while the highest sediment flux measured in the water depth blocked by the screen was 160 mg per meter width (see Figure 4.42). During the ebb tide, as shown in Figure 4.43, the sediment flux profiles obtained also indicate higher sediment flux in the lower water column. The measured flux reached a peak value

of 50 mg per meter width at the depth of 17 metres from the surface (refer to Figure 4.43). The lower sediment concentration observed in Figure 4.43 could be due to the fact that in the particular measurement, the sediment source was in the lee of the silt screen according to the direction of the incident flow.

4.4.2.2 *Sediment concentration distribution*

Appendix I gives field observations of suspended sediment concentration (SSC) profiles about a screen at different tidal and current conditions. Examples of the typical vertical SSC profiles obtained upstream and downstream of a silt screen as observed in the field are presented in Figure 4.44 and Figure 4.45. It is noted that majority of the vertical concentration profiles obtained upstream of the screen show high sediment concentration in the upper water layer and lower values of sediment concentration in deeper water depth, as can be seen in Appendix I and Figure 4.44 and Figure 4.45. For example, in the SSC profile shown in Figure 4.44(c), the highest SSC value (16.3 mg/l) was recorded at 2 metres from the surface. In the profile shown in Figure I8 in Appendix I, the measured sediment concentration at the surface was 30 mg/l while the concentration recorded in the lower water layer was about 20 mg/l.

Figure 4.44: Examples of suspended sediment concentration profiles measured upstream of the silt screen - (a) at 10 m upstream of the silt screen on 09 September 2009 during ebb tide and West going current, (b) at 10 m upstream of the silt screen on 24 March 2009 during flood tide and East going current, (c) at 10 m upstream of the silt screen on 09 September 2009 during ebb tide and West going current.

Figure 4.45: Examples of suspended sediment concentration profiles measured downstream of the silt screen - (a) at 10 m downstream of the silt screen on 09 September 2009 during ebb tide and West going current, (b) at 10 m downstream of the silt screen on 24 March 2009 during flood tide and East going current, (c) at 10 m downstream of the silt screen on 24 March 2009 during flood tide and East going current.

Figure 4.46: Development of suspended sediment concentration profiles as the flow approaches the screen. Diagram (a) was observed at approximately 30 meter upstream of the screen, while diagram (b) was observed at approximately 10 meter upstream of the screen (data collected on 24 March 2009, DHI Singapore).

Figure 4.46 shows the streamwise variation of the SSC profiles upstream of a silt screen. At 30 metres upstream of the screen, the vertical suspended sediment concentration profile shows a region of higher concentration in the lower layer of the water column. At 10 metres upstream of the screen, the SSC is relatively uniform in the water column, and is smaller than that at 30 metres.

4.4.2.3 Sediment distribution in the stream-wise direction

In an attempt to relate the sediment distribution to the flow distribution, consider the control location CL (as indicated in Figure 4.47 below) which represents the location where sediment containment is to be assessed. With reference to the flow patterns observed around a silt screen described in section 4.2, Q_{out} denotes the flow that travels out of the control space and Q_{re} refers to the reverse flow as shown in Figure 4.47. The incident flow rate is Q_0 . S_0 , S_{re} and S_{out} refer to the sediment flux transported along with the flow rates Q_0 , Q_{re} and Q_{out} respectively.

Figure 4.47: Schematic diagram of the flow distribution around a control location downstream of a silt screen (represented as the thick red solid line)

Also consider the containment of sediment inside the control location CL. It may be hypothesized that the amount of sediment transported out of the control location CL (S_{out}) correlates to the flow Q_{out} flowing out of the control line. The author attempts to relate the detention capacity of a silt screen at location CL, and represented by the ratio $\frac{S_{out}}{S_0}$, to the change in flow rate, represented as the ratio

$\frac{Q_{out}}{Q_0}$. Assuming the sediment load relates to the flow redistribution as suggested

by Wilcock (2004), i.e. $S = aQ^b$, the relationship between the sediment load ratio and flow rate ratio can be represented as $\frac{S_{out}}{S_0} = \left(\frac{Q_{out}}{Q_0}\right)^b$. The coefficient b can be

determined from the linear relationship of $\log\left(\frac{S_{out}}{S_0}\right)$ and $\log\left(\frac{Q_{out}}{Q_0}\right)$ (see Figure 4.48).

Figure 4.48: Correlation of the change in sediment flux and flow rate distribution around a silt screen as monitored in the field surveys

As can be deduced from Figure 4.48, the excellent linear fit ($b = 0.9952$) indicates a strong linear relationship between the amount of sediment transported and the discharge. This observation was obtained based on the data collected at a field site where the sediment consists of mostly fine silt particles. With the correlation equation established, the distribution of sediment flux around a silt screen can be estimated indirectly based on the flow rate.

5. Discussion

In this chapter, the findings on the hydraulics and sediment patterns around a silt screen are discussed and presented in a suitable manner to answer the three questions that are set forth in this study, i.e.

- (1) What is the physics that governs sediment redistribution around a silt screen;
- (2) What are the factors that affect the containment effectiveness of a silt screen; and
- (3) How to establish a design methodology to achieve the desired objective of sediment containment.

Section 5.1 focuses on the physics that defines sediment redistribution. In this section, the results obtained from the laboratory experiments, numerical simulations and field observations are summarized and compared. Two particular issues are discussed:

- (1) The phenomenon of sediment movement and redistribution around a silt screen; and
- (2) The mechanism and driver of redistribution of sediment by the flow.

In sections 5.2 and 5.3, the relevant factors and criteria for an effective design of a silt screen system are established. Based on these findings, the effectiveness of the prevailing design practice is discussed in section 5.4.

5.1 Establishment of the physics of sediment movement in the vicinity of a silt screen

In sections 4.3 and 4.4, the sediment movement patterns and sediment distribution around a silt screens have been discussed. With the findings obtained on the flow characteristics around a silt screen, the mechanism that governs such sediment distribution and sediment movement patterns can be explained.

From the results presented in Chapter 4 on the velocity profiles in the vicinity of a silt screen, the development of the velocity profiles along the stream-wise direction was established and is shown in Figure 5.1.

Figure 5.1: Stream-wise transformation of the velocity profile upstream of a silt screen.

Based on the laboratory study and the simulation results, three notable features in the flow patterns in the vertical plane around a silt screen are discerned: (1) a recirculation zone/retarded flow formed in the upper water layer upstream of the silt screen, (2) a recirculation zone in the upper water layer downstream of the screen, and (3) a stronger submerged plane jet flow in the lower water layer downstream of the silt screen. Some of these features were also seen in the velocity profiles measured in the field (see section 4.4).

In the upper water layer upstream of the screen, under the effects of the reverse/retarded flow in the upstream retarded zone, the downstream movement of the particles is delayed, and the sediment entrained in the flow could remain as suspension in the water column for a longer period of time. As a result, high sediment concentration is to be expected in the upper water layer. Due to the longer retention time, some particles begin to settle. Hence, in the lower water layer, relatively lower sediment concentration can be expected. Because of these processes, as the flow approaches a silt screen, the SSC profiles are expected to develop and evolve in the manner as shown in Figure 5.2 .

Figure 5.2: Stream-wise transformation of the suspended sediment concentration profile upstream of a silt screen.

At or near to the sediment source (dredging/ reclamation activity), high sediment concentration could be expected in the lower water layer as depicted in profile (1). As the sediment particles are advected from the site, deposition of larger particles takes place. As a result, the concentration profile of the sediment shows lower concentration compared to that near the source. The distinctive feature of higher sediment concentration at the lower depth is less obvious and may disappear altogether, as shown in profile (2) of Figure 5.2. Nearer to the screen and if the screen design is effective, the suspended sediment concentration [profile (3)] along the water depth is expected to be significantly lower than that of the profiles observed near the source. Because of sediment settlement and the retardation effects of the upper water layer, near to the screen, in the upper water layer, the sediment concentration is higher than in the lower water layer. The stream-wise variation of suspended sediment concentration profiles upstream of the screen as recorded in the field also follows the described trend, as shown in Figure 4.41 and Figure 4.46. As shown in the examples in Figure 4.44, near the silt screen, higher sediment concentration was observed in the upper water layer.

On the other hand, from the field data, little can be concluded on the containment of sediment upstream of a silt screen. According to the simulation results, no particles were contained in the upstream zone of the silt screen in steady state. However, it is also noted that the numerical simulation could not reproduce the upstream recirculation zone. Hence, this outcome might have been too

conservative and might have under-estimated the amount of sediment contained in the upstream region.

Downstream of the screen, it is anticipated that majority of the particles are transported in the lower water layer, as indicated in both the simulation results and the field data. Within the recirculation zone formed in the upper water layer, the forward movement of sediment is likely to be delayed. The spiral movement in the trajectories of particles 2 and 3 in Figure 4.37 shows typical trajectories of the particles within the recirculation flow region. Here, high sediment concentration is formed in the upper water layer downstream of the screen, as also observed in the field data (see Figures I7 and I8 in Appendix I).

The lower water layer, on the other hand, is dominated by a submerged plane jet-like flow below the screen. Because of the high velocity and strong turbulence (as presented in Chapter 4), in this layer, it is expected that particles are entrained and transported. The sediment profiles obtained from the field also suggest such entrainment and transport. As seen in Appendix I, several sediment profiles obtained downstream of the silt screen show decreasing sediment concentration with depth. According to Fredsøe and Deigaard (1992), such sediment concentration profiles are observed in wave-dominated environments, or in areas with a sediment source, or when there is flushing of sediment in the area. The observed hydraulic condition of the area, however, does not indicate wave plunging, large wave heights, or the presence of sediment sources. Thus, the low sediment concentration in the lower water layer is likely to have been formed under the flushing effects by the submerged plane jet.

5.2 Effects of screen structure and flow environment on the hydraulic characteristics and sediment containment of a silt screen

From the previous section, and as discussed in section 4.2, containment of sediment by a silt screen is governed by the settling of particles and trapping of particles in the upstream region, as well as the entrainment of particles in the lower water layer. According to the results presented in section 4.2, the characteristics of the “containment flow” are governed by screen properties (screen penetration ratio, vertical configuration) and the incident flow velocity. Based on the results presented in Chapter 4, this section summarizes the important design parameters and their potential effects on sediment containment.

Based on the results obtained on the hydraulics of silt screens, when screen penetration length increases, the upstream retarded zone is enlarged. Therefore, the containment by the upstream retarded flow can be enhanced when the screen penetration ratio is increased. At the same time, the maximum flow velocity also increases and stronger turbulence is formed downstream (refer to section 4.2.2). In such strong turbulent flow condition, the potential of entrainment by the flow in the lower water layer also increases with screens of greater SPR.

The results obtained also confirmed incident flow velocity as an important determinant to the distribution of flow around a silt screen. Overall, the flow characteristics around a screen in a stronger flow environment are less preferable for sediment containment. Upstream of the screen, as the incident flow increases, the upstream retardation zone diminishes. In faster flow environments, stronger turbulence intensity was recorded. At the same time, the magnitude of the flow in the submerged plane jet increases with stronger incident flow as discussed in section 4.2.3. As a result, in environments of stronger flow, because of higher turbulence and the increased flow magnitude, sediment entrainment and transport is likely to be enhanced. Indeed, the simulated sediment patterns also

indicate that in stronger flow conditions, the detention time of sediment particles in the upstream region is shortened. Based on the simulation results of silt screens that follow the prevailing design practice, and when the particles are released from the location $x=-6H$ upstream of the screens ($H=25\text{m}$), the detention time, which is defined as the duration for at least 90% of the particles to be retained in the upstream zone, is estimated to be roughly 1000 seconds, 300 seconds and 140 seconds when the incident velocity is 0.05 m/s, 0.1 m/s and 0.2 m/s respectively (refer to Table K1). The observed variation of the characteristics of the “containment flow” with incident flow velocity helps explain the recorded high percentage of sediment reduction across a silt screen in low flow conditions (de Wit et al., 2011; Johanson, 1976) and the reported lower efficiency of silt screens when deployed in stronger flow (JBF Corporation, 1978).

To estimate the potential of settling of particles, the detention times obtained from the simulations are compared with settling times of the particles. The settling potential is defined as the ratio of the detention time to the settling time. From Figure 5.4 and Figure 5.5 (which show the settling potential of particles around a silt screen with $\text{SPR}=0.9$ and when sediment particles were released from location $x=-6H$ upstream), the settling potential varies with not only the gap velocity but also the particle size. The gap velocity (U_{gap}), as shown in Figure 5.3, is defined as the average velocity which is based on the flow rate Q_{gap} , which flows through the gap between the silt screen and the bed, divided by the clearance H_{gap} between the tail of the screen and the bed.

Figure 5.3: Schematic diagram illustrating the definitions of incident flow velocity and gap velocity around a silt screen as adopted in this study

As seen in Figure 5.4 and Figure 5.5, smaller particles have lower settling potential. For particles of diameters $D=0.5$ mm and $D=1$ mm, the detention times are always longer than the settling time in all cases of gap average flow velocity. With particles of diameter $D=0.2$ mm, when the gap velocity is larger than 0.83 m/s, the detention time is always smaller than the settling time, suggesting that the particles could not settle in the upstream region in such flow conditions.

Figure 5.4: Variation of the settling potential according to simulation results of sediment of different sizes approaching a silt screen of the prevailing design practice (the silt screen was deployed at a distance of $6H$ away from the sediment source). The range of the detention times for particles with diameters of 0.01 mm, 0.05 mm and 0.1 mm are enlarged in Figure 5.5.

Figure 5.5: Variation of the settling potential according to simulation results of sediment of different sizes approaching a silt screen of the prevailing design practice (the silt screen was deployed at a distance of 6H away from the sediment source).

In both Figure 5.4 and Figure 5.5, the settling potential tends to decrease with increasing gap velocity. Hence, it is expected that positive containment efficiency can only be achieved for a limited range of flow velocity.

On the other hand, for a screen set in an open configuration, the incident flow velocity is diverted transversely. Based on the findings of the flow simulation study, it is proven that the magnitude of the flow around a silt screen deployed in an open configuration is governed by the length of the silt screen in the transverse direction and the location of silt screen deployment, see section 4.3.

The findings obtained also illustrate the effects of the vertical configuration on the distribution of the “containment flow” around a silt screen. The flow characteristics from the experiments with deflected silt screens show that the velocity profiles around a deflected screen deviate considerably from that of a vertical screen. The flow patterns obtained with a silt screen whose lower end deflects towards the downstream direction shows a smaller upstream recirculation zone than that of a vertical configuration (refer to section 4.2.3). The simulation results of the flow and sediment movement around compound silt screens also

suggest the potential effects of the vertical configuration on the containment of sediment. As seen in Table K1, the detention times of particles around compound screens were generally longer compared to that of the vertical configuration. This suggests a possibility of improving the containment of sediment in the upstream region with compound configurations. Besides, the simulated magnitude of the flow around compound screens suggests that compared to the vertical configuration (as adopted in the prevailing design practice) and convex configurations (configurations 2.1, 2.3 and 3.1), the potential of resuspension is the lowest when concave configurations (configurations 2.2, 2.4 and 3.2) are used (refer to section 4.3.1.2).

5.3 Establishment of the criteria for the design of silt screens for sediment containment

As discussed in the previous sections, among the various sediment transport processes, three processes are identified as the main drivers of the containment of sediment around a silt screen:

- (1) Settling of sediment particles as the particles are transported by the flow from the sediment source;
- (2) Trapping/ detention of suspended sediment particles in the upstream eddy zone or retarded flow region; and
- (3) Transport/ entrainment of sediment particles by the submerged plane jet-like flow in the lower water layer.

On the other hand, the field data demonstrated that sediment flux distribution appears to be a function of flow rate (see section 4.4). Based on the findings of the laboratory experiments, the upstream recirculation rate contributes to less than 5% of the forward flow in the upstream region (see section 4.2). Using the approximated quasi-linear relationship between the sediment flux distribution and flow distribution presented earlier (refer to Figure 4.48), the sediment transport capacity of the recirculation zone upstream of the screens designed according to the prevailing design guideline would be insignificant.

In effect, it turns out that settling and entrainment of particles are the dominant processes governing the containment of sediment by a silt screen. For a silt screen to be effective, the screen would have to be designed in such a way to enhance or induce settlement of sediment particles upstream of the screen and at the same time, prevent entrainment of sediment by the submerged plane jet-like flow. For a sediment particle to settle, the detention time must be longer than the settling time, i.e. the ratio of detention time to settling time must be at least 1. To prevent scouring and entrainment of bed materials, the flow velocity should be lower than the threshold velocity.

5.4 Discussion of the effectiveness of the prevailing design practice

The criteria for an effective design of silt screens for sediment containment have been set out in the previous sections. The location of the screen, screen penetration ratio and incident flow velocity have been shown to be important parameters that would determine the containment efficiency of a silt screen system. The prevailing design practice, however, does not include these parameters in the design consideration (as illustrated in Figure 2.13, which summarizes the steps involved in a conventional procedure as adopted in the prevailing design practice, according to Francingues and Palermo, 2005, JBF Corporation, 1978, and Taiyo Kogyo, 2008). This is the most severe shortcoming of the prevailing design methodology.

The variation of the effectiveness of a silt screen system with the incident flow velocity has been reported in the literature but briefly. Sediment level was not reduced across silt screens as observed at sites with high environmental flow velocity. Francingues and Palermo (2005) suggest a threshold incident flow velocity of 1-1.5 knots (0.51-0.78 m/s) for effective silt screen deployment. This threshold condition has been established based on the observation of the distribution of sediment at both sides of silt screens at several field sites and has not been

investigated rigorously. In addition, the influence of the environmental flow velocity on the performance of silt screens has not been assessed carefully during the design stage. To the best knowledge of the author, information on incident flow velocity has largely been used to estimate the loading and hence the structural stability of a silt screen system. Reference to the incident flow has not been made with respect to the consideration of containing sediment, but rather to the structural loadings on the screen.

The only available guideline on the design of screen penetration depth suggests that the depth of the screen needs to be at least 1 metre above the bed to prevent the silt screen from being buried under the effects of sediment deposition (Elastec, 2004). In the design that follows the conventional procedure as described above (refer to Figure 2.13), the choices of screen penetration depth and screen deployment location are not justifiable from the perspective of the sediment containment efficiency of the system.

On the other hand, as observed in the experimental and simulation results, the flow characteristics around a silt screen are also significantly affected by the vertical and transverse configurations of the screen. Several publications had noted that silt screens deployed in closed configuration are more effective than those deployed in open configuration (Johanson, 1976; JBF Corporation, 1978). The findings in this study show that for a silt screen deployed in open configuration, because of flow separation, only a fraction of the incident flow approaches the silt screen normally (see section 4.3). On the other hand, with closed configurations, the source sediment is enclosed by the silt screen. The design length of the silt screen, thus, depends on economic feasibility, but should also be determined based on consideration of the magnitude of the incident turbid water. The design of the length of the screen also needs to account for the effects of flow separation on the incident flow immediately adjacent to the screen. If the length of the screen is not long enough to enclose the turbid flow, the sediment

carried by the flow that diverts towards the trailing edges of the screen would be transported downstream and consequently renders the screen ineffective.

In addition, the findings presented in sections 4.2 and 4.3 also illustrate the significance of the vertical configuration of a silt screen on the flow characteristics around the screen. In particular, the characteristics of the upstream vortex formation were found to vary when different vertical configurations were adopted. As can be seen in Table K1 and Appendix K, the effectiveness of sediment containment improves when using certain compound configurations as compared to the configuration based on the prevailing design.

6. Conclusions

This study was initiated to address the long-overdue questions about silt screens deployment:

- (1) Is the current design of silt screens effective,
- (2) Under what circumstances would silt screens be effective, and
- (3) How to design an effective silt screen system?

A comprehensive review of the prevailing practice of silt screen design shows that the design procedure is biased towards structural stability. The effects of silt screens on sediment redistribution have been overlooked during the design process. Moreover, despite the wide application, the exact working mechanism of a silt screen remains unquantified and relatively unknown. In this study, these questions have been addressed and pertinent observations and conclusions are summarized and presented in this thesis.

In the laboratory experiments, the flow patterns, velocity and turbulence distribution were obtained using the technique of Particle Image Velocimetry, a non-intrusive flow measurement technique. The commercial software ANSYS FLUENT (version 11) was employed to simulate the 2-D flow around a silt screen. Based on the simulated flow patterns, the movement of particles around a silt screen was elucidated using the Discrete Particles Modeling module in ANSYS FLUENT. Together with the simulated flow patterns and sediment distribution patterns, field observations were employed to establish a comprehensive view of the development of flow and sediment patterns in the vicinity of a silt screen. The measured data on flow and sediment at the field site were recorded with an Acoustic Doppler Current Profiler (ADCP) along a 400-metre-long silt screen deployed in open configuration. The ADCP recorded the flow and sediment information along transects located at both sides of the silt screen.

1. Based on the results obtained from the laboratory study, numerical simulation and field observation, the flow characteristics in the vicinity of a

silt screen have been identified. Notable features of the hydraulics of a silt screen are:

- With a silt screen deployed in open configuration, flow separation takes place along the transverse direction as the incident flow approaches the silt screen.
 - In the vertical plane, as the flow approaches the screen, the flow deflects towards the gap between the lower end of the silt screen and the bed. As a result, the following patterns are observed: (1) slow flow formed in the upper water layer upstream of the silt screen, (2) a recirculation zone in the upper water layer downstream of the screen and (3) a submerged plane jet-like flow below the silt screen and in the lower water layer.
 - There is significant increase in flow turbulence in the lee side of the screen. The increase in turbulence intensity is found to be dependent on the screen penetration depth and flow velocity.
2. Based on the findings of the laboratory experiments, numerical simulation study and field observations, the mechanism of sediment containment in the presence of a silt screen has been identified. The relevant flow characteristics and the prime drivers of sediment distribution around a silt screen deployed in open configuration have been established. For a silt screen to be effective in containing sediment, the desirable flow patterns for containment are formed around the silt screen and must satisfy two criteria: (1) the flow upstream of the screen should be favourable for settling of sediment particles and (2) the flow below the silt screen should not induce entrainment of bed materials. On the other hand, the findings obtained indicate that the characteristics of the “containment-flow” are dependent on screen parameters (screen penetration ratio, screen deflection angle, and the vertical configuration of the silt screen) and the incident flow velocity. Containment of sediment about a silt screen in the

open configuration is governed by the site conditions (suspended sediment particle size and incident flow velocity), the distance between the silt screen and the sediment source and the transverse length of the silt screen.

Final remarks:

The objectives of the investigation as set out in this thesis have been achieved. The desirable sediment containment characteristics of a silt screen have been established.

7. Recommendations

An overview of the processes and parameters involved in a silt screen system is illustrated in Figure 7.1. Based on the findings of this study, a number of issues pertaining the flow and sediment processes in the presence of a silt screen have been addressed (*highlighted in italics*).

Figure 7.1: Summary of the processes involved in a silt screen system (the processes/ parameters studied in this project are highlighted in italics)

The results obtained in this study have established a comprehensive understanding of the process on sediment transport and flow distribution around a silt screen. However, the relevant issues have not been addressed exhaustively. There remain a number of potential research areas that need further investigation.

On the processes around a silt screen

- In this study, the distribution of sediment in clear water was simulated and the presence of a sediment cloud in the water was not accounted for. This assumption could be deemed valid in the case of low sediment concentration. However, in flow with high concentration of sediment, the behaviour of the slurry/sediment would be affected by the properties of water-sediment (e.g. the density of the mixture) and the flocculation and coagulation of fine particles. The presence of high concentration of sediment also affects the settling process. It will be useful to understand the contribution of these factors to the movement of sediment along the flow.
- As illustrated in Figure 7.1, this study investigated the flow phenomena in the current-dominated environment. On the other hand, silt screens have been widely deployed in the sea. Therefore an investigation of the sediment dispersion and distribution in the presence of waves and tides will be invaluable.
- The work reviewed and conducted on silt screens also reveals the gap of knowledge on the flow behavior around flexible structures. Despite several successful applications in practice, the understanding of hydraulics around flexible structures remains limited. This observation suggests that research on the relevant hydraulic processes around flexible structures would contribute significantly to the field of coastal and ocean engineering.
- In the presence of complex flow patterns such as those observed around a silt screen, conventional sediment transport formulae may not be applicable to estimate the transport capacity of the flow. Despite some attempts reported in recent years, challenges remain about how to predict the sediment transport in the vicinity of complex flow fields.

On the design of silt screens

- This study focused on sediment movement around silt screen without deflection. Taking into account the possible deflection of silt screens in water, it would be useful to investigate other possible configurations of silt screens and in three-dimensions with different screen deployment layouts.
- In an attempt to develop a universal view of silt screens performance, this study has addressed three types of silt screens. However, the available silt screens exhibit relatively similar permeability properties. It would also be helpful to investigate the roles of porosity on the hydraulics and sediment distribution around a silt screen.

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APPENDIX A SEDIMENT CHARACTERISTICS

Table A1: Sediment compositions and sources and distribution in marine environment

	Sources	Distribution
Lithogenous (rock-derived)	Continental source Weathering by water-chemical, wind abrasion, freeze cycles. Erosion and transportation in streams and rivers, winds and glaciers “Red clay” – terrigenous and volcanic ash, transported to ocean by winds and surface currents	Contributed to 75% of all marine sediment Usually present in near-land area such as continental margins and may be deep sea floor In deep ocean regions where there is little biogenous or terrigenous sediment
Biogenous (life-derived)	Produced by organisms , so called biogenic oozes In warm and shallow seas, present as shells of animals such as clams and corals In deep sea, may be include shells of “microscopic plankton”	Widespread in relatively shallow areas of the sea In polar and equatorial bacnds where nutriend are supplied to surface
Hydrogenous (Water derived)	Direct precipitation from seawater e.g. salts New mineral from chemical reactions between sediment on sea floor and seawater	Deep basins, especially the Pacific
Cosmegeinous (cosmic-derived)	Micro-meteorites and asteroids, comets, Silicates, metals, mixtures	Wide-spread but not abundant

Table A2: Sediment size classification (Passlow, 2005)

	Size (mm)	Classification
Mud	0 – 0.002	Fine-medium clay
	0.0021 – 0.004	Coarse clay
	0.0041 - 0.008	Very fine silt
	0.0081- 0.016	Fine silt
	0.0161 – 0.031	Medium silt
	0.0311 - 0.063	Coarse silt
	0.0631 – 0.125	Very fine sand
Sand	0.1251 – 0.250	Fine sand
	0.251 – 0.500	Medium sand
	0.501 – 1.000	Coarse sand
	1.001 – 2.000	Very coarse sand
Gravel	2.01 – 4.000	Granules
	>4.000 mm	Pebbles and larger

APPENDIX B: SEDIMENT FROM DREDGING

Table B1: Recommended TGU values (adapted from Nakai, 1978 and Johnson and Pachure, 1999)

Type of dredger	Power/Bucket volume	Dredged materials			TGU (kg/m ³)
		D<0.74 mm(%)	D<0.005mm (%)	Classification	
Hydraulic cutterhead	4000 hp	99.0	40.0	Silty clay	5.3
	4000 hp	98.5	36.0	Silty clay	22.5
	4000 hp	99.0	47.5	Clay	36.4
	4000 hp	31.8	11.4	Sandy loam	1.4
	4000 hp	69.2	35.4	Clay	45.2
	4000 hp	74.5	50.5	Sandy loam	12.1
	2500 hp	94.4	34.5	Silty clay	9.9
	2000 hp	3.0	3.0	Sand	0.2
	2000 hp	2.5	1.5	Sand	0.3
	2000 hp	8.0	2.0	Sand	0.1
Hopper	Two at 2400 hp each	92.0	20.7	Silty clay loam	7.1
	1800 hp	83.2	33.4	Silt	25.2
Mechanical grab	8 cu m	58.0	33.4	Silt	25.2
	4 cu m	54.8	41.2	Clay	84.2
	3 cu m	45.0	3.5	Silty loam	15.8
	3 cu m	62.0	5.5	Silty loam	11.9
	3 cu m	87.5	6.0	Silty loam	17.1
Mechanical bucket		10.2	1.2	Sand	17.6
		12.7	12.5	Sandy loam	55.8

Table B2: Estimation of suspension rate from different types of dredger (adapted from Pennekamp et al., 1996)

Dredger type	Production (m ³ /hr)	Suspension rate S (kg/m ³)
TSHD	5500	14
TSHD	2170	8-22
Dragline with open clamshell	90	3
Dragline with open clamshell with silt curtain	84	9
Bucket dredge	714	18-21

APPENDIX C: SEDIMENT TRANSPORT FORMULAE

Table C1, C2 and C3 summarized some commonly used formulae for estimating the transport rate of bed load and suspended load.

Table C1: Suggested formulae to estimate bed load transport based on flow discharge
(adapted from Yang, 1996)

Author	Formula
Meyer-Peter (1934)	$\frac{0.4q_b^{2/3}}{d} = \frac{q^{2/3}S}{d} - 17$ <p>where d is the particle diameter, q is the water discharge per unit width of the channel, and q_b is the bed load per unit width of the channel, and S is the energy slope.</p>
Schoklitsch (1934, 1943)	$q_b = 7000 \frac{S^{3/2}}{d^{1/2}} (q - q_c) \quad \text{with}$ $q_c = \frac{0.00001944d}{S^{4/3}}$ $q_b = 2500S^{3/2} (q - q_c) \quad \text{with}$ $q_c = \frac{0.6d^{3/2}}{S^{7/6}}$ <p>where d is the particle diameter, q_b is the bed load per unit width of the channel, q is the water discharge per unit width of the channel, q_c is the critical discharge at incipient motion, and S is the energy slope.</p>

Table C2: Suggested formulae to estimate bed load transport based on critical shear stress
(adapted from Yang, 1996)

Author	Formula
DuBoys (1879)	$q_b = \frac{0.173}{d^{3/4}} \tau (\tau - \tau_c)$ <p>where τ is the tractive force, τ_c is the critical tractive force along the bed, d is the particle diameter and q_b is the bed load per unit width of the channel</p>
Shields (1936)	$\frac{q_b \gamma_s}{q \gamma S} = 10 \frac{\tau - \tau_c}{(\gamma_s - \gamma) d}$ <p>With $\tau = \gamma HS$ Where τ is the tractive force, τ_c is the critical tractive force along the</p>

	<p>bed, q_b is the bed load per unit width of the channel, q is the water discharge per unit width of the channel, S is the energy slope, γ_s and γ are specific weights of sediment and water respectively, d is the particle diameter, and H is the water depth.</p>
Kalinske (1947)	$\frac{q_b}{U_* d} = f' \left(\frac{\tau_c}{\tau} \right)$ <p>where τ is the tractive force, τ_c is the critical tractive force along the bed, d is the particle diameter, q_b is the bed load per unit width of the channel, and U_* refers to the shear velocity.</p>
Van Rijn (1984, 1993)	$\frac{q_b}{[(s-1)g]^{0.5} D_{50}^{1.5}} = 0.053 \frac{T^{2.1}}{D_*^{0.3}}$ <p>With particle parameter $D_* = D_{50} \left[\frac{(s-1)g}{\nu^2} \right]^{1/3}$ and transport stage parameter $T = \frac{(u_*')^2 - (u_{*,cr})^2}{(u_{*,cr})^2}$ (refer to chapter 2)</p>
Chang, Simons and Richardson (1967)	$q_b = K_t V (\tau - \tau_c)$ <p>where τ is the tractive force, τ_c is the critical tractive force along the bed, K_t is a coefficient. The values of K_t was obtained from a graph with velocity profiles and particles diameter, V is the average flow velocity.</p>
Meyer-Peter and Muller (1948)	$q^* = 8(\tau^* - \tau_c^*)^{3/2}$ <p>With $\tau_c^* = \frac{\tau_c}{(s-1)\rho_w g d}$</p> $\tau^* = \frac{\tau}{(s-1)\rho_w g d} \text{ and } q^* = \frac{q_b}{\sqrt{(s-1)gd^3}}$ <p>where τ is the tractive force, τ_c is the critical tractive force along the bed, d is the particle diameter, q_b is the bed load per unit width of the channel, s is the ratio of the density of the particle to the density of water, and ρ_w is the density of water.</p>

Besides using the above mentioned formulae, bed load transport could also be predicted with probabilistic or stochastic approach. This approach was proposed by Einstein, who related the movement of the particles to turbulent flow fluctuations, but not to the average values of forces exerted by the flow on sediment particles. The motion of the particles was hence described in terms of probability.

Table C3: Examples of formulae estimating suspended load transport (adapted from Yang, 1996)

Author	Formula
Lane & Kalinske (1941)	$q_{sw} = q C_a P_L \exp\left(\frac{15 w_s a}{U_* D}\right)$ <p>C_a refers to the suspended sediment concentration at distance a above the bed, q is the flow rate, U_* refers to the shear velocity, and H is the water depth.</p> <p>$P_L = \bar{C} / C_a$ with $\bar{C}$ is the depth-integrated average sediment concentration, and could be estimated based on relative settling velocity w_s / U_*</p>
Einstein (1950)	$q_{sw} = 11.6 U_*' C_a a \left[2.303 \log\left(\frac{30.2 H}{\Delta}\right) I_1 + I_2 \right]$ $I_1 = 0.216 \frac{E^{Z-1}}{(1-E)^Z} \int_E^1 \left(\frac{1-y}{y}\right)^Z dy$ $I_2 = 0.216 \frac{E^{Z-1}}{(1-E)^Z} \int_E^1 \left(\frac{1-y}{y}\right)^Z \ln y dy$ <p>Where y refers to the water depth, C_a refers to the suspended sediment concentration at the reference level a above the bed, $\Delta = d_{65} / x$, $E = a / H$ and $Z = \frac{\omega}{0.4 U_*'}$ where U_*' is the shear velocity due to grain roughness and H is the water depth.</p>
Chang, Simon & Richardson (1965)	$q_s = \frac{H}{0.8 a V} \left(V I_1 - \frac{2 U_*}{\kappa} I_2 \right)$ $a = j \frac{\tau - \tau_c}{(1 - \lambda)(\gamma_s - \gamma) \tan \phi}$ <p>Assumed parabolic distribution of eddy viscosity With a is the thickness of the bed layer λ refers to the porosity of bed material ϕ is the angle of repose of the submerged bed material U_* refers to the shear velocity. I_1 and I_2 are functions of the relative contact bed material layer thickness. V is the depth-averaged velocity $j = 10$ H is the water depth</p>

	<p>γ_s and γ are specific weights of sediment and water respectively.</p> <p>κ is the von-Karman constant</p> <p>q_s is the suspended load.</p>
Van Rijn (1984, 1993, 2007)	$C_a = 0.015(1 - p_{clay})f_{silt} \frac{d_{50}}{a} \frac{T^{1.5}}{D_*^{0.3}}$ <p>With Z and Z' are suspension parameters, which could be deduced from w_s / U_*, f_{silt} is the silt factor, p_{clay} is the clay content in the sediment, T_b is the dimensionless bed shear stress parameter and D_* is the dimensionless particle size parameter (refer to Chapter 2).</p> <p>For the flow environment in which the water depth ranges from 1 to 20 meters and flow velocity ranges from 0.5 to 2.5 m/s, van Rijn (1993) proposed a simplified formula to estimate the volumetric suspended load transport, $q_{s,c}$ for particles of 100 to 2000 μm as followed:</p> $\frac{q_{s,c}}{\overline{V}H} = 0.012 \left(\frac{V - \overline{V}_{cr}}{\left(\left(\frac{\rho_s}{\rho_w} - 1 \right) g d_{50} \right)^{0.5}} \right)^{2.4} \left(\frac{d_{50}}{H} \right) \left(\frac{1}{D_*} \right)^{0.6}$ <p>with $\overline{V}_{cr}$ is the critical depth-average velocity according to Shields:</p> $\overline{V}_{cr} = 0.19(d_{50})^{0.1} \log(12H / 3d_{90}) \quad \text{for } 0.0001 \leq d_{50} \leq 0.0005 \text{ (} d_{50} \text{ in metres) , and}$ $\overline{V}_{cr} = 8.50(d_{50})^{0.6} \log(12H / 3d_{90}) \quad \text{for } 0.0005 \leq d_{50} \leq 0.002$ <p>V is the depth- averaged velocity, g is the acceleration of gravity, D_* is the dimensionless particle size parameter H is the water depth, d_{50} is the median particle size, and d_{90} is a particle diameter of bed material.</p>
Celik & Rodi (1991)	$C_T = \beta \left[1 - \left(\frac{k_s}{H} \right)^n \right] \frac{\tau_w}{(\rho_s - \rho_w)gH} \frac{V}{w_s}$

	$C_T = \frac{q_s}{q}$ $\frac{k_s}{H} = E_r \exp\left(-1 - \kappa \frac{V}{U_*}\right)$ <p>In which β is the portion of the turbulence kinetic energy that is used to keep the sediment in suspension. For particles of 0.005 mm to 0.6 mm, the recommended values of $\beta = 0.034$, sediment concentration < 10%.</p> <p>V is the average flow velocity, C_T is the mean transport capacity concentration, w_s is the settling velocity, κ is the von-Karman constant, τ_w refers to the wall shear stress, U_* refers to the shear velocity, H is the water depth, E_r is the wall-roughness parameter, k_s is the equivalent sand-roughness height, q_s is the suspended load transport with the flow rate q, and n is an empirical constant.</p>
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APPENDIX D: EXAMPLES OF FLOW RESULTS FROM PIV MEASUREMENT AND RESULTS ANALYSIS

Table D1: An example of the PIV data used to estimate the recirculation rate
(the data were extracted from the experimental data for the case of $U_0=0.05$ m/s; $SPR=0.5$, and at location $x/H=1$)

Row No.	x (mm)	z (mm)	u (m/s)	u/ U_0	v (m/s)	v/ U_0	z/H	q (m^3/ms)	q _{forward} (m^3/ms)	q _{reverse} (m^3/ms)
1	-62.8262	157.691	-0.01198	-0.23525	-0.00256	-0.00228	0.006311	-1.27939E-06	0	-1.279E-06
2	-62.8262	157.4774	-0.01198	-0.23525	-0.00256	-0.00228	0.007213	-2.55878E-06	0	-2.559E-06
3	-62.8262	157.2637	-0.01198	-0.23525	-0.00256	-0.00228	0.008116	-2.55878E-06	0	-2.559E-06
4	-62.8262	157.0501	-0.01198	-0.23525	-0.00256	-0.00228	0.009018	-2.55878E-06	0	-2.559E-06
5	-62.8262	156.8364	-0.01198	-0.23525	-0.00256	-0.00228	0.009921	-2.55878E-06	0	-2.559E-06
6	-62.8262	156.6227	-0.01198	-0.23525	-0.00256	-0.00228	0.010823	-2.55878E-06	0	-2.559E-06
7	-62.8262	156.4091	-0.01198	-0.23525	-0.00256	-0.00228	0.011726	-2.55878E-06	0	-2.559E-06
8	-62.8262	156.1954	-0.01198	-0.23525	-0.00256	-0.00228	0.012628	-2.55878E-06	0	-2.559E-06
9	-62.8262	155.9817	-0.01198	-0.23525	-0.00256	-0.00228	0.013531	-2.55878E-06	0	-2.559E-06
10	-62.8262	155.7681	-0.01208	-0.23721	-0.00258	-0.00245	0.014433	-2.58015E-06	0	-2.58E-06
11	-62.8262	155.5544	-0.01218	-0.23917	-0.0026	-0.00262	0.015336	-2.60152E-06	0	-2.602E-06
12	-62.8262	155.3408	-0.01228	-0.24114	-0.00262	-0.00279	0.016239	-2.62289E-06	0	-2.623E-06
13	-62.8262	155.1271	-0.01238	-0.2431	-0.00264	-0.00296	0.017141	-2.64426E-06	0	-2.644E-06
14	-62.8262	154.9134	-0.01248	-0.24509	-0.00267	-0.00313	0.018044	-2.66585E-06	0	-2.666E-06
15	-62.8262	154.6998	-0.01258	-0.24705	-0.00269	-0.0033	0.018946	-2.68721E-06	0	-2.687E-06
...	...	...	...	...	...	...	...	...	...	...

Table D2: Description of data analysis for estimation of recirculation rate

Parameter	Description	Sources
x	Streamwise location	PIV data
z	Local depth from the surface	PIV data
u	Horizontal velocity	
u/U_0	Normalized horizontal velocity	
v	Vertical velocity	PIV data
v/U_0	Normalized vertical velocity	
H	Water depth	Experimental setup
q	Local flow rate per metre width	For example, $q(3)=u(3) \times \{[(z(3)-z(2))/2 + [(z(4)-z(3))/2]\}$. Here, (i) refers to the relevant data in row i of Table D1.
q_{forward}	Rate of the forward flow per metre width	$q_{\text{forward}}=q$ if $q>0$
q_{reverse}	Rate of the reverse flow per metre width	$q_{\text{reverse}}=-q$ if $q<0$
q_0	Incident flow rate	Based on H and U_0
Recirculation rate	Percentage of the rate of the reverse flow to the incident flow rate	$\Sigma q_{\text{reverse}}/q_0$ (%)

APPENDIX E: SIMULATION PROCEDURE EMPLOYED IN FLUENT

Figure E1: Flow chart of the simulation steps adopted in FLUENT simulation

APPENDIX F: GRID GENERATION FOR THE NUMERICAL SIMULATIONS

Figures F1, F2, F3, F4, F5, F6, F7, F8 and F9 show the mesh used for the numerical simulations of the flow around a silt screen. For the case of transverse flow, a mesh of size 202 x 85 (Figure F1) was generated for the simulation. For the case of vertical flow, the mesh size used for each simulation case is summarized in Table F1.

Table F1: Summary of the size of the meshes used for simulation of flow in the vertical plane around silt screens of various configurations

Scale	Domain size	SPR	Vertical configuration	Mesh size	Mesh type
Laboratory scale	H=0.24 m	0.7	prevailing design	801 x 50	Structured mesh
Pilot scale	H=25 m	0.9	prevailing design (Case 1.1)	421 x 46	Structured mesh
Pilot scale	H=25 m	0.9	Case 2.1	421 x 55	Structured mesh and unstructured mesh
Pilot scale	H=25 m	0.9	Case 2.2	491 x 55	Structured mesh and unstructured mesh
Pilot scale	H=25 m	0.9	Case 2.3	421 x 56	Structured mesh and unstructured mesh
Pilot scale	H=25 m	0.9	Case 2.4	430 x 76	Structured mesh and unstructured mesh
Pilot scale	H=25 m	0.9	Case 3.1	491 x 96	Structured mesh and unstructured mesh
Pilot scale	H=25 m	0.9	Case 3.2	491 x 96	Structured mesh and unstructured mesh

Figure F1: Zoom-in image of the mesh used for simulation of flow around a silt screen of length L_s along the transverse plane

Figure F2: Zoom-in image of the mesh used for simulation of flow around a silt screen with $SPR=0.7$ in flume scenario

Figure F3: Zoom-in image of the mesh used for simulation of flow around a silt screen with $SPR=0.9$ in pilot scale

Figure F4: Zoom-in image of the mesh used for simulation of flow around a compound silt screen (Case 2.1) with $SPR=0.9$ in pilot scale

Figure F5: Zoom-in image of the mesh used for simulation of flow around a compound silt screen (Case 2.2) with $SPR=0.9$ in pilot scale

Figure F6: Zoom-in image of the mesh used for simulation of flow around a compound silt screen (Case 2.3) with SPR=0.9 in pilot scale

Figure F7: Zoom-in image of the mesh used for simulation of flow around a compound silt screen (Case 2.4) with SPR=0.9 in pilot scale

Figure F8: Zoom-in image of the mesh used for simulation of flow around a compound silt screen (Case 3.1) with SPR=0.9 in pilot scale

Figure F9: Zoom-in image of the mesh used for simulation of flow around a compound silt screen (Case 3.2) with SPR=0.9 in pilot scale

APPENDIX G: VELOCITY PROFILES OBTAINED FROM FLUENT SIMULATION OF THE FLUME SCENARIO WITH A SILT SCREEN OF SPR=0.7

(a)

(b)

(c)

(d)

Figure G1: Velocity profiles obtained upstream (a&b) and downstream (c&d) of a silt screen from the numerical simulation of the flow around a silt screen with SPR=0.7 in incident flow $U_0=0.05$ m/s.

APPENDIX H: SIMULATION RESULTS ON THE FLOW DISTRIBUTION AROUND A SILT SCREEN IN THE TRANSVERSE DIRECTION

Figure H1: Spatial variation of the percentage of flow approaching the silt screen ($L=100$ m, $U_0=0.05$ m/s) to the original environmental flow. In the simulations, $H=25$ m.

Figure H2: Spatial variation of the percentage of flow approaching the silt screen ($L=250$ m, $U_0=0.05$ m/s) to the original environmental flow. In the simulations, $H=25$ m.

Figure H3: Spatial variation of the percentage of flow approaching the silt screen ($L=500$ m, $U_0=0.05$ m/s) to the original environmental flow. In the simulations, $H=25$ m.

Figure H4: Spatial variation of the percentage of flow approaching the silt screen ($L=1000$ m, $U_0=0.05$ m/s) to the original environmental flow. In the simulations, $H=25$ m.

Table H1: Example of the approach employed to estimate the streamlines deflection as the flow approaches the screen's edge (based on simulation data at location $x=-1\text{m}$ upstream of the screen of $L_s=500\text{m}$ and with $U_0=0.05\text{ m/s}$)

Projected screen length (m)	u (m/s)	v (m/s)	u/v	Angle of deflection of the flow (°) (estimated based on the ratio u/v)
0	0.0014	0.0050	0.2740	15.3
20	0.0006	0.0041	0.1414	8.0
40	0.0004	0.0033	0.1055	6.0
60	0.0003	0.0028	0.0922	5.3
80	0.0002	0.0024	0.0886	5.1
100	0.0002	0.0020	0.0905	5.2
120	0.0002	0.0017	0.0970	5.5
140	0.0001	0.0014	0.1091	6.2
160	0.0001	0.0011	0.1292	7.4
180	0.0001	0.0008	0.1639	9.3
200	0.0001	0.0006	0.2321	13.1
220	0.0001	0.0003	0.3977	21.7
240	0.0001	0.0001	1.2075	50.4
260	0.0001	-0.0001	-1.2291	-50.9
280	0.0001	-0.0003	-0.4001	-21.8
300	0.0001	-0.0006	-0.2330	-13.1
320	0.0001	-0.0008	-0.1643	-9.3
340	0.0001	-0.0011	-0.1294	-7.4
360	0.0001	-0.0014	-0.1093	-6.2
380	0.0002	-0.0017	-0.0972	-5.5
400	0.0002	-0.0020	-0.0905	-5.2
420	0.0002	-0.0024	-0.0887	-5.1
440	0.0003	-0.0028	-0.0923	-5.3
460	0.0004	-0.0033	-0.1055	-6.0
480	0.0006	-0.0041	-0.1415	-8.1
500	0.0014	-0.0050	-0.2741	-15.3

Table H2: Example of the data used to estimate the percentage of the flow approaching the screen (based on simulation data at location $x=-H$ upstream of the screen) ($L_s=500\text{m}$, $U_0=0.05\text{ m/s}$)

Projected screen length (m) (1)	u (m/s) (2)	v (m/s) (3)	Q approaching screen (m^3/s) (estimated based on the value of u) (4)
0	0.0162	0.0431	0.1619
20	0.0108	0.0375	0.2169
40	0.0076	0.0319	0.1521
60	0.0059	0.0273	0.1175
80	0.0049	0.0233	0.0972
100	0.0042	0.0198	0.0842
120	0.0038	0.0166	0.0753
140	0.0035	0.0137	0.0691
160	0.0032	0.0110	0.0645
180	0.0031	0.0084	0.0612
200	0.0029	0.0059	0.0589
220	0.0029	0.0035	0.0575
240	0.0028	0.0012	0.0566
260	0.0028	-0.0012	0.0566
280	0.0029	-0.0035	0.0575
300	0.0029	-0.0059	0.0589
320	0.0031	-0.0084	0.0612
340	0.0032	-0.0110	0.0645
360	0.0035	-0.0137	0.0691
380	0.0038	-0.0166	0.0753
400	0.0042	-0.0197	0.0842
420	0.0049	-0.0232	0.0972
440	0.0059	-0.0273	0.1175
460	0.0076	-0.0319	0.1521
480	0.0108	-0.0374	0.2169
500	0.0162	-0.0431	0.1619
Flow rate approaching screen (m^3/ms) (a) [=sum of column (4)]			2.55
Original environmental flow (corresponding to the screen length) (m^3/ms) (b)			25
% of flow approaching screen [= (a)/(b) x 100%]			10.2

Table H3: Examples of the estimated angle of deflection of the streamlines as the flow approaches the screen's edge

L_s (m)	U_0 (m/s)	Angle of deflection (°)
100	0.1	15.3
250	0.1	15.3
500	0.1	15.3
1000	0.1	15.3
100	0.05	15.3
250	0.05	15.3
500	0.05	15.3
1000	0.05	15.3

APPENDIX I: TYPICAL PROFILES OF VELOCITY DISTRIBUTION AND SUSPENDED SEDIMENT CONCENTRATION OBSERVED IN FIELD DATA

1. Flow data

Figure I1: Typical vertical velocity profiles measured at 10m upstream of the silt screen on 09 September 2009 during ebb tide and West going current

Figure I2: Typical vertical velocity profiles measured at 10 m upstream of the silt screen on 24 March 2009 during flood tide and East going current

Figure I3: Typical vertical velocity profiles measured at 10 m downstream of the silt screen on 09 September 2009 during ebb tide and West going current

Figure I4: Typical vertical velocity profiles measured at 10 m downstream of the silt screen on 24 March 2009 during flood tide and East going current

2. Sediment data

Figure 15: Typical vertical SSC profiles measured at 10 m upstream of the silt screen on 09 September 2009 during ebb tide and West going current

Figure I6: Typical vertical SSC profiles measured at 10 m upstream of the silt screen on 24 March 2009 during flood tide and East going current

Figure 17: Vertical SSC profiles measured along the transect located at 10 m downstream of the silt screen on 09 September 2009 during ebb tide and West going current

Figure I8: Typical vertical SSC profiles measured at 10 m downstream of the silt screen on 24 March 2009 during flood tide and East going current

APPENDIX J: RESULTS OF THE EXPERIMENTS ON THE ENVIRONMENTAL DEGRADATION AND CLOGGING OF SILT SCREENS

Figure J1: The measured variation of permeability of silt screen samples submerged at different environmental condition. In all environmental conditions tested, the change in the permeability of the silt screens were within 15%.

Figure J2: Temporal variation of permeability measured with three types of silt screens. The figure shows significant changes in the permeability of the silt screens during clogging experiments.

APPENDIX K: RETENTION OF PARTICLES IN THE VICINITY OF SILT SCREENS OF DIFFERENT VERTICAL CONFIGURATIONS

Table K1: Variation of the detention time of particles upstream of silt screens of different configurations and submerged in different flow velocities

Velocity (m/s)	without screen	Configuration						
		original	2.1	2.2	2.3	2.4	3.1	3.2
0.05	750 s	1000 s	2000s	1500 s	1200 s	1500 s	1500 s	1350 s
0.1	300 s	300 s	500 s	750 s	600 s	750 s	600 s	670 s
0.2	140 s	140 s	300 s	380 s	250 s	340 s	250 s	380 s

In Table K1, the detention time was estimated as the duration in which at least 90% of the particles could be found in the upstream region. For the baseline condition (without silt screen), the detention time was estimated as the duration that at least 90 % of the particles could be found in the first 150 m of the simulation domain (corresponding to the upstream region in the simulations with screens).

Figure K1 shows the variation of the percentage of particles contained in the simulation domain when different configurations are used. The domain, as elaborated, stretches from 150 m upstream to 450 m downstream of the screen. Although there were no particles retained in the upstream regions, simulation results show positive percentage of particles retained in the domain in certain cases (Figure K1). This suggests that sediment particles could also be trapped in the downstream recirculation zone. However, as this study focuses on the retention of particles upstream of the screen, the effects of the downstream recirculation zone on particles retention are not considered in this study.

Figure K1: Variation of the percentage of particles contained in the simulation domain when silt screens of different configurations were used (SPR=0.9)