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Sediment Sorting by Hopper Dredging and Pump-Out Operations

Conceptual Model and Literature Review

Anthony M. Priestas, S. Jarrell Smith, and Katherine E. Brutsché

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Conceptual Model and Literature Review

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Abstract

Dredged sediment placed on beaches or nearshore environments is customarily evaluated for compatibility with the native beach sediment to avoid unintended impacts to economic, environmental, or recreational resources. Consequently, some state regulatory authorities establish limits upon the fine-grained content for sediment designated for placement on certain beaches and nearshore environments. Hopper dredging operations for beach and nearshore placement typically include periods of overflow, which is recognized to produce some degree of separation between the size fractions of the dredged sediment. The degree of separation and the controlling factors of separation are presently poorly known and are the subject of this research. This report provides a conceptual model of the hopper dredging and placement processes, including the relevant processes associated with hopper dredge-associated sediment dynamics, generation and transport of the overflow sediment plume, and sediment winnowing at the beach outflow. Prior research is described, and knowledge gaps are identified. Finally, a research plan to validate prior research and to address knowledge gaps is presented. An annotated bibliography of relevant literature is given in an appendix. Documentation of the planned research presented herein will appear in future publications associated with this study.

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Preface

This study was conducted for the Regional Sediment Management Program through an Interagency Agreement (IAA, number M16PG00023) between the US Department of the Interior, Bureau of Ocean Energy Management (BOEM); the US Army Corps of Engineers (USACE), Jacksonville District (SAJ); and the US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Regional Sediment Management (RSM) Program, under Funding Account Code D86F00; AMSCO Code 008303. Funding was provided by BOEM and the USACE ERDC RSM Program.

Dr. Clay McCoy was the Technical Lead and Project Manager from SAJ, Mr. Doug Piatkowski was the Contracting Officer's Representative for BOEM, and Ms. Leighann Brandt was the Technical Lead from BOEM. Support for the development and implementation of the IAA was provided by Ms. Jackie Keiser, Mr. Jason Engle, and Dr. Kelly Legault of the RSM Regional Center of Expertise. The USACE administrative point of contact was Ms. Liz Fiocchi. Mr. Douglas Piatowski, Ms. Leighann Brandt, and Mr. Paul Knorr (BOEM), Dr. Michael Miner (The Water Institute of the Gulf), and Dr. Clay McCoy (SAJ, RSM Regional Center of Expertise) are thanked for the development of the study concept and their valuable input toward the study plan and methods.

The work was performed by the CHL Field Data Collection and Analysis Branch and the Coastal Engineering Branch of the Navigation Division, ERDC, CHL. At the time of publication of this technical report, Mr. William C. Butler was Chief of the Field Data Collection and Analysis Branch, and Ms. Lauren M. Dunkin was Chief of the Coastal Engineering Branch. Dr. Jacqueline S. Pettway was Chief of the Navigation Division. Dr. Katherine E. Brutsché was the USACE National RSM Program Manager, and Mr. Charles E. Wiggins was the ERDC Technical Director for Navigation. The Deputy Director of CHL was Mr. Jeffrey R. Eckstein, and Dr. Ty V. Wamsley was the Director.

COL Teresa A. Schlosser was the Commander of ERDC, and the Director of ERDC was Dr. David W. Pittman.

1 Introduction

This report is part of a broader effort to determine the separation (Phase I) and fate (Phase II) of fine sediments discharged through hopper dredging and pump-out operations. Phase I consists of three research components: (1) background review, (2) laboratory experiments, and (3) field sampling and analysis. As part of the Phase I research, this (first) report conceptually evaluates the degree of sediment separation from trailing suction hopper dredges (TSHD) and pump-out operations, and presents a background review of the relevant literature. A subsequent (second) report from Phase I will present the findings from laboratory tests and numerical experiments aimed at determining appropriate sediment collection and analysis methods. The final (third) report from Phase I will present the findings of the field campaign whereby the loss rate of fine sediment is quantified at various stages of the dredging process. The final report will be published through the Bureau of Ocean Energy Management (OCS Study BOEM 2019-010).

1.1 Background

In shore protection, ecosystem restoration, and navigation projects where sediment is placed on the beach or in the nearshore, coastal project managers are required to ensure that sediment taken from source areas (e.g., offshore borrow site, navigation channel, inlet complex) is compatible with the sediment characteristics at the placement site (e.g., the beach or nearshore). Important factors to consider are sediment grain size, composition, sorting, and color. Additionally, some state regulations across the nation specify allowable thresholds of percent abundance of fine sediment relative to sand content. The threshold size for fine sediment is defined as either the sediment passing the #200 (0.075 mm)¹ sieve, in accordance with the Unified Soil Classification System, or the material passing the #200 (0.063 mm) sieve in accordance with the Udden-Wentworth scale.

¹ For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

When determining compatibility between the source sediment and the native sediment, it is typically assumed that textural properties (e.g., sorting, mean grain size, and percent sand) are maintained from the in situ borrow area, through dredging and conveyance, to the placement site. However, it is generally recognized that hopper dredges implementing overflow (the intentional discharge of supernatant water) coarsen their load relative to the source material through preferential loss of fines suspended in overflow (the gain in hopper load through this process is known as economic loading). Generally, the present methods for assessing sediment compatibility do not adequately reflect the changes in grain size characteristics between the borrow area and what is subsequently placed on the beach.

Understanding and quantifying the coarsening of sediment in the hopper load would allow coastal managers to better estimate the size characteristics of the material at the placement location compared to the source material. It is hypothesized that, based on this coarsening process during dredging operations, use of source material containing a higher concentration of fines could be used in coastal flood risk management, ecosystem restoration, and navigation projects, leading to potential cost savings while expanding potential source volumes.

1.2 Objective

The objective of this study is to quantify changes in sediment characteristics (i.e., grain size, sorting) and the degree, timing, and variability of sediment sorting during dredging, pump out, and placement operations. This information is presented so that the results and methods can be applied to inform sediment compatibility analyses and subsequent management of offshore sediment resources. The degree of sediment separation by size class will be quantified throughout the dredging process including (1) at the in situ borrow site as a baseline for comparison, (2) during overflow with particular emphasis on the proportion of fines lost, and (3) during pump out at the beach. As discussed in detail in Chapter 3, several tasks have been outlined to meet the objectives of this study, including this report, a lab experiment to test and refine sampling methodologies, and the employment of those methodologies in the field to quantify fines loss from in situ source material to placement location.

1.3 Approach

Chapter 2 of this report presents the conceptual model beginning with an overview of the dredging process from source to placement area, and identifies points of sediment sorting and loss of fines during that process. Generally, loss occurs in the hopper during overflow, as well as at the pipeline outflow at the placement site. Once placed on the beach or the nearshore, sediments are further winnowed by natural coastal processes (i.e., waves and currents). Chapter 2 also includes a discussion on the transport processes of the fine sediment in the plume associated with overflow and potential sampling methods for the study. A brief discussion of uncertainty in quantifying losses is also included. Chapter 3 discusses the proposed research including both laboratory and field experiment methods. An appendix is included containing an annotated bibliography of the relevant references by topic.

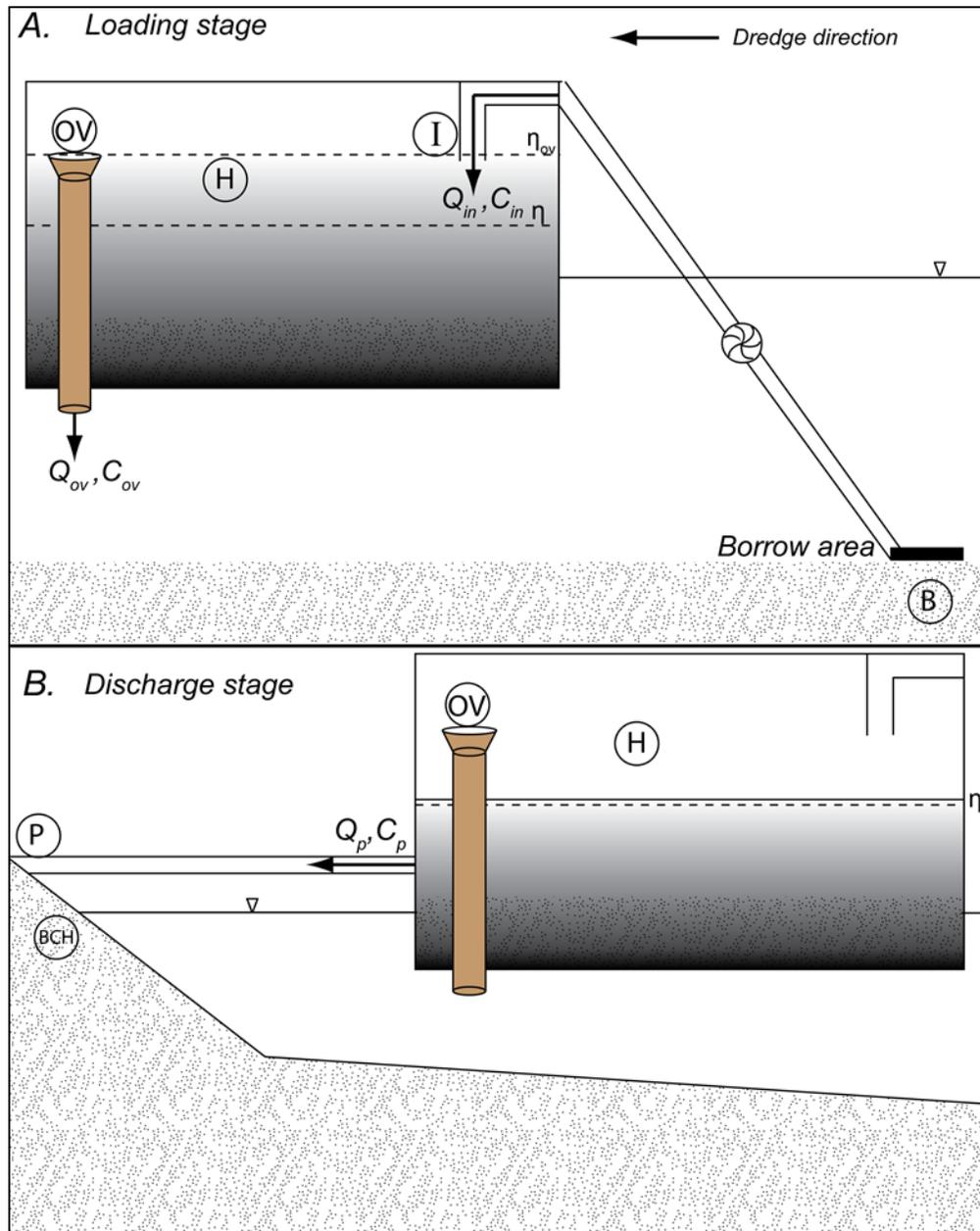
2 Conceptual Model

The primary aim of this study is to determine the size-dependent loss of material at each stage of the dredging process, particularly the fine fraction lost during overflow. This research focuses on fine sediment losses from a TSHD; other dredge types (such as cutter-suction dredges) are recognized as subsets of the TSHD process but are not considered here. Mechanical dredgers are also not considered here as they are not typically used for nearshore and beach placement operations.

This section briefly summarizes the loading cycle and sedimentation processes within hopper dredges and identifies the points of separation where sediments may be fractionated or removed. Additionally, the mass balance of material flow is defined for each stage in the process and used as the basis to quantify those losses.

In TSHDs, the dredging cycle can be categorized into three primary stages: (1) removal of the bed material, (2) loading of the hopper, and (3) discharging the hopper load through pump out, rainbowing, or bottom dump. Referring to Figure 1(A), first, sediments are hydraulically excavated from the borrow area (B) through a drag head and impeller pump system while the dredger is in forward motion. The sediment-water mixture, which is approximately 10%–20% solids by volume (Bray et al. 1997) is then discharged into the hopper (H) at point (I) at a given flow rate (Q_{in}) and mixture density (C_{in}). As the hopper fills, particles segregate as coarser particles settle to the bottom while finer particles remain in suspension depending on size distribution, slurry density, and hydrodynamic conditions within the hopper. Once the slurry level (η) reaches the level of overflow (η_{ov}), excess water and suspended sediments are expelled through an overflow weir (W) that discharges into the water column either near the water surface or through the base of the ship's hull. Pumping is stopped when the bed level reaches the overflow weir, which is adjustable in the constant tonnage system (CTS) or fixed in the constant volume system (CVS). Finally, discharging of the hopper load is accomplished by either direct dumping through bottom doors or use of a split hull, rainbowing (pressurized aerial discharge from the bow), or direct pump out (P) onto a shoreline (BCH) or confinement area, as depicted in Figure 1(B).

Figure 1. Schematization of the dredging cycle and sampling points during the loading stage (A) and discharge stage (B). A mass balance approach is used to determine the loss of fine material between the borrow area (B) and placement area along a beach (BCH). The mass balance approach tracks flow (Q) and sediment concentration (C) at the inflow (I), overflow (OV), and pump out (P). See text for additional details.



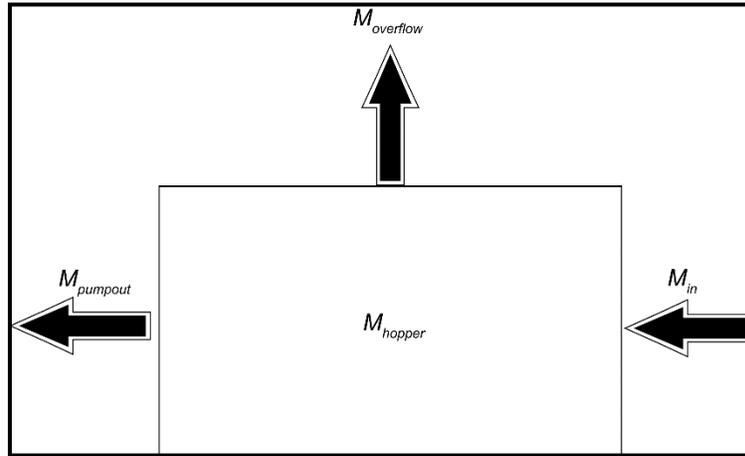
The expulsion of sediments during overflow is expected to be the primary conduit for the loss of fines. The separation of fines may also occur during pump out onto the shoreface of a beach; turbulence may resuspend sediment, and return flow from the outfall may entrain and transport fine

sediments, which are then carried offshore, in addition to winnowing by subsequent waves and tides. The goal of the present research is to quantify these losses at each point in this process using a mass balance approach (Figure 2). For this approach, the following assumptions are made:

- Negligible loss of fines at the drag head.
- Negligible effect or likelihood that overflow sediments are reintroduced at the drag head.
- Negligible loss of fines associated with pipeline transport.
- All sediments are fully retained within the hopper during the loading stage (excepting during overflow) and fully removed during the discharge stage.

At the site of the drag head, some sediment resuspension may occur as the drag head is often equipped with jets or teeth to loosen the sediment prior to being suctioned to improve production efficiency, which may mobilize fine sediment to the water column. This process may be exacerbated if the forward speed of the dredger is too fast (i.e., not optimized relative to suction capacity). In general, however, these are thought to not contribute significantly to the loss of fines because the pressure difference over the drag head causes high flow potentials close to the drag head (Vlasblom 2007), which is speculated to minimize resuspension. Instead, based on previous experience, there exists the possibility that some finer material from the overflow plume (discharged from the hopper) may settle and be re-entrained into the suction line, which would enrich the inflow with fine sediment (though the extent to which this condition occurs is unknown and likely dependent of site-specific conditions). Additional losses may occur through leakage of the hopper doors or hull and through pipeline connections; however, all these losses are considered negligible from a mass balance perspective and are not considered in this analysis.

Figure 2. Mass balance of sediments during a dredging cycle.



The total mass of sediments entering the hopper ($M_{in} = Q_{in}C_{in}$) (Figure 1[A]) is balanced by the sum of masses exiting, thus

$$M_{in} - (M_{overflow} + M_{pumpout}) = 0 \quad (1)$$

$$M_{in} = M_{overflow} + M_{pumpout} \quad (2)$$

During the loading stage, the mass retained in the hopper is

$$M_{hopper} = M_{in} - M_{overflow} = M_{pumpout} \quad (3)$$

During the discharge stage, the mass transferred to the placement area during pump out is equal to the mass retained in the hopper (Equation 3), assuming no leakage from the hopper and 100% of the sediment was removed.

The mass flow of sediments into the hopper can be expressed as

$$\frac{dm_{in}}{dt} = Q_{in}\rho_m = Q_{in}(\rho_w(1 - C_v) + \rho_s C_v) \quad (4)$$

where

Q_{in} = flow rate, (m³/s)

ρ_m = slurry density, (kg/m³)

ρ_w = water density, (kg/m³)

ρ_s = sediment density, (kg/m³)

C_v = volume fraction occupied by sediment [-] $\circ \frac{\rho_m - \rho_w}{\rho_s - \rho_w}$

However, quantifying the percentage of fines lost in the dredging process does not require explicit knowledge of the slurry density if the volumetric flow and sediment concentration by mass in and out of the hopper can be measured. The total mass of sediments into the hopper is

$$m_{in} = \sum Q_{in} C_{in} \Delta t_{in} \quad (5)$$

where C_{in} is the incoming slurry sediment concentration.

If the particle size distribution is known, the percentage of fines (f) is also known so that the mass of fines into the hopper is

$$m_{in} = \sum Q_{in} C_{in} f_{in} \Delta t_{in} \quad (6)$$

During loading, sediment mass is assumed to be fully retained inside the hopper when the slurry level (η) in the hopper is below the level of the overflow weir (η_{ov}). Once $\eta = \eta_{ov}$ the flow volume into the hopper is equal to the flow discharged at the weir ($Q_{in} = Q_{ov}$). Likewise, the sediment mass discharged through the overflow weir can be estimated as

$$m_{ov} = \sum Q_{in} C_{ov} \Delta t_{ov} \quad (7)$$

where Δt_{ov} is the dredging time past overflow. The total mass of sediment retained in the hopper is calculated as

$$m_H = m_{in} - m_{ov} = \sum Q_{in} (C_{in} t_{in} - C_{ov} t_{ov}) \quad (8)$$

The average fraction of sediments lost through overflow is estimated as the ratio of overflow to inflow sediment mass:

$$ov = \frac{m_{ov}}{m_{in}} \quad (9)$$

Similarly, the fraction of fines lost during overflow is

$$f_{ov} = \frac{m_{fov}}{m_{fin}} \quad (10)$$

The fines content during pump out, which theoretically should equal that of the hopper, could be used as a check against the calculation for the fines content retained in the hopper (Equation 5).

2.1 Separation of sediment by hopper dredging

This section reviews the processes related to size fractionation of sediment and their subsequent removal through the dredging cycle.

2.1.1 Tank sedimentation

Sedimentation in general is categorized into Types 1-4. In Type 1 settling, discrete particles settle freely and independently according to Stokes' Law, and independent of concentration. Particle sizes do not change, and therefore settling times are constant. In Type 2 settling, particles may flocculate and grow, which accelerates their fall velocity, also in accordance to Stokes' Law; settling times are therefore nonlinear. Type 3 is characterized by hindered settling, whereby settling velocities are reduced due to modification of the flow field induced by very high particle concentrations. Finally, Type 4 refers to compression settling, which describes the process of sediment compaction and resulting upward displacement of water.

The decrease in settling velocity is often described by the power law formulation from Richardson and Zaki (1954):

$$\frac{w(c)}{w_o} = (1 - c)^n \quad (11)$$

where w is the hindered settling velocity, w_o is the settling velocity of a single grain in still water, and c is the average volumetric sediment concentration; the exponent n depends on the Reynolds number and is typically between 2.5 and 5.5. Van Rijn (1984) suggested a value of $n = 4$ for very fine to medium sand. For sand grains, the transition to hindered settling occurs when particle concentrations are approximately 10%-20% by volume depending on particle type (Tomkins et al. 2005). Formulations by Soulsby (1997), Toorman and Berlamont (1999), Winterwerp (1999), and others have also been proposed to account for cohesive floc settling at high concentrations.

All four settling types are likely physically represented at different stages in the loading process. As sediments enter the hopper (assumed to be fully retained prior to overflow), they immediately separate according to settling type, the nature of which depends on particle size, shape, concentration, and degree of cohesiveness. During separation a sediment-

water interface develops, and some fraction of the finer sediments will remain suspended in the overlying water column, assisted by a net upward velocity of water from the hindered settling effect. Conversely, coarser sediments predominately settle prior to overflow while the depth of the water layer outpaces the bed layer thickness until overflow is reached. Prior to overflow, water velocities are relatively low, allowing grains to settle. During overflow, flow velocity increases and sediments in suspension are discharged as the bed continues to rise. The rising bed level further increases the flow velocity above the bed, which can contribute to scouring and acceleration of overflow losses depending on grain size; therefore, the dredging of finer sediments increases total overflow losses (Miedema and Vlasblom 1996). A generalization given by Vlasblom (2007) states that sediment with $d_{50} < 75$ micrometers (μm) are entrained in overflow, although this does not consider fine sediments in the form of clay balls, aggregates, and flocs, which have greater settling velocities.

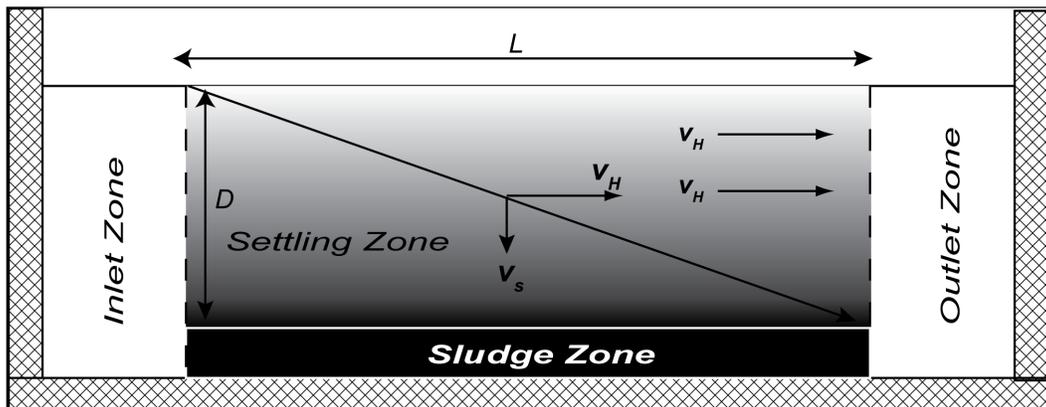
2.1.2 Models of tank sedimentation and separation

Hoppers can be considered as large-capacity settling tanks with an inflow and outflow. Much of the work on sedimentation within settling tanks was originally developed for the wastewater treatment industry. The ensuing theories were primarily developed for the purposes of removing suspended fines or *clarifying* the water column through the settling process. Reference is made to Camp (1936, 1946) and Dobbins (1944), whose theory on sedimentation (rooted in the work of Hazen [1904]) within ideal settling tanks is often regarded as the basis for settling theory and overflow losses within hopper dredges.

The Camp (1936) model (Figure 3) considers the trapping efficiency of sediments subjected to steady, uniform flow. The ideal basin is separated into an inflow zone, a settling zone, and an outflow zone. Sediments enter the basin in the direction of uniform, horizontal flow with uniform concentration in the vertical plane. Each particle then settles at a constant rate according to Stokes' Law. As such, the particle trajectories move along downward trending parallel paths across the length of the basin, equal to the vector sum of horizontal flow v_H and vertical settling velocities v_s . All particles are removed from the flow (i.e., the flow is clarified) if they settle at a distance less than the length of the basin (by corollary, removal from flow implies retention in the basin). In Camp's model, this vector is the critical settling velocity, sometimes called the overflow rate or surface loading rate. When applied to hoppers this is often referred to as the

hopper load parameter defined as $v_0 = v_H \left(\frac{D}{L}\right) = \frac{Q}{A}$, where Q is the volumetric inflow rate; D and L are basin depth and length, respectively; and A is the basin area. In this model (Figure 3), sediments entering from the top of the basin that settle at a rate equal to or greater than the critical flow velocity will be retained. Slower-settling particles will be partially retained only if they entered the zone starting from a lower depth in the basin. Ultimately, sediment retention is independent of basin depth in this model. For this reason, and considering Type 1 settling behavior only, the settling efficiency depends only on the overflow rate (hopper load parameter); smaller overflow rates increase settling efficiency (retention) for a non-rising bed level. Thus, Camp's model can estimate the flow-weighted concentration in the overflow by depth averaging over the outlet zone. Camp (1946) and Miedema and Vlasblom (1996) later added turbulence effects and resuspension by scouring to investigate the resulting changes in settling efficiency.

Figure 3. Conceptual model of an ideal settling tank. In this model, D is the basin depth, and L is the basin length. Sediment enters the basin from the inlet zone with a uniform vertical concentration and horizontal velocity V_H . Particles then settle with velocity V_s according to Stokes Law. A particle is considered lost to overflow only if the vector sum of V_H and V_s is greater than the basin length (i.e., the settling time is less than the time to travel the distance L). Adapted from Camp (1936).



Vlasblom and Miedema (1995) and Miedema and Vlasblom (1996) further modified the Camp (1936) model to incorporate a grain size distribution, hindered settling effects, and a rising bed level; the constant horizontal flow field was retained with no vertical velocities except that derived from turbulence. The outflow concentration is calculated instantaneously based on the incoming flow concentration and settling efficiency. The model generates loading curves (i.e., production rate in tons dry solid [TDS]) based on measures of influent mixture flow and density. The settling

efficiency is determined by accounting for turbulence and velocity changes due to a rising bed level for either a CTS or CVS hopper. The model produces an evolution of the grain size distribution and then calculates the mass of solids lost during overflow.

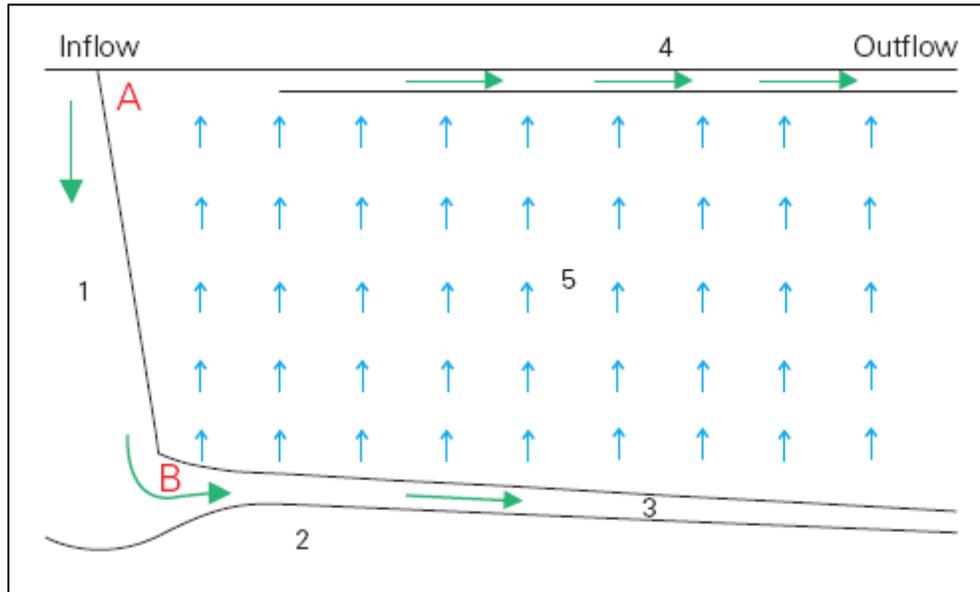
The model of Ooijens (1999) adds to the Miedema and Vlasblom (1996) model by introducing an unsteady state in flow volume and slurry concentration to estimate overflow losses, and considering the hopper as an ideal mixing tank. Virtual concentrations were used as input to the model and compared to measured overflow losses, which were estimated using shipboard measurements of incoming flow (Q_{in}) and volumetric sediment concentration (C_{vin}), along with the change in measured TDS (Rullens 1993) for a given time interval (Δt) and particle density ($\rho_s = 2650 \text{ kg/m}^3$):

$$ov = \frac{C_{vin}Q_{in}\Delta t\rho_s - TDS(t) - TDS(t-\Delta t)}{C_{vin}Q_{in}\Delta t\rho_s} \quad (12)$$

The model captured the estimated overflow loss reasonably well for two of three dredging test cases with a reported correlation of 0.75 to 0.85.

van Rhee (2001, 2002) used laboratory experiments and numerical modeling to investigate the hopper sedimentation process. Five different flow field regions of a model hopper were identified based on visual observations from laboratory experiments that used a rectangular glass-sided settling tank. Referring to Figure 4, these flow field regions are the inflow section (1), settled sand bed (2), density flow over the bed (3), horizontal surface flow toward the outlet (overflow section) (4), and sediment suspension (5). The incoming flow creates an erosion crater and density current from which sediments are deposited, resulting in a rising bed level. Part of the sediment that does not settle moves upward into suspension, and the incoming flow induces a strong horizontal flow toward the overflow section.

Figure 4. Schematization of flow for a single inlet settling tank based on the observations of van Rhee (2001). Figure adapted from van Rhee (2002).



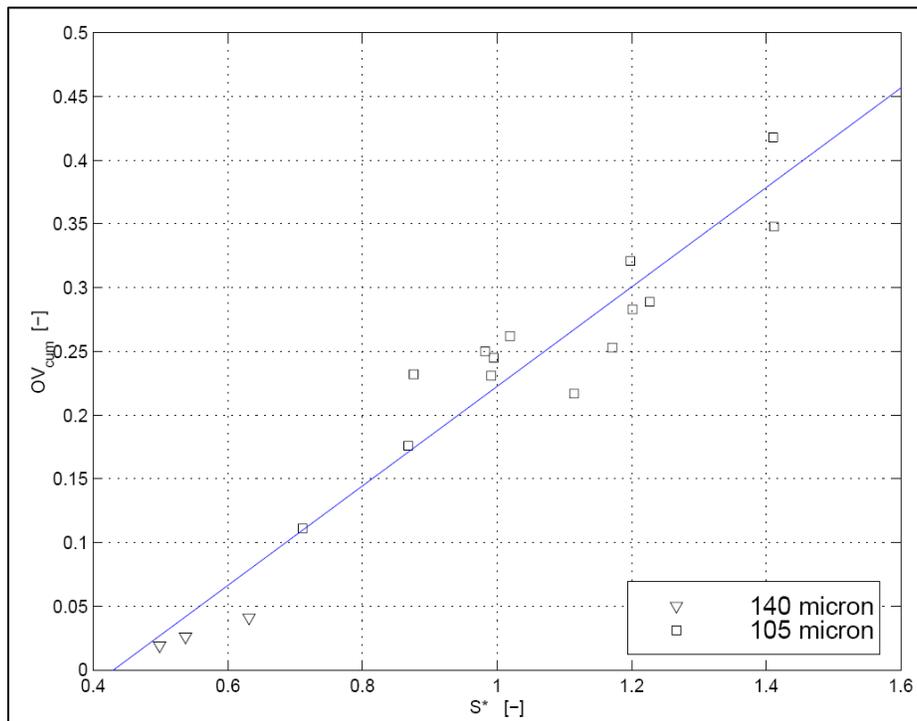
The amount of fine material lost in the overflow was quantified over 19 experiments. The experiments showed that cumulative overflow losses could be expressed as a linear function of the dimensionless hopper load parameter $H^* = v_o/w_o(1 - c)^n$, which is the overflow rate divided by the sedimentation velocity of the suspension (i.e., hindered settling given by Equation 11); therefore, overflow losses increase with the hopper load parameter (Figure 5). This linear relationship was found to improve if the load parameter was instead based on sand fluxes (ratio between the inflow fluxes and settling fluxes) given as

$$S^* = \left(\frac{c_{in}}{c_{bed}} \right) \frac{1-n_o-c_{bed}}{1-n_o} H^* \quad (13)$$

where c_{in} and c_{bed} are the inflow and bed concentrations, respectively, and n_o is the porosity. Since c_{bed} is not known, it is assumed equal to c_{in} as a first approximation. The cumulative overflow loss was regressed against S^* to obtain

$$Ov_{cum} = 0.39(S^* - 0.43) \quad (14)$$

Figure 5. Cumulative overflow losses as a function of the dimensionless hopper load parameter based on sand fluxes. Adapted from van Rhee (2001).



van Rhee (2002) noted that it is uncertain if the relationship holds for different scales, and it only accounts for spherical grains of uniform diameter. Likewise, the concentration at the bottom is not known, and must be approximated by the incoming concentration.

One of the conclusions based on the laboratory study was that turbulence plays a lesser role in sedimentation processes within hoppers, although that may not hold at prototype scale. However, given the often observed viscous flow behavior during hopper loading stages, that conclusion may indeed be applicable in many cases.

For the modeling component, a one-dimensional (1D) model of hopper sedimentation was developed using the advection-diffusion equation for a poly-disperse mixture, and includes the influence of the overflow rate (hopper load parameter). As opposed to the horizontal settling tank model of Camp (2001), this model simulates hopper loading in the vertical dimension with sediments introduced from the bottom fed by the density current, and the overflow located at the top. The model was compared with 1D tests in a settling column, which showed reasonably good agreement. Van Rhee (2002) later developed a two-dimensional model based on the

Reynolds-Averaged Navier Stokes equations with a $k - \varepsilon$ turbulence model. The modeled overflow losses compared similarly to the simplified Camp (2001) model of Miedema and Vlasblom (1996).

Miedema (2009b) investigated the influence of the bed rise velocity on the hopper load parameter, as the decrease in the hopper depth influences the settling time and increases the overflow rate. This gives rise to a modified hopper load parameter and settling efficiency. A secondary research topic examined potential scaling laws from small- to large-capacity hoppers, which determined to keep the hopper load parameter constant and derive other scale laws for the flow and not to scale the sand (Miedema 2009a).

In all of the above-mentioned models, the monitoring system aboard the dredge would be used to quantify flow and sediment concentration into the hopper. Overflow losses are typically quantified in terms of the effect on production (i.e., total mass of sediment lost per hopper load). However, the fraction of fines lost cannot be determined without knowledge of the particle size distributions (PSD) at the inflow and overflow pipes. Since PSD are not part of the monitoring system, direct samples must be taken for particle size analysis and quantification of the fraction of fines lost.

2.2 Separation of sediment by pipeline outfall and beach processes

Previous research regarding sediment dispersion at a pipeline outfall is dominated by open water placement of material (i.e., nearshore placement). Models have been created to illustrate the mixing zone of dredged material as well as the near-to-far field models of mixing. Models have also been created to simulate the underflow at discharge points caused by the formation of fluid mud layers at the bed that flow away from the discharge point, and are dependent on bottom slope, ambient currents, and their initial discharge trajectory (Teeter 2002). These models are summarized in this section; however, they apply only to open water placement of material. In many cases, the studies do not summarize separation of the sediment based on grain size, but instead use the dispersion of the dredged material as a whole. Much of the literature regarding separation of fines at this point in the process (i.e., pipe outfall on the beach) pertained to beach processes that occur naturally before, during, and after placement of material on the beach.

2.2.1 Pipeline outfall

Pipeline outfalls associated with open water disposal of dredged material have been studied since the 1970s to determine potential environmental impacts of dredging due to suspension of sediments in the water column (e.g., Gordon 1974; Brandsma and Divoky 1976; Henry et al. 1978; Nichols and Thompson 1978). These studies were mainly focused on resuspension and the behavior of the material to predict the extent and duration of the fluid mud and, ultimately, determine potential environmental impacts due to dredging. In subsequent studies, focus was turned to the dispersion and underflow of the material once it was placed in the open water. Teeter (1994) describes three dispersion phases of pipeline disposal of dredged material: (1) discharge plume descent, (2) underflow spreading and entrainment of the underflow material into the overlying ambient flow, and (3) passive dispersion. The Plume Measurement System (PLUMES) was used at a field site in the James River Estuary in Virginia to detect relative concentrations, measure current fields, and chart vessel position during a dredging event. Suspended sediment samples were also collected for ground truthing. The field data indicated that the discharged sediment descended and reached the bed directly below the discharge point. An underflow formed and spread to a distance approximately 100 m from the source, and the spreading was controlled by the bathymetry of the site. It was also concluded that most entrainment would occur during higher current speeds.

Although no literature was found on studies regarding pipeline outfall on the beach, the sedimentation processes due to outfall on the beach are similar to those in the hopper. Sorting of sediments at the beach outfall is governed by the balance of particle settling and the physical processes of the flow. Sediments in the pumped slurry within the pipeline are kept in suspension by maintaining sufficiently high flow velocities (and turbulent mixing) in the pipe. The flow exiting the pipe plunges into a mixing cell and then spreads out under gravitational effects as dictated by the geometry of the beach and exit velocity of the flow. The beach geometry may be altered by temporary construction works such as berms or dikes to direct the outflow and/or enhance sedimentation. As the flow becomes less confined and spreads under gravitational forcing, velocities typically decrease, leading to decreased turbulent mixing and deposition of the suspended sediments. The degree of sedimentation is governed by factors such as the horizontal velocities, the beach slope, water depth in the outfall flow, length of the outfall flow path, and sediment settling velocity.

2.2.1.1 Modeling of discharge from pipeline outfalls

Several models illustrate discharge at pipeline outfalls. CORMIX is a US Environmental Protection Agency near-field mixing analysis model that simulates the initial mixing of the dredged material immediately upon submerged discharge from the dredge pipe (Doneker and Jirka 2007; MG Associates 2012; Purnama et al. 2016). The Pipeline Discharge FATE (PDFATE) model is used to evaluate underflow spreading and to predict the deposition of sediments on the bottom, as well as entrainment of sediments in the water column (Teeter 2000, 2001; MG Associates 2012). The model formulation includes deposition of sediment particles according to concentration-dependent settling rates and shear stress thresholds related to sediment characteristics, entrainment of overlying water into the underflow, appropriate flow properties of the underflow suspension, lateral spreading of the underflow, and variable bottom slope (Teeter 2001; MG Associates 2012). To determine long-term fate of material once it deposits on the bottom, the Environmental Fluid Dynamics Code (EFDC) coupled with the SEDiment dynamics algorithms as developed by Ziegler, Lick, and Jones (SEDZLJ) model is often used (Ziegler and Lick 1986; Ziegler and Lick 1988; Jones and Lick 1999; Jones and Lick 2001). EFDC is a model for simulating three-dimensional (3D) flow, transport, and biogeochemical processes in surface water systems (Hamrick 1996). EFDC was modified by the Sandia National Laboratories to include sediment dynamics such as erosion and bed load transport, bed sorting, and armoring (James et al. 2010; Thanh et al. 2008; MG Associates 2012). The US Army Corps of Engineers (USACE) later incorporated EFDC-SEDZLJ in the Long Term FATE (LTFATE) modeling analysis for material placed in open water (e.g., Hayter et al. 2012). These models are generally not applicable for subaerial pipeline outfalls on the beach; however, they are applicable for nearshore placement.

2.2.2 Separation of sediment due to nearshore and beach processes

Once material is placed on the beach, sediment separation due to natural beach and nearshore processes such as waves and currents can occur. The concept that fine material winnows out of beach sands through hydrodynamic or aeolian forcing is well established (e.g., Stapor and Tanner 1975; McCave 1978; Kana and Mohan 1998). However, recent studies have begun to focus on detailed monitoring of sediment characteristics following beach nourishments to determine if current state regulations regarding placing certain amounts of fines on beaches are

necessary (e.g., Warrick 2013, Goodrich and Warrick 2015, Maglio et al. 2015). Generally, because fine material has a slower settling velocity than coarse material, once material is suspended in the water column, fine sediment is entrained in the orbital motions of the wave for a longer time, and consequently, the fine fraction of the sediment is transported farther offshore than the coarse fraction (e.g., Dean 1973, 1977; Hallermeier 1981).

Warrick (2013) studied a nourishment at Imperial Beach, California, which contained 40% fines by weight. The study showed that the mean residence time of fine material suspended in the surf zone through wave action was approximately 1 hour. Decreases in fine sediment within the surf zone along the beach were due to offshore transport by rip currents. In the swash zone, because the material was placed directly on the beach, elevated levels of suspended fines lasted several days after nourishment as fine material was being winnowed from the beach. Deposition of the fine material was greatest on the seafloor directly offshore of the nourishment area; however, a mass balance of the sediment suggested that the majority of fine sediment was deposited over 2 km away from the nourishment site or to water depths greater than 10 m. The study concluded that the fate of fine material was strongly influenced by wave conditions, surf zone and rip current transport, and the vertical density and flow conditions of coastal waters. Goodrich and Warrick (2015) summarized this study as well as a study conducted at Santa Cruz Harbor. The two demonstration projects were used as tools to communicate with coastal managers regarding the use of material with relatively large amounts of fines in beach and nearshore nourishments.

Maglio et al. (2015) studied several beach nourishment projects in Florida to determine fines loss through the dredging process. Specifically, at Egmont Key, Florida, fine material initially found on the surface of the beach, and in the nearshore immediately post-placement, was no longer seen in successive surface sediment samples along the profile 5 months post placement, indicating that fine sediment found on the surface was likely winnowed through wave-current processes and transported away from the beach.

2.3 Transport processes in TSHD overflow plumes

During overflow of TSHDs, the suspended sediments passing over the overflow weir are introduced outside of the dredge and into the water column. In most cases, the overflow stream is denser than the surrounding

water, and a negatively buoyant cloud or jet is formed. This dense *dynamic plume* is transported towards the sediment bed primarily by buoyancy effects. During the descent of the dynamic plume, ambient water is entrained into the plume, and the plume becomes less dense. The descent of the dynamic plume may be arrested by neutral buoyancy or interaction with the bed. During descent and interaction with the TSHD hull or propellers, turbulence may eject and mix smaller clouds of suspended sediment with cloud densities that are nearly equal to the surrounding water body. In this case, the settlement of the clouds can become dominated by particle settling. These *passive plumes* settle at rates governed by the size and density of individual particles suspended in the cloud.

2.3.1 Dynamic plume

The TSHD dynamic plume is challenging to observe and sample in the field environment as it is typically positioned beneath the hull of the moving dredge. Due to the difficulties of directly measuring the dynamic plume in the field, most research of the governing processes has been performed with physical and numerical modeling. Chu and Lee (1996) provide a review of theoretical physical processes of plumes and jets in crossflow. Winterwerp (2002) conducted experimental laboratory studies relating the relative importance of dynamic plume spreading by mixing and gravity effects. Recently, DeWit et al. (2014) expanded upon this work by examining the interaction of the dynamic overflow plume with the nearfield effects of the TSHD hull and propellers under varying operational parameters with a combination of physical and Computational Fluid Dynamics models.

2.3.2 Passive plume

Relatively speaking, the TSHD passive plume has received much more attention than the dynamic plume in recent research. The passive plume is of interest primarily because of the slower settling rates of suspended sediment in the passive plume, and consequently the greater capacity for these suspended sediments to be transported relatively large distances from the dredging site. To model the passive plume appropriately, numerous dredge and sediment properties must be defined. At the TSHD, the density and overflow rate of dredged material must be determined, as well as the sediment size distributions. The mass exchange rate (or exchange fraction) between the dynamic plume and the passive plume must be quantified, along with the initial vertical distribution of passive

plumes. Furthermore, the settling rates of suspended sediment must be determined. Advances in optical and acoustic instrumentation in the 1990s permitted measurement of suspended sediment concentrations and sizes in dredge plumes (Kraus and Thevenot 1992; Land and Bray 2000; Mikkelsen and Pejrup 2000). Spearman et al. (2007, 2011) summarize field research performed in the early 2000s in Europe to determine the exchange rate between the dynamic and passive plumes. Mikkelsen and Pejrup (2000) documented increasing suspended particle size with distance from the dredging operation, suggesting that flocculation was an important process influencing settling rates in passive plumes. Smith and Friedrichs (2011) deployed their Particle Imaging Camera System (PICS) in a TSHD overflow plume in San Francisco Bay to measure suspended particle size, settling velocity, and density. Smith and Friedrichs (2011) found that flocculation occurred in the overflow plume and a population of dense *bed aggregates* was present, which further increased the settling velocity of the suspended aggregates relative to their constituent particles.

2.3.3 Modeling of the overflow plume

The buoyancy-driven dynamic plume and the particle-settling dominated passive plume are governed by different physical processes operating over distinctly differing time- and space-scales. Consequently, numerical modeling of these two phases of the overflow plume is typically handled with separate frameworks and modules for the distinct phases. The required process representations for modeling the overflow plume begin with the overflow process of the TSHD itself. The mass rate of overflow is expected to vary in space and time. A model representing the variances in the mass rate of overflow and the composition of overflow provides the initial conditions for the dynamic plume. The dynamic plume model would then represent the descent of the plume from the overflow discharge to the bed or a position of neutral buoyancy in the water column. Included in this process would be any mixing of sediment into the water column as passive plumes. Finally, a passive plume model will transport suspended sediment contained in passive clouds until conditions permit deposition.

The modular description of the modeling workflow described above is common among dredged material plume and outfall modeling (Koh and Chang 1973; Johnson et al. 1990; Spearman 2011). The models derived from these efforts (Confined Disposal Fate and Turbidity Assessment Software [TASS]) operate on a Lagrangian, cloud-based framework. Lackey and Smith (2008) applied the initial passive plume estimates of the

bottom dump model Short-term Fate (STFATE) as initial conditions to the Lagrangian Particle Tracking Model (PTM) for a navigation dredging study. The advantage of this approach is that the local-scale Lagrangian cloud models can approximate overflow and the dynamic plume while a high-fidelity 3D Lagrangian model (such as PTM) can represent particle mixing and deposition in the far field. Point-based Lagrangian models such as PTM offer significant advantages over the cloud-based Lagrangian approach, primarily through higher fidelity of transport processes over long distances. The coupling of appropriate hopper and dynamic plume models to a 3D, point-based Lagrangian sediment transport model (in the style of Lackey and Smith [2008]) will be further explored over the course of this research.

In addition to the numerical modeling framework, specific issues of fine-sediment separation in the hopper and fine-sediment settling velocities in the passive plumes must be addressed. Separation of sand and fines by hopper overflow is largely dependent upon the settling velocity of sediment particles. Sand-sized and coarser sediment particles have relatively large settling velocities (typically 6 mm/s or more), which allow them to settle in the hopper, and disaggregated fine sediments have small settling velocities (typically less than 2 mm/s), which allow them to be maintained in suspension to the overflow weir. However, fine sediments may be cohesive, forming aggregates that are greater in size but less dense than the constituent particles. The largest of these aggregates, known as clay balls in the dredging community, are recognized to deposit in hopper dredges during overflow (Palermo and Randall 1990; Burt and Hayes 2005). However, these fine-sediment aggregates are likely to form in a wide range of sizes. Smith and Friedrichs (2011) documented 40–250 μm fine-sediment aggregates settling at rates as fast as 5 mm/s in a TSHD overflow plume. Smith and Friedrichs (2011) further postulated that larger, faster settling aggregates were likely trapped in the hopper. In fact, dense *bed aggregates* 300 μm or larger would have settling velocities equal to or greater than fine sand. Of course, fine-sediment aggregates produced during the dredging process must survive the large mechanical and hydrodynamic stresses of the dredging process. The strength of mud aggregates (Krone 1963; Kranenburg 1994) is related primarily to the density of particle packing (or bulk density) and the cohesion of the minerals (related to clay mineralogy). Considering these issues, bed density, fines content, and some measure associated with the cohesiveness of the fine-grained material may be key predictors of the target sediment's

propensity to produce fine sediment aggregates, which influences the separation rate of fine sediments from the desired sand.

Flocs are low-density aggregations of fine-sediment particles formed in the water column through inter-particle collisions and aggregation. The bonds formed through aggregation are initially weak, and consequently flocs are relatively delicate. When exposed to turbulent shear or collisions with the bed or other suspended particles, flocs may be broken into smaller, constituent particles or disaggregated completely. Therefore, *flocculation* is a balance between aggregation and disaggregation. Factors favoring aggregation are particle concentration, turbulent shear, and particle cohesiveness. Factors favoring disaggregation are high turbulent shear and floc collisions. Flocculation is relevant to the transport of the passive overflow plume in that as particle sizes increase, so do settling velocities. Therefore, flocculation can lead to decreased transport distances and increased sedimentation rates surrounding the dredging site compared to the case of completely disaggregated fine sediment. Mikklesen and Pejrup (2001) and Smith and Friedrichs (2011) have observed particle sizes of fine sediment increasing with time in passive overflow plumes, suggesting that flocculation can occur in these situations. Smith and Friedrichs (2011) further observed that the increase in particle size with flocculation led to a doubling of settling velocity over a period of 80 min. Size and settling velocity of suspended particles in the passive plume will be quantified in the subject research in such a way as to inform the numerical modeling of these processes.

2.4 Sampling methods

The primary aim of sediment sampling is to determine sediment size distributions and mass concentrations at all stages in the dredging, transport, and placement process. Ample guidance is available on the sampling of bed materials and suspended loads within riverine and coastal environments. However, guidance for sampling from hopper dredgers is generally lacking, and the majority of what is known from the literature originates from a few studies. This section reviews the proposed methods for sediment sampling and processing to characterize bed materials at the borrow and placement sites, tracking the size and quantity of sediments entering and exiting the hopper dredge, and characterizing the sediment plume of the dredger. These methods include direct physical sampling and indirect surrogate monitoring using instrumentation.

2.4.1 Bed material sampling

To determine the proportion of fine sediments lost in the process of dredging and placement, it is necessary to collect samples at both borrow and placement sites. Accurately quantifying the loss of fines through dredging requires an accurate characterization of bed materials at the dredge site. Bed materials at depth are often collected through the use of grab, drag, or core-type samplers; the suitability of each depends on the in situ grain size, consolidation, water depth, required sample volume, and the necessity to recover an undisturbed versus disturbed sample.

2.4.1.1 Grab samplers

Grab samplers (e.g., Shipek and Van Veen samplers) are clamshell-style gravity samplers that have opposing jaws to scoop and retain surficial sediments. The jaws are closed upon impact with the bottom by weights, springs, or cords. These samplers work best for fine sediments as coarser sediments generally prevent the jaws from closing properly. The penetration depth of most grab samplers is approximately 10–15 cm while sample volumes are typically 3–15 L depending on sampler dimensions.

2.4.1.2 Drag samplers

For coarser sediments, a drag sampler is sometimes more appropriate. A drag sampler used by field workers at the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, uses a steel pipe approximately 1 m long, closed on one end, 10 cm in diameter flaring to 20 cm on the open end. The sampler is allowed to drag behind a moving vessel using a length of rope 2–3 times the water depth to keep the sampler horizontal. An advantage of the drag sampler is that the retrieved sample may better represent the average bed composition at the surface because the sample is taken across a larger spatial extent. For this project, however, the penetration depth should exceed the expected dredging depth to obtain a representative composite sample. A disadvantage of this sampler is that it remains open, potentially losing some fine material during retrieval.

2.4.1.3 Core samplers

Coring devices are used to take relatively undisturbed bed samples. Penetration into the surface is accomplished using gravity as they are heavily weighted. Box corers typically penetrate between 0.4 to 0.75 m and

yield sample volumes from 10 to 200 L. Once at the penetration depth, a cable releases a closing shovel underneath the box before retrieval. Similarly, free-fall corers use a weighted stainless steel tube fitted with a cutting head to penetrate the sediment and steering fins to keep the corer vertical. Sediment is captured within a plastic casing, and sample loss is prevented by means of a core catching device at the opening and flaps that seal off the core surface.

Sediment sampling at the nourishment area following pump out can be achieved through the use of vibracoring. Cores should be taken in the moist state to prevent collapse and at a sufficient depth to capture the horizon between native and placed sediments. The entire portion of the core above the horizon should be retained to maintain sample representativeness so that an appropriate subsample can be prepared for grain size analysis.

The sampling scheme specific to this project will be outlined in the field experiment plan based on the completion of the literature review and laboratory experiment.

2.4.2 Overflow weir sampling

Reliable measurements of the solids concentration passing an overflow weir may only be achieved through direct sampling, as turbulence, bubbles, and vertical gradient of sediment concentration prohibit the use of surrogate monitoring via sensors (HR Wallingford 2003). Sampling of the overflow weir may be accomplished using bottle, flow-through, or pump samplers.

2.4.2.1 Bottle sampling

Bottle samplers, in their most basic form, use a collection bottle attached to a dipping pole or rope to extract a sample. Kerssermaker (2004) used a modified version to sample the overflow weir of the hopper dredge *Cornelia*. Here, a 1.0 L bottle was placed within a steel container and, using a rope, lowered to a depth of approximately 30 cm at the center of the overflow pipe. A second rope was used to open the lid of the steel container once in position; approximate fill times varied between 2 s and 6 s. Sample contents were transferred to a separate container; then the bottle was flushed with a known water volume to remove residual sediments. This volume is later subtracted for concentration calculations.

Given the simplicity of this method, a high sampling frequency can be achieved. A considerable disadvantage is that it cannot be known precisely when the bottle is filled; overfilling the bottle likely results in sample bias (Kessermaker 2004).

2.4.2.2 Flow-through sampling

The flow-through sampler allows a sediment-water mixture to pass from the front to the rear of the sampler, ideally without accelerating (isokinetic). This type of sampler was also used by Kessermaker (2004) to compare mass concentrations of samples taken using the bottle sampler. The flow-through sampler consisted of an aluminum body with dimensions $40 \times 20 \times 5$ cm giving a sample volume of 4 L. This custom sampler used rubber-sealed doors held open at the ends using elastic bands that close using a release cord. When closing, the timing of the doors was slightly offset to increase volume capture since the sampler is not completely submerged. The flow-through samplers were deployed using guide ropes attached to the outer flange of the weir pipe parallel to the direction of flow (Figure 6). Kerssermaker (2004) reported that each sample took approximately 3–4 min to obtain; at least 10 samples are needed to characterize the overflow period (HR Wallingford 2003). Using a rotation of three crews and three samplers, a sampling rate of one per minute was achieved, a total yield of 30–50 samples per 40 min overflow period.

Figure 6. Photo of the custom flow-through sampler used by Kerssermaker (2004). Image on the right shows the sampler deployed on the bell mouth of an overflow weir. Figure adapted from HR Wallingford (2003).



There was a concern that turbulence generated around the sampler's opening meant that the flow into the sampler was not likely isokinetic, which may bias the sample. Additionally, this method appeared to be

somewhat cumbersome in that it required a crew of 10 to collect samples at the aforementioned rate (HR Wallingford 2003).

2.4.2.3 Pump sampling

Pump sampling draws a sample into a collection bottle by applying a vacuum to a sampling tube. The sampling tube should be completely submerged and placed in a zone where the slurry is well mixed. Guidance on pump sampling of open channel flows suggests that the orientation of the intake be pointed downstream relative to flow direction to maximize sample representativeness (Gray and Landers 2014). This implies that the intake be pointed vertically downward within the throat of the overflow pipe and lowered to a sufficient depth to minimize air entrainment. The diameter of the sampling tube should be chosen such that velocities within it are high enough to prevent sedimentation. Bosman et al. (1987) suggested an intake velocity three times greater than the ambient fluid velocity (they were measuring sediment concentrations under waves). However, pump sampling is not recommended according to some guidelines, stating that significant errors may arise due to momentum effects (HR Wallingford 2003). Additionally, the limited diameter of the intake tube would not be able to capture a vertically integrated sample since the flow depth over the weir may be up to 30 cm (HR Wallingford 2003). To overcome this, an open-ended housing could be fabricated that attaches to the intake of the tube from which a representative sample is drawn. Such modified pump sampling devices are under consideration for the laboratory sampling evaluation.

2.5 Uncertainty in quantifying losses

With any experimental endeavor comes measurement error and uncertainty. It is incumbent upon the researcher to communicate estimates of the uncertainties in the measurements of the research. The researchers on this team will quantify the measurement uncertainties following the principles of error analysis (Taylor 1997). This exercise will be completed during the experimental planning phase of the research, and will be documented in the field experiment plan. The field uncertainty estimates will incorporate findings of the laboratory evaluation of sampling methods and then later results of the field measurements themselves.

3 Conclusions and Recommendations

3.1 Conclusions

Models exist for representing the settling rate of sandy sediments in TSHD hoppers. While these models have shown some skill in representing specific dredging operations, they are limited in their capacity to predict the quantity of fines lost during the dredging process because particle size distributions are currently undetermined without direct sampling. Having particle size distribution information would prove valuable not only in predicting the loss of fines but also in developing a comprehensive source term for modeling the fate of overflow plumes.

Additionally, research is required to quantify the propensity of fine sediments, particularly those with appreciable clay content, to form robust aggregates that settle at rates comparable to that of sand. These aggregates could significantly increase the retention of fine-grained sediments in the hopper in some instances. Research is needed to characterize the flocculation propensity of fines separated from sandy materials during hopper overflow. Previous research (Mikkelsen and Pejrup 2000; Smith and Friedrichs 2011) has identified flocculation as a first-order process in passive overflow plumes. Smith and Friedrichs (2011) further determined that settling velocities in suspension doubled in a period of just over an hour due to flocculation of the suspended sediment.

A modeling framework was discussed for representing transfer of sediment from the hopper overflow to the water column in suspension. The framework involves modular near-field models of the hopper retention and overflow process, followed by cloud-based Lagrangian representation of the dynamic plume. The dynamic plume model will then generate initial conditions of the passive plume clouds of suspended sediment. The passively transported sediment can be represented with 3D point-based Lagrangian methods, such as the PTM. This approach has been demonstrated previously by Lackey and Smith (2008) with a bottom dumping operation with STFATE generating the initial cloud conditions for PTM.

Previous research regarding sediment dispersion at a pipeline outfall is primarily related to open water disposal of sediment and the fluid mud flows that occur at the bed as a result. Models exist to demonstrate this

mixing and dispersion; however, they do not show the separation of fine material specifically. On the beach, there have been studies that aim to quantify fines loss through natural beach processes. However, there have not been studies that combine fines loss through the pipeline outfall with placement on the beach. Hence, more investigation into the fines loss during the outfall and return water resulting from the slurry needs to be completed.

3.2 Proposed research

The objectives of the broader effort are to quantify sediment sorting during hopper dredging and pump-out operations of sandy sediments containing fine-grained silt and clay. The research aims to associate contributing factors such as dredging operations, environmental conditions, and sediment characteristics with separation rates of sediment classes in the dredging process. The mass transfer rates by size class will be quantified in each of the potential exchange points with the water column: (1) the draghead, (2) overflow, and (3) pump out. Additionally, the suspended sediment characteristics of sediments introduced to the water column are to be determined in a manner that facilitates bounded estimates of ultimate transport and fate of these sediments. The research is being executed in defined tasks focused on specific research requirements. Each of these efforts is described in greater detail in the following sections.

3.3 Conceptual model and literature review

A conceptual model of the governing processes has been developed and is discussed in this present report. The purpose of this task is to present the present state of understanding for the physical processes controlling separation of sediments during the TSHD process from dredging site to pump out, and reworking of the relocated sediments. As part of this process, specific research needs are identified. These needs are developed and justified in Chapter 2 Conceptual Model. The remaining tasks will incorporate the associated research requirements into their workflow.

3.4 Sampling methods

Sampling suspended sediments from the inflow stream and overflow weirs of an operating hopper dredge is challenging due to high-velocity flows and temporal and spatial variabilities in both the flows and sediment

concentrations. A testing basin has been designed and is presently under construction for evaluating candidate sampling procedures. The sampling methods will be evaluated through controlled laboratory experiments considering sampling methods, sampling locations, sampling containers, sampling frequency, and dredged material composition. The sampling methods investigation will also evaluate sample compositing and sample splitting schemes.

Based in part on the laboratory evaluation, a written sampling plan will be developed. The sampling plan will be developed to determine (1) appropriate sampling techniques, (2) the appropriate sample size and number to obtain statistically significant results under field conditions, (3) the expected uncertainty in the field measurement plan, and (4) sampling requirements for supporting sediment tracking models (such as water chemistry and physical sediment characteristics and processes).

3.5 Field measurements of sediment sorting during dredging operations

Sediment separation and fractionation during dredging operations will be determined from field sampling campaigns of offshore sand mining and navigation maintenance dredging operations. These field sampling campaigns will be conducted on both USACE and contract dredges. The aim of these measurements will be to determine the relationships between sediment sorting during the dredging process, and physical sediment properties and dredge characteristics. Sampling locations are associated with the exchange points of the dredging process, including the sediment bed at the dredging site, the inflow and outflow of the hopper dredge during dredging and overflow, the hopper discharge during pump out, and the beach. These locations will be sampled according to the experiment and sampling plan. Additionally, the settling velocity and dynamics of the suspended surface overflow plume will be quantified. Execution of field measurements was scheduled between summer 2017 and summer 2018. Associations will be examined between the dredge characteristics, sediment characteristics, and the separation of sediments in the hopper during overflow and pump out. Existing models of hopper settling and overflow will be evaluated with the collected data, and new models will be devised and evaluated if necessary.

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Appendix: Annotated Bibliography of Relevant References by Topic

Overview of Hopper Dredges

Martin, J. P., and L. J. Mauriello. 1983. "Hopper Dredges and Certain Aspects of Their Design." *Marine Technology* 20 (2): 164-176.

This journal article gives an overview of trailing suction hopper dredges, their design characteristics and classification, and includes a summary of the dredging subsystems: drag arm, pumps, discharge, overflow, dumping, pump-out, subsystems. Other useful information includes schematic diagrams of various vessels and a table of physical attribute data, including dredge pump characteristics.

Separation of Sediment by Hopper Dredging

Camp, T. R. 1936. "A Study of the Rational Design of Settling Tanks." *Sewage Works Journal* 8(5): 742-758.

This journal paper concerns the development of a sedimentation theory within an ideal settling tank, with flow entering one side and exiting the other. Originally constructed for sewage engineering works, Camp's theory is cited as the basis for settling theory and overflow losses within hopper dredges. The ideal settling tank assumes that (1) the flow is horizontal and uniform, (2) a uniform concentration of particles in a vertical plane perpendicular to flow, (3) each particle is independent and settles at a constant velocity, and (4) particles are removed when they strike the bottom (hence no sediment accumulation). One caveat is that the horizontal velocity should not cause scour.

Miedema, S. A., and W. J. Vlasblom. 1996. "A Theory for Sedimentation in Hoppers." *29th Annual Texas A&M Dredging Seminar*. New Orleans, Louisiana, USA.

This work is a follow up to the previous work by Vlasblom and Miedema (1995). Modifications to the previous work include modification of some equations for turbulent settling efficiency resulting in different hopper loading curves and a change to the implementation of scour velocity.

Noted was the difficulty in obtaining field data to verify the model, which include loading curves and grain size distributions of the sediment within the overflow. No discussion was provided in terms of the percent loss of the total load or the percent loss of fines.

Miedema, S. A., and C. van Rhee. 2007. “A Sensitivity Analysis on the Effects of Dimensions and Geometry.” *WODCON XVIII*. Orlando, Florida, USA.

This work compares the results between the models used in Vlasblom and Miedema (1995) based on simplifying Camp’s equations, and a two-dimensional model (horizontal and vertical directions) developed by van Rhee (2001), which is based on Reynolds-averaged Navier-Stokes equations. Differences in the overflow losses and loading times are discussed. The results between the two models were not drastically different.

Miedema, S. A. 2010. “The Effect of the Bed Rise Velocity on the Sedimentation Process in Hopper Dredges.” *WODCON XIX*. Beijing, China.

This work investigates the influence of the bed rise velocity on the hopper load parameter since this influences settling time. A secondary research topic examined potential scaling laws from small to large capacity hoppers, which determined to keep the hopper load parameter constant and derive other scale laws for the flow and not to scale the sand.

Ooijens, S. 1999. “Adding Dynamics to the Camp Model for the Calculation of Overflow Losses.” *Terra et Aqua* 76: 1–21.

This paper modifies the model of Vlasblom and Miedema (1995) by adding a time effect by considering a dynamic input of flow volume and slurry concentration. This is different from the previous models as the outflow concentration is based on instantaneous settling efficiency based on the inflow concentration. The model appeared to capture the estimated total overflow loss reasonably well for two of three dredging test cases (reported correlation of 0.75 to 0.85).

Vlasblom, W. J., and S. A. Miedema. 1995. “A Theory for Determining Sedimentation and Overflow Losses in Hoppers.” *Proceedings, WODCON XIV*. Amsterdam, The Netherlands.

Published in the proceedings for WODCON 1995, this work modifies Camp's (1936, 1946) theory for ideal settling tanks but included a grain distribution as opposed to using a single grain size, a sedimentation zone, hindered settling, and adjustable overflow. The model is run on a computer program called *TSHD* (Medina 1991), which aims to determine the settling efficiency (a function of the settling velocity to horizontal flow ratio) for individual grain sizes and the evolution of the grain size distributions in time through the overflow and at the top of the sedimentation zone. An analytical treatment of the settling processes are provided along with a case study using three sand distributions ($d_{50} = 0.10, 0.30, \text{ and } 1.0 \text{ mm}$) and hypothetical hopper dimensions, flow rate, mixture density, and loading cycle times. The primary objective was to estimate an optimal hopper loading time and overflow losses. No discussion is provided in terms of the percent loss of the total load or the percent loss of fines.

van Rhee, C. 2001. “Numerical Simulation of the Sedimentation Process in a Trailing Suction Hopper Dredge.” *Proceedings, WODCON XVI*. Kuala Lumpur, Malaysia.

The primary aim of this work was to understand the sedimentation process during hopper loading. The rationale for the study concerns the economic payload, that some sand will be discharged in the overflow mixture. Both laboratory experiments and numerical modeling were used to investigate the sedimentation processes. Detailed observations of settling and flow processes were observed during the experiments. The modeling component uses a more complex schematization of the hopper sedimentation processes than that of Vlasblom and Miedema (1995).

The amount of fine material lost in the overflow was quantified over 19 experiments. The experiments showed that cumulative overflow losses could be expressed as a linear function of the hopper load parameter, which is proportional to the discharge per unit surface area into the hopper and inversely proportional to the sedimentation velocity of the suspension (i.e., hindered settling given by the Richardson and Zaki [1954])

formulation). This linear relationship was found to improve if the load parameter was based on sand fluxes (ratio between the inflow fluxes and settling fluxes). The authors noted that it is uncertain if the relationship holds for different scales and it only accounts for spherical grains of uniform diameter.

Separation of Sediment by Pipeline Outfall and Beach Processes

Goodrich, K. A., and J. A. Warrick. 2015. “Fines: Rethinking Our Relationship.” *Proceedings, Coastal Sediments 2015*.

Two studies where dredging projects contained a relatively large percentage of fines were summarized. The Santa Cruz Harbor demonstration project placed material with up to 71% fines by weight in the nearshore, and the Tijuana River demonstration project placed material with 40% fines by weight on the beach. Both projects aimed at seeing whether relatively large proportions of fines had any negative impact on the beach. Results from the Santa Cruz project showed that the energetic conditions of the ocean quickly moved the fine material farther offshore. The Tijuana River project showed that fines had approximately a 1-hour residence time in the surf zone and then subsequently moved far away (approximately 2 km) from the nourishment area. The paper also summarized outreach efforts to the coastal management community in California.

Teeter, A. M. 1994. “Dredged Material Dispersion from the Vicinity of Pipeline Discharge, Tylers Beach, Virginia.” *Proceedings of the Second International Conference on Dredging and Dredged Material Placement*, 918-927.

A submerged pipeline discharge of hydraulically dredged sediment in Tylers Beach, Virginia, was studied. The PLUMES was used at a field site to detect relative concentrations, measure current fields, and chart vessel position during a dredging event. Suspended sediment samples were also collected for ground truthing. The field data showed that the discharged sediment descended and reached the bed directly below the discharge point. An underflow formed and spread to a distance approximately 100 m from the source, and the spreading was controlled by the bathymetry of the site. The paper gives an overview of the dispersion process including the discharge plume descent, the underflow spreading and entrainment of the underflow material into the overlying ambient flow, and the passive dispersion of the material.

Teeter, A. M. 2000. *Underflow Spreading from an Open-Pipeline Disposal*. ERDC TN-DOER-N7. Vicksburg, MS: US Army Engineer Research and Development Center.

This technical note summarizes the mixing and dispersion processes associated with open-water pipeline discharges from hydraulic dredging operations. Specifically, it discusses the underflow plume spreading of disposed dredged material. The underflow is a layer of fluid mud on the bottom that flows away from the point of discharge, depending on bottom slope, ambient currents, and their initial discharge trajectory. The paper also describes the entrainment process of sediment from the fluid-mud layer into the water column, as well as factors contributing to turbidity generation (including spreading or stripping of material at the water surface, gas entrained in the dredged material and released during disposal, stripping of material by the water column during descent, and entrainment of material by the water column during underflow spreading. The paper also begins discusses an analytical model that was developed to illustrate the spreading of the underflow layer.

Teeter, A. M. 2001. *Simulating Underflow Spreading from a Shallow-Water Pipeline Disposal*. ERDC TN-DOER-N11. Vicksburg, MS: US Army Engineer Research and Development Center.

This technical note is a follow on to the Teeter (2000) technical note where the computation model for simulating underflow from a pipeline discharge in shallow water is described. The model computes sediment flux, total flow or discharge breadth, and height along the length of the underflow. These state variables are calculated by numerically integrating a set of governing equations downslope in the direction of the underflow. The Pipeline Disposal Model (PDFATE) can use a single grain class (PDFATEs) or multiple grain classes (PDFATEm), but does not include near-field processes directly because they are assumed to be known or calculated using a separate nearfield model such as CD-CORMIX. PDFATEm can be connected to SSFATE (Suspended Sediment Fate) to compute entrainment of disposed material into the overlying water column and subsequent plume dispersion by currents. The initial results from the PDFATEs agree well with features observed in the field. At the time of the writing, additional data were needed to validate the PDFATEm model.

Warrick, J. A. 2013. “Dispersal of Fine Sediment in Nearshore Coastal Waters.” *Journal of Coastal Research* 29(3): 579–596.

A study was conducted on a nourishment at Imperial Beach, California, which contained 40% fines by weight. It was found that the mean residence time of fine sediment in the surf zone was approximately 1 hour, and rapid decreases in the surf zone alongshore were transported offshore by turbid rip heads. A mass balance of the sediment suggested that the majority of fine sediment was deposited 2 km away from the nourishment site or to water depths of greater than 10 m. Because fine sediment was being winnowed from the beach through natural beach and nearshore processes, elevated levels of fines were observed in the swash zone. The study concluded that the fate of fine material was strongly influenced by wave conditions, surf zone and rip current transport, and the vertical density and flow conditions of coastal waters.

Transport Processes in TSHD Overflow Plumes

de Wit, L., C., van Rhee, and A. Talmon. 2014. “Influence of Important Near Field Processes on the Source Term of Suspended Sediments from a Dredging Plume Caused by a Trailing Suction Hopper Dredger: The Effect of Dredging Speed, Propeller, Overflow Location, and Pulsing.” *Environmental Fluid Mechanics* 15(1): 41–66.

Laboratory and large eddy simulation experiments were performed to evaluate the influence of dredging operational parameters (vessel speed, overflow position, propeller, and overflow pulsing frequency) on near-field mixing of the dynamic plume. The hull position of overflow and relative speed of water to the hull significantly influenced the attachment of the dynamic plume to the hull and consequently the mixing of sediments into a lower-density, passive, surface plume. The study indicates a potential wide variation in the fraction of sediment stripped from the dynamic plume, ranging from 0 to 2 percent under typical conditions to a maximum of 18 percent.

Mikkelsen, O. A., and M. Pejrup. 2000. "In Situ Particle Size Spectra and Density of Particle Aggregates in a Dredging Plume." *Marine Geology* 170: 443–459.

A field study in a dredging plume in the sound Øresund between Denmark and Sweden measured suspended particle sizes in a passive dredge plume with a Laser In-Situ Scattering and Transmissometry (LISST) particle sizer. Particle sizes in suspension increased from approximately 40 µm to approximately 110 µm over a distance of 1.5 km and a time scale of 50 min. This study was the first showing that flocculation processes occur in dredge plumes over short time- and space-scales. The implication of flocculation in passive plumes is that fine sediments settle faster from suspension, reducing the distance that these sediments travel from the dredging activity but increasing sedimentation close to the dredging activity.

Spearman, J., A. DeHeer, S. Aarninkhof, and M. Van Koningsveld. 2011. "Validation of the TASS System for Predicting the Environmental Effects of Trailing Suction Hopper Dredgers." *Terra et Aqua* 125: 14–22.

The TASS is described, including field measurements of hopper overflow conducted on a sand mining TSHD. The numerical model includes a 1D vertical model of the hopper and cloud-based Lagrangian models of the dynamic and passive plumes.

Smith, S. J., and C. T. Friedrichs. 2011. "Size and Settling Velocities of Cohesive Floccs and Suspended Sediment Aggregates in a Trailing Suction Hopper Dredge Plume." *Continental Shelf Research* 31: S50–S63.

A field study is presented for passive plumes generated during overflow of the TSHD Essayons in San Francisco Bay. Measurements of suspended sediment size and settling velocity were made with a LISST particle sizer and the PICS. The study found that the passive plume was initially well-aggregated (less than 20 min after overflow), and floccs in suspension continued to increase in size and settling velocity over the observation period (90 min after overflow). Also documented were 40–250 µm fine-sediment aggregates with inferred densities near that of the bed sediments settling at rates as fast as 5 mm/s in a TSHD overflow plume. Smith and Friedrichs further postulated that larger, faster settling aggregates were

likely trapped in the hopper. In fact, dense *bed aggregates* 300 μm or larger would have settling velocities equal to or greater than fine sand. The implications of these observations are that due to cohesive effects, some fine sediments that otherwise would have been lost in the overflow are retained in the hopper. Additionally, these sediments settle 2-200 times faster from the passive overflow plume than their constituent particles.

Winterwerp, J. C. 2002. "Near-Field Behavior of Dredging Spill in Shallow Water." *Journal of Waterway, Port, Coastal, and Ocean Engineering* 128: 96–98.

Laboratory experiments were conducted to determine the relative spread of the dynamic plume under the influence of gravitational (buoyancy) and turbulent mixing effects. Expressions for the time-dependent radial dispersion of the dynamic overflow plume are given for two regimes: gravity-driven and mixing-driven conditions.

Sampling Methods

Dredging Research Ltd., HR Wallingford. 2003. *Protocol for the Field Measurement of Sediment Release from Dredgers.* <http://el.erdc.usace.army.mil/dots/accord/index.html>

This document provides guidance regarding the protocols and measurement methods of sediment plumes generated by dredging operations. Chapter 2.6 gives an overview of TSHD release mechanisms while Chapter 7 focuses on measuring TSHD overflow. The rate of overflow is typically measured indirectly using shipboard instrumentation via the inflow rate (as they should be equivalent during overflow) due to turbulence and air entrainment, which prevents direct measurement at the weir. In contrast, the solids concentration was measured directly from water sampling at the weir. The frequency of sampling was suggested as often as possible, approximately 30–50 samples per 40 min overflow period. Other guidance includes a checklist of supporting data that should be recorded for each dredging cycle (Appendix B5).

Kerssemakers, K. A. 2004. *Overflow Sampling of Trailing Suction Hopper Dredgers: A Case Study on the TSHD Cornelia*. M.S. Thesis, Delft University of Technology.

A primary goal stated in this thesis was to determine if the solids concentration from the overflow weirs of hopper dredges could be accurately measured. Other pertinent focus questions were related to sampling techniques, prediction of sediment concentrations using TDS systems, and sampling frequency. Useful descriptions of sampling methods used in the field were discussed in detail, which included two different geometries of flow-through samplers and a bottle-type sampler. Variances in sediment compositions pulled from the overflow were compared by sampler type for consistency.

Unit Conversion Factors

| Multiply | By | To Obtain |
|---|----------------|----------------------------|
| cubic feet | 0.02831685 | cubic meters |
| cubic inches | 1.6387064 E-05 | cubic meters |
| cubic yards | 0.7645549 | cubic meters |
| feet | 0.3048 | meters |
| gallons (US liquid) | 3.785412 E-03 | cubic meters |
| microns | 1.0 E-06 | meters |
| miles (nautical) | 1,852.0 | meters |
| miles (US statute) | 1,609.347 | meters |
| miles per hour | 0.44704 | meters per second |
| ounces (mass) | 0.02834952 | kilograms |
| ounces (US fluid) | 2.957353 E-05 | cubic meters |
| pounds (mass) | 0.45359237 | kilograms |
| quarts (US liquid) | 9.463529 E-04 | cubic meters |
| square feet | 0.09290304 | square meters |
| square miles | 2.589998 E+06 | square meters |
| square yards | 0.8361274 | square meters |
| tons (2,000 pounds, mass) | 907.1847 | kilograms |
| tons (2,000 pounds, mass) per square foot | 9,764.856 | kilograms per square meter |
| yards | 0.9144 | meters |

Acronyms and Abbreviations

| | |
|--------|--|
| 1D | one-dimensional |
| 3D | three-dimensional |
| CTS | constant tonnage system |
| CVS | constant volume system |
| EFDC | Environmental Fluid Dynamics Code |
| LISST | Laser In-Situ Scattering and Transmissometry |
| PDFATE | Pipeline Discharge FATE |
| PICS | Particle Imaging Camera System |
| PLUMES | Plume Measurement System |
| PSD | particle size distribution |
| PTM | Particle Tracking Model |
| SEDZLJ | Ziegler, Lick, and Jones model |
| STFATE | Short-term Fate |
| TASS | Turbidity Assessment Software |
| TDS | tons dry solid |
| TSHD | trailing suction hopper dredgers |
| USACE | US Army Corps of Engineers |

REPORT DOCUMENTATION PAGE

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| 14. ABSTRACT Dredged sediment placed on beaches or nearshore environments is customarily evaluated for compatibility with the native beach sediment to avoid unintended impacts to economic, environmental, or recreational resources. Consequently, some state regulatory authorities establish limits upon the fine-grained content for sediment designated for placement on certain beaches and nearshore environments. Hopper dredging operations for beach and nearshore placement typically include periods of overflow, which is recognized to produce some degree of separation between the size fractions of the dredged sediment. The degree of separation and the controlling factors of separation are presently poorly known and are the subject of this research. This report provides a conceptual model of the hopper dredging and placement processes, including the relevant processes associated with hopper dredge-associated sediment dynamics, generation and transport of the overflow sediment plume, and sediment winnowing at the beach outflow. Prior research is described, and knowledge gaps are identified. Finally, a research plan to validate prior research and to address knowledge gaps is presented. An annotated bibliography of relevant literature is given in an appendix. Documentation of the planned research presented herein will appear in future publications associated with this study. | | | | | |
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