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Coastal and Hydraulics Laboratory

Dredging Operations and Environmental Research Program

Hydraulic Sorting of Dredged Sediment in a Pipeline: An Evaluation of the Sediment Distribution Pipe

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Technologies: Sediment Distribution Pipe”

Abstract

The US Army Corps of Engineers (USACE) recently established a goal to beneficially use 70% of material dredged from the nation's navigable waterways by the year 2030. Most of the sediments dredged by the USACE are heterogeneous mixtures of mud and sand, which can limit beneficial use of dredged material (BUDM) applications. Innovative technologies that can sort material during the dredging process are needed to help increase BUDM practices. This investigation sought to evaluate the ability of a sediment distribution pipe (SDP) to sort particles during transport in a pipeline. Field demonstrations were conducted during dredged material placements at Sturgeon Island, New Jersey. Velocity within the pipeline was found to be inadequate for efficient hydraulic sorting of fines (<75 μm) and produced inconclusive results. Small scale laboratory SDP experiments found that effluent from the SDP holes had an altered sediment texture compared to the initial slurry and that hydraulic sorting was occurring within the pipeline. However, outflow from the SDP holes was inconsistent, and typically >90% of the sediment mass was discharged out the end of the pipeline. Sorting efficiency of the SDP could not be accurately assessed in the current experimental configuration.

Contents

Figures and Tables

Figures

Tables

Preface

This study was conducted for US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory for the Dredging Operations and Environmental Research (DOER) Programs, Funding Account No. U4389229, AMSCO 089500, under “Innovative Sediment Placement Technologies: Sediment Distribution Pipe.”

The work was performed by the Field Data Collection and Analysis Branch and the Coastal Engineering Branch of the Navigation Division, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication of this report, Mr. William Butler was chief of the Field Data Collection and Analysis Branch; Ms. Lauren Dunkin was chief of the Coastal Engineering Branch; Ms. Ashley Frey was Navigation Division chief; and Mr. Eddie Wiggins was the Technical Director for Navigation. The deputy director of ERDC-CHL was Mr. Keith Flowers, and the director was Dr. Ty Wamsley.

COL Christian Patterson was the commander of ERDC, and Dr. David W. Pittman was director.

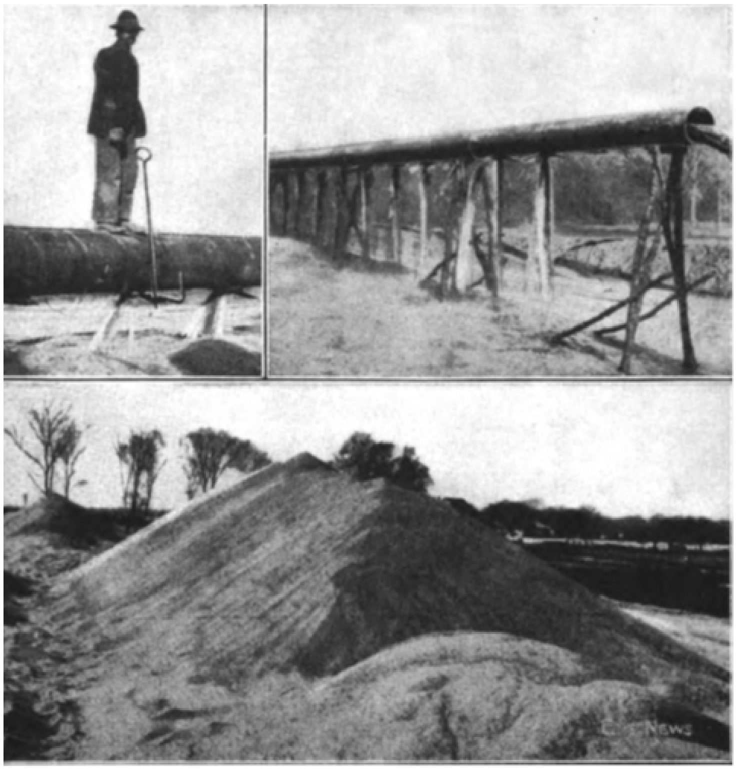
1 Introduction

1.1 Background

In January of 2023, an official directive was released by the Chief of Engineers of the US Army Corps of Engineers (USACE) entitled "Beneficial Use of Dredged Material Command Philosophy Notice." This notice established a goal that by the year 2030, 70% of the sediments dredged for navigation purposes be beneficially utilized. To increase beneficial use of dredged material (BUDM) practices, the USACE, the dredging industry, and stakeholders need to adopt the use of innovative technologies and equipment that can improve placement efficiency and reduce costs associated with dredging. One possible innovation is the ability to dredge, sort, and place the sediment in-line during the placement process, producing sediment with specific engineering properties (e.g., separate sand from mud) without rehandling the material multiple times. Such a process may be achievable using a specialized pipe, termed here as a Sediment Distribution Pipe (SDP).

In the past, coarse-grained dredged material was used to create levees by using "shutter pipe" technology (Allen 1914). A shutter pipe consisted of a hydraulic dredge's discharge pipeline elevated on a trestle foundation that had openings along the pipe bottom. This in-line separation methodology, later referred to as a "bleeder pipe" (Huston 1986), was commonly used to construct levees in a linear configuration (Figure 1). The operational assumption was that hydraulic sorting would occur in the pipe during pumping allowing larger materials to preferentially drop out of the holes. Unfortunately, this placement technique, termed here as the SDP, has been poorly documented, and no performance metrics or design guidance exist for its implementation. The SDP is currently being studied for use as an economic in-line separation technology for targeted placement of fine- and coarse-grained material along the length of a pipe.

Figure 1. Historic use of a “bleeder pipe,” which is described as an in-line separation technology to build levees. (Image reproduced from Allen 1914.)



1.2 Objective

The goal of this study was to evaluate the feasibility and effectiveness of sorting dredged material based on particle size as it is transported through a pipeline.

1.3 Approach

Both field and laboratory experiments were conducted to evaluate the sediment grain size sorting potential of the SDP. A field proof-of-concept demonstration of the SDP was conducted on Sturgeon Island, New Jersey, to quantify the efficacy to nourish a wetland and demonstrate functionality of its ability to sort sand and mud. To reduce variability inherently associated with a field dredging project, a series of laboratory-based experiments were also conducted with a small-scale SDP system. In addition to presenting the methods and findings of both sets of experiments, this report provides a description of the slurry transport dynamics used in hydraulic sorting prediction of sediment in a pipeline.

2 Slurry Transport Considerations for Hydraulic Sorting

2.1 Hydraulic Dredging Basics

A common placement method for hydraulic dredging is direct pipeline discharge to the placement area. Hydraulic dredging is commonly completed with a cutter suction dredge powered by a centrifugal pump. The suction end of the pipe is fitted with a mechanical device to loosen in situ sediments, which are then entrained into the dredge suction line as a slurry. This dredge slurry is transported through the pipeline to the selected discharge location. Using an SDP allows material to discharge through the pipeline holes as well as through the end of the pipe. It is anticipated that the nature of the dredge slurry mixture may influence how material is deposited from the SDP. This section of the report provides an overview of pipeline slurries and associated transport theory.

2.1.1 Pipe Flow Regimes

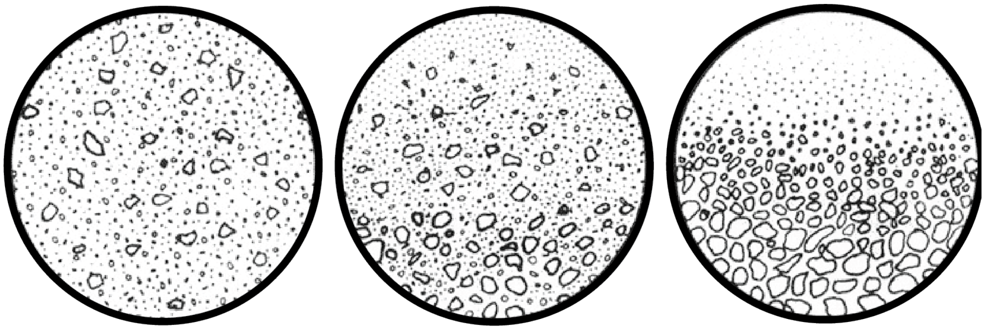
Dredged material in a slurry is generally divided into the following four pipe flow regimes (Figure 2):

- Fixed bed
- Moving bed (saltation)
- Heterogeneous
- Homogeneous

In the fixed bed regime, particles are deposited along the bottom of the pipe and are not transported. During moving bed (saltation), particles begin to alternate between moving and staying on the bottom of the pipe. The solid particles travel by “bouncing” in this flow regime. Heterogeneous flow is a nonuniform slurry flow with all solid particles in suspension and with the concentration of solid particles increasing toward the bottom of the pipe. Based on Stoke’s Law (1847), larger particles would be expected to be lower in the water column in this flow regime while finer particles may appear higher in the water column. Homogeneous flow describes a flow regime in which there is uniform slurry flow such that the distribution of particles is equal over the pipe cross section. Homogeneous flow is sometimes referred to as pseudohomogeneous (Herbich 2000).

To prevent deposition and subsequent plugging of pipelines, it is typical to target pipeline velocities that would keep the dredge material (DM) in either the heterogeneous or homogeneous flow regimes (Herbich 2000; GIW Industries 2001). However, operating in the homogeneous flow regime requires more energy and increases pipeline deterioration; therefore, the heterogeneous flow regime is considered the most economical (Turner 1996).

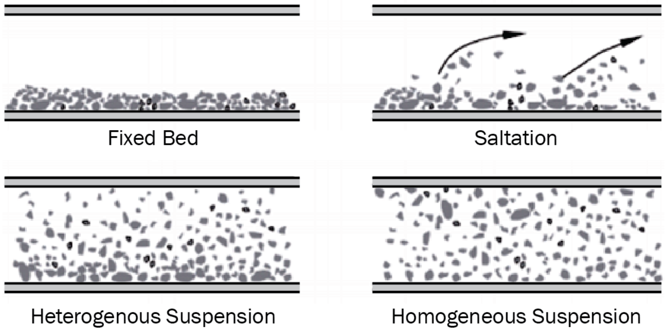
Figure 2. Pipe flow regimes: (*a*) homogeneous flow, (*b*) heterogeneous flow, and (*c*) flow with moving bed. (Image adapted from Turner 1996, reprint from Herbich 1975.)



(a) Uniform distribution of sediment. Excessive power requirements.

(b) Nonuniform distribution of sediment. Optimum power.

(c) Segregated distribution of sediment. Bed moving at lower velocity than material above. Excessive power requirements.



The following section provides an overview of how to determine the flow regime. This calculation was used to evaluate the results of the study. It is hypothesized that sediment sorting in the slurry influences the sediment gradation of the slurry being discharged.

2.1.2 Slurry Critical Velocity

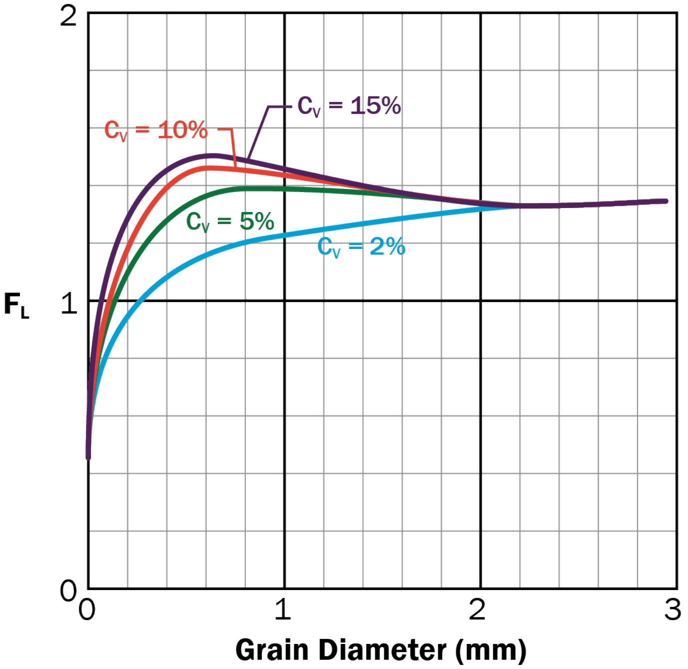
The slurry critical velocity is the minimum velocity needed to keep sediment particles suspended in the pipeline and to prevent deposition and potential clogging of the pipeline (Herbich 2000). One method to determine the critical velocity for a slurry mixture is the 1952 Durand and Condolios method (Herbich 2000). The method is shown in Equation (1):

$$V_C = F_L \left[2gD\left(\frac{SG_S - SG_W}{SG_W}\right)\right]^{1/2}, \qquad (1)$$

where

V_C = critical velocity in feet per second,
g = gravitational acceleration = 32.2 ft/s^2,*
D = inside pipeline diameter in feet,
SG_S = specific gravity of solid particles,
SG_W = specific gravity of water, and
F_L = coefficient that is a function of slurry concentration by volume (Figure 3).

Figure 3. Variation of F_L, with grain diameter. (Image adapted from Herbich 2000, Figure 7.27.)



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* For a full list of the spelled-out forms of the units of measure used in this document and their conversions, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52 and 345–47, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

In order to use Figure 3 to determine F_L, the concentration by volume (C_V) for different solid particle specific gravities (SG_S) and concentrations by weight (C_W) are determined using Equation (2) and (3) (Herbich 2000).

$$C_W = \frac{SG_S(SG_M - SG_F)}{SG_M(SG_S - SG_F)}, \tag{2}$$

$$C_V = \frac{SG_M}{SG_S}(C_W), \tag{3}$$

where

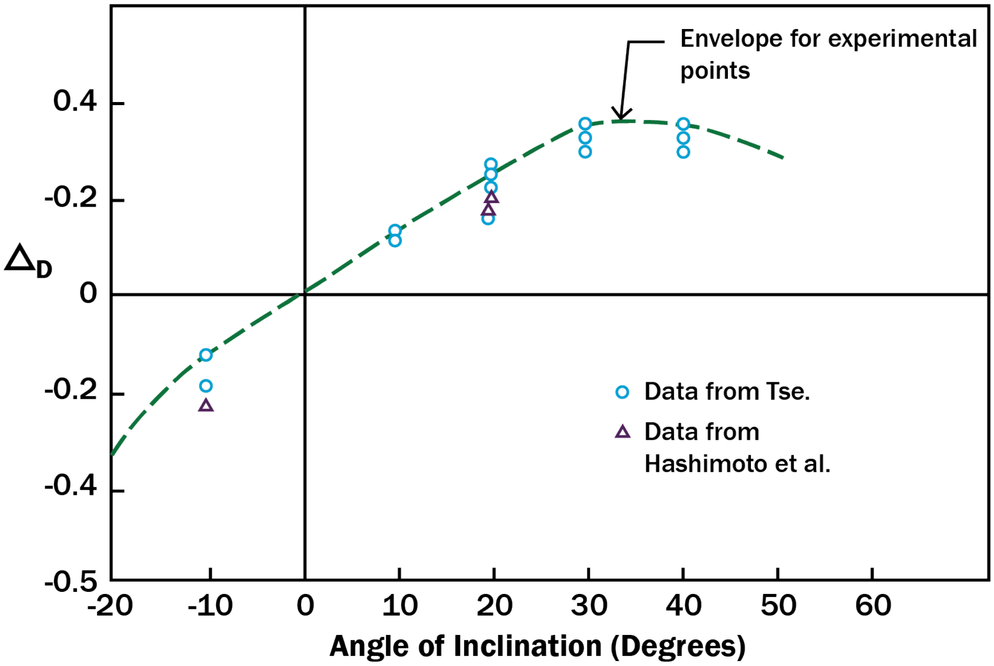
C_v = concentration of solids in the slurry by volume,
C_w = concentration of solids in the slurry by weight,
SG_S = specific gravity of solid particles,
SG_F = specific gravity of fluid (water), and
SG_M = specific gravity of mixture (slurry).

To account for the inclination of the pipeline on the required velocity for the slurry, Equation (4) can be used to estimate the modified critical velocity due to pipe inclination.

$$V_{C(inclined)} = V_{C(horizontal)} + \Delta_D\sqrt{2g(SG_S - 1)D}, \tag{4}$$

where Δ_D is from Figure 4.

Figure 4. Effect of angle of inclination on critical slurry velocity. (Image adapted from Herbich 2000, Figure 7.29.)



2.1.3 Transitional Velocity

The transitional velocity defines the velocity above which the flow is in a homogeneous regime and below which the flow is in a heterogeneous regime. If the velocity is above the transitional velocity, particles would be expected to be evenly distributed over the cross section of the pipeline.

Equation (5) (Herbich 2000) is used to compute the transition velocity.

$$V_{th} = (1800 g D V_t)^{1/3}, \tag{5}$$

where

V_{th} = transition velocity in feet per second,
V_t = particle terminal settling velocity in ft/s,
g = gravitational acceleration = 32.2 ft/s^2, and
D = inside pipeline diameter in feet.

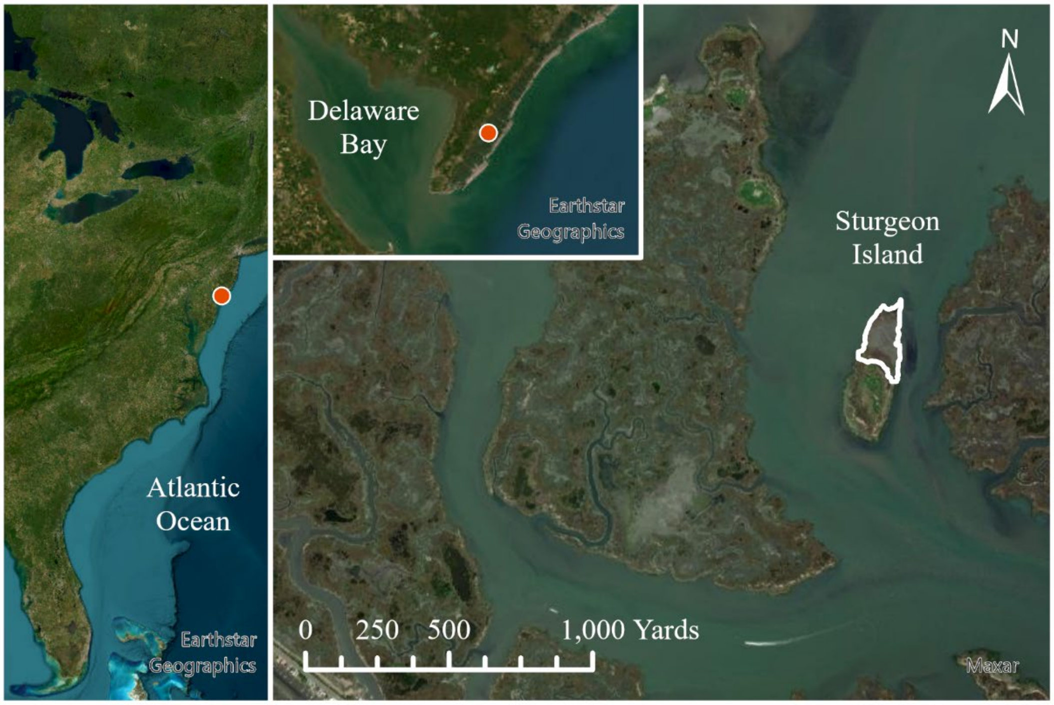
3 Sediment Distribution Pipe (SDP) Demonstration Projects

This study involved both field and laboratory evaluations of the SDP. The following sections describe the design, methods and procedures associated with these evaluations. The field study is presented first followed by the laboratory demonstration.

3.1 Field Demonstration Project

A field proof-of-concept demonstration of the SDP was conducted on Sturgeon Island, New Jersey, in March 2020, to demonstrate functionality and begin quantification of its capacity to hydraulically sort sediment. Sturgeon Island is a 13.5 acre island adjacent to the New Jersey Intracoastal Waterway (NJIWW) and part of the Seven Mile Island Innovation Laboratory (SMIIL) (Figure 5). SMIIL was established in 2019 by the USACE Philadelphia District (NAP), in conjunction with the State of New Jersey and The Wetlands Institute (TWI) to evaluate innovative sediment management practices and alternatives to advance and improve dredging and marsh restoration techniques through research, collaboration, knowledge sharing, and practical application. Sturgeon Island was selected for this field study to test new approaches to increasing elevation to preserve and enhance a critical wading bird nesting colony.

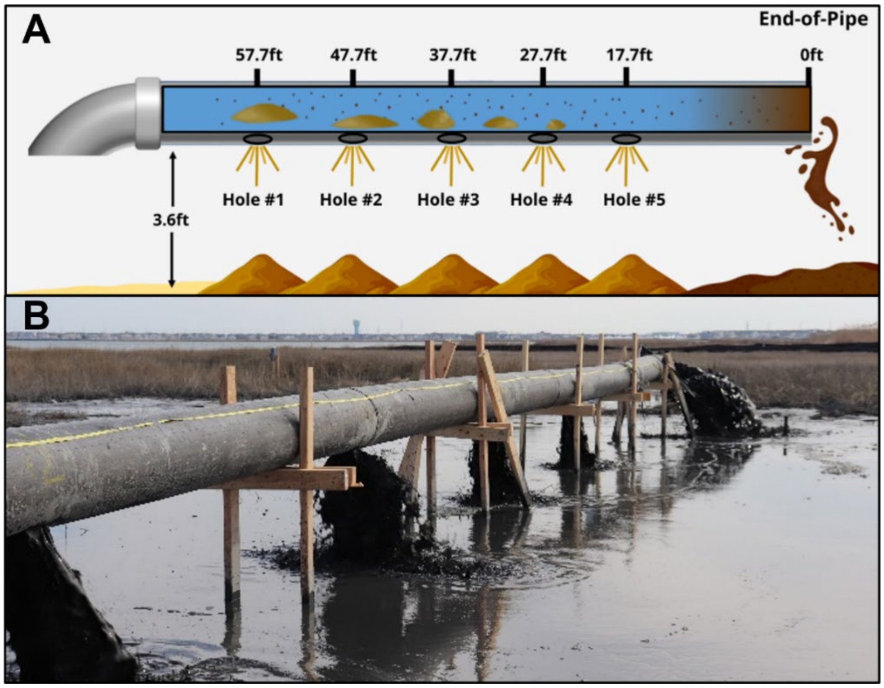
Figure 5. Location of Sturgeon Island, New Jersey.



Dredging was performed from March 16 to 19, 2020 by the *Fullerton*, a cutterhead dredge with a 14 inch discharge pipeline. The discharge pipe was positioned on the northern end of Sturgeon Island and equipped with a wye-valve that split the outflow into two branches (Figure 6). Both segments were composed of 12 inch diameter pipe, with one branch terminating in either a spreader plate or spray nozzle while the other branch segment discharged material through the SDP (Figure 6). Outflow from the dredge was intermittingly switched between the spreader bar and spray discharge pipe and SDP branch segments or flowed through both pipes throughout dredging activities. The SDP consisted of a 70 ft section of pipe toward the end of the eastern branch from the wye-valve. It was elevated with wooden scaffolding 3.6 ft off the marsh surface, and five square holes were installed 10 ft apart, centered along the bottom of the pipe, as shown in Figure 7. The most upstream hole was designated as hole No. 1, and hole designations increased sequentially. Three different hole sizes were tested (2 × 2 in., 4 × 4 in., and 6 × 6 in.) during the experiment.

Figure 6. Aerial photograph of the March 2020 dredged material pipeline orientation (facing northwest).

Figure 7. (*A*) Schematic of the Sediment Distribution Pipe (SDP) with locations of sorting holes identified; and (*B*) isometric view of the SDP operating on Sturgeon Island.



3.1.1 Field Data Collection Methods

To evaluate the hydraulic sorting efficiency of the SDP, data were collected to characterize the flow velocity within the SDP as well as the grain size of sediment dredged from the channel. The methods used to collect these data are presented in the following sections.

3.1.1.1 Slurry Velocity

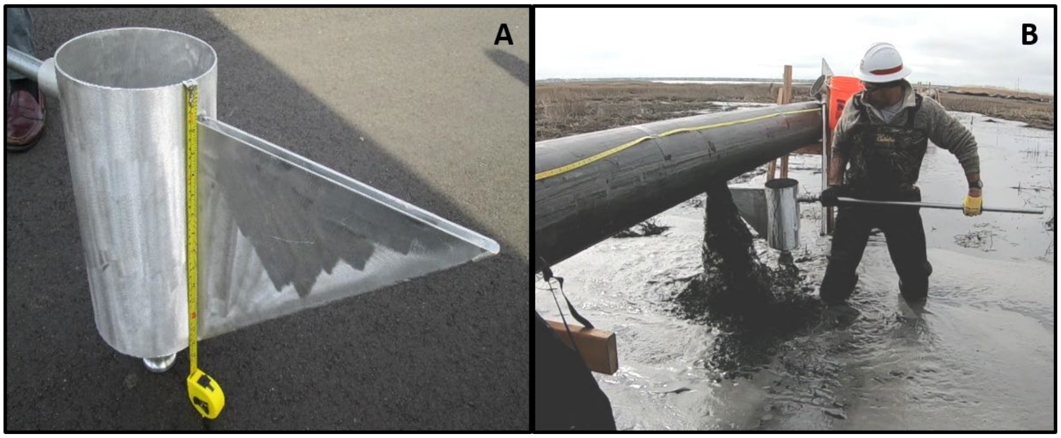
Slurry pipeline velocities were measured at two locations on the pipeline discharge network using Greyline 5.1 noncontacting doppler flow meters (Figure 8). These flowmeters were clamped to the exterior of the pipe with a liberal application of dielectric grease to ensure an airtight seal and programmed to take a measurement every 10 seconds. Positioning of the flowmeters varied through the course of dredging. From March 16 to 17, 2020, one flow meter was located 20 ft upstream of the wye-valve (position 1) and the second flow meter was located 40 ft downstream of the wye-valve and upstream of the SDP (position 2). On March 18, 2020, the flow meter at position 1 was relocated to the elevated SDP, 9 ft upstream of the pipe's discharge (position 3) and remained there through March 19, 2020.

Figure 8. Greyline 5.1 noncontacting Portable Doppler Flow Meter (PDFM) with ultrasonic sensor clamped to pipeline.

3.1.1.2 Slurry Sampling

During dredging, five replicate slurry samples were collected in succession from each hole and from the end of the pipeline (EoP) with a sample cutter to quantify the percent fines (<75 μm) discharged along the SDP. The sample cutter is an approximately 11.5 L sampler equipped with a 30 inch long × 0.5 inch wide funnel protruding from the side of the bucket (Figure 9*a*). During sample collection, the funnel was passed through the discharge to capture sediment from the entire width of the outflowing slurry stream (Figure 9*b*). To reduce sample variability associated with periods of active and nonactive dredging, slurry samples were collected when the SDP discharge color was black, indicating active dredging. The contents of the sampler were transferred to 1 L bottles and transported to the US Army Engineer Research and Development Center Coastal and Hydraulics Laboratory (ERDC-CHL) sediment properties laboratory for grain size analysis. An aliquot of each sample was dispersed in a 40 g/L solution of sodium hexametaphosphate and screened with a No. 200 sieve (75 μm). Following procedures described in method B of American Society for Testing and Materials (ASTM) D1140-17 (2017), the mass percentage of fines was determined for each replicate sample and a mean percent fines and standard error (SE) of the mean were calculated for each SDP outflow location.

Figure 9. (*A*) Schematic of the SDP with locations of sorting holes identified; and (*B*) isometric view of the SDP operating on Sturgeon Island.

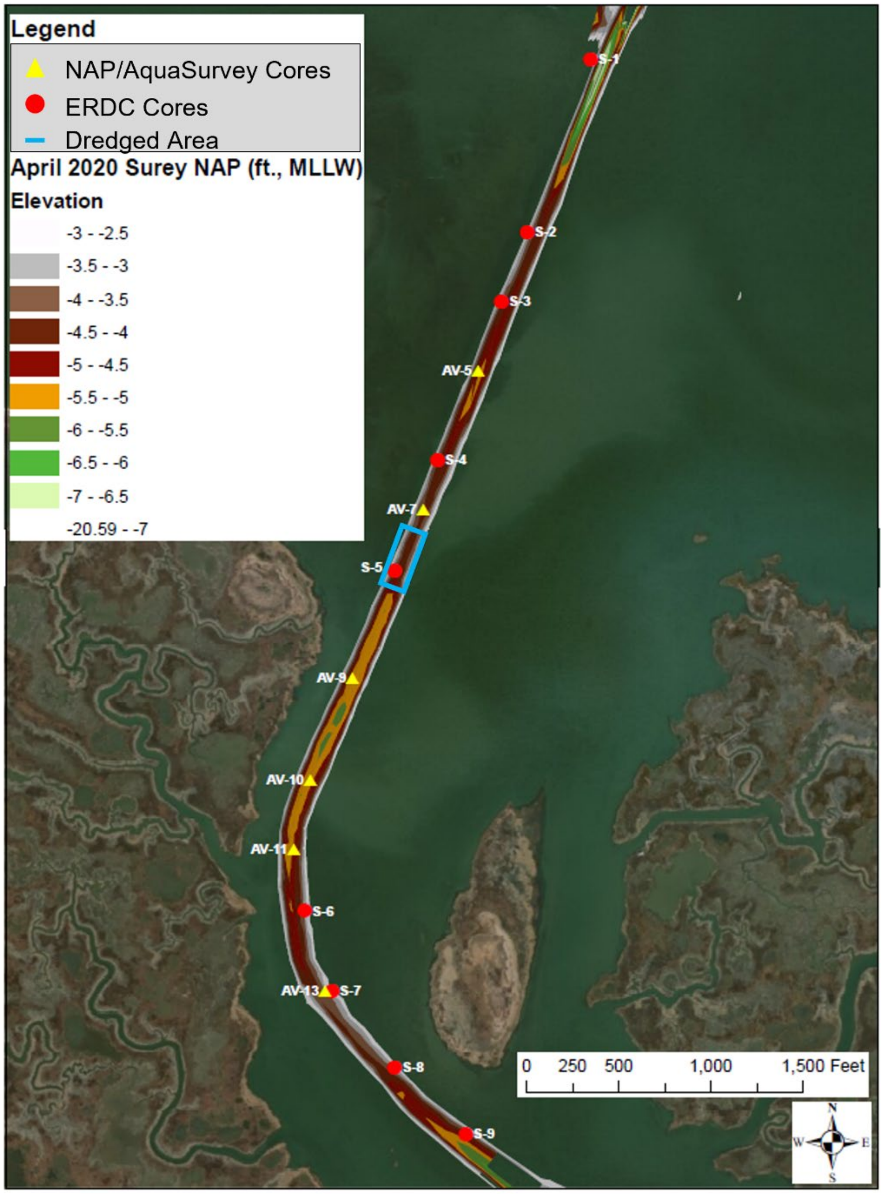


3.1.1.3 Channel Sediment

A series of 15 sediment cores were collected within the reach of the NJIWW where maintenance dredging was planned (Figure 10). However, material placed on Sturgeon Island was limited to a reach of channel in the proximately of cores S-5 and AV-7, as indicated by the blue box in Figure

10. These cores were composed of a combination of 6 inch and 2 inch diameter push cores with lengths ranging from approximately 1–3 ft Contents of the core were used to determine the percent fines of sediments within the channel. Procedures detailed in ASTM D1140-17 (2017), method B and described in section 3.2.1.3 of this report were used to calculate the mass percent fines of each core. Figure 10 below shows the locations of the sediment cores as well as survey elevations of coring locations.

Figure 10. Seven Mile Island Innovation Laboratory (SMILL) – Intercoastal Waterway bathymetry and sample locations.



3.2 Laboratory Demonstration Project

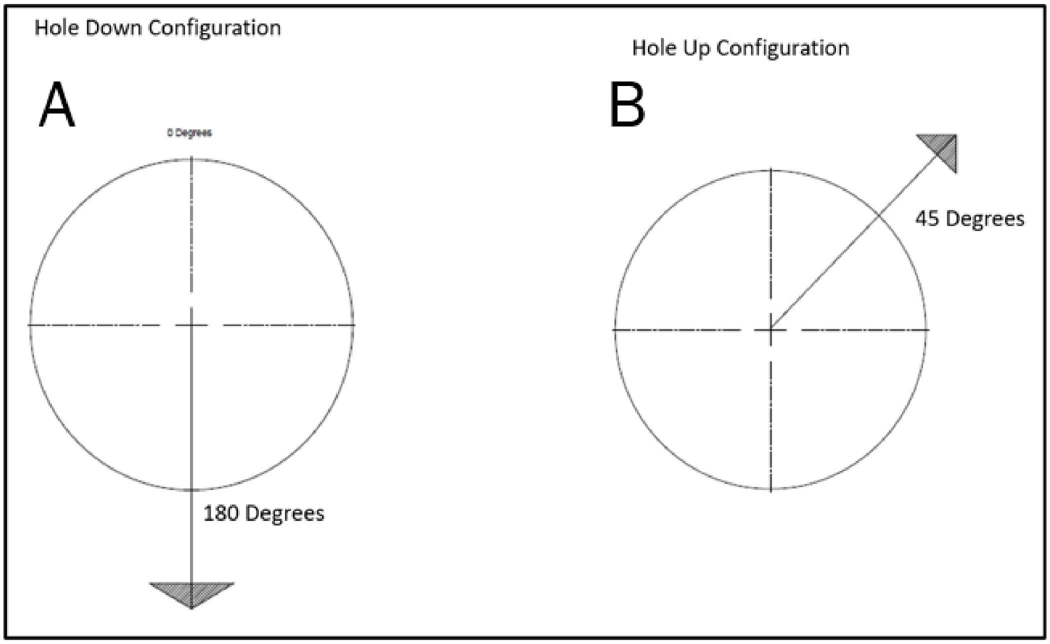
In July of 2022, a series of laboratory tests were performed at ERDC-CHL to further evaluate the sediment sorting efficiency of an SDP system. The laboratory SDP measured 32 ft in length and was composed of 3 inch diameter clear PVC. Similar to the field demonstration, the laboratory SDP was elevated 2.5 ft off the ground by placing the pipe on sawhorses. Four circular holes were drilled into the SDP, each spaced 6 ft apart. Hole numbering was consistent with the field demonstration with hole No. 1 being the most upstream position and subsequent hole numbers increased sequentially towards the EoP. The SDP terminated with a downward 90° elbow that directed outflow into a 300 gal. catch basin.

The impacts of both hole size and orientation on sediment sorting efficiency were evaluated in these laboratory experiments. Tests were run in triplicate with 0.5 inch diameter and 1 inch diameter holes that were positioned either downward at 180° or upward at 45° (Figure 11). The downward hole configuration mimicked the setup of the field demonstration and in theory allowed for coarser particles to preferentially fall out during transit down the SDP, resulting in a finer slurry at the EoP. In contrast, the upward (45°) hole configuration theoretically should allow finer grained material suspended in the pipeline to preferentially discharge with transit distance, yielding a coarser slurry at the EoP. This experimental design resulted in a total of 12 individual test runs (Table 1).

Table 1. Experimental matrix showing the conditions for each of the 12 tests conducted.

Hole Orientation	1 in. Diameter Hole			½ in. Diameter Hole		
Downward (180°)	1	2	3	7	8	9
Upward (45°)	4	5	6	10	11	12

Figure 11. SDP cross-sectional view showing holes orientated: (*A*) downward at 180° and (*B*) upward at 45°.



To simulate dredged material moving through the SDP, a 20% solids by volume slurry was prepared for all laboratory tests. Slurry solids were sourced from two commercially available sands of different size gradations (AGSCO 50-80 and AGSCO 140-270). AGSCO 50-80 is a fine to medium grained sand (125–500 μm) while AGSCO 140-270 is composed of silt to very fine-grained sand (50–125 μm). The manufacturers technical data and size specifications for the AGSCO sediments is provided in the Appendix. Approximately 150 gal. of slurry was prepared for each test by combining 244 lb of each sand with 125 gal. of water. The slurry was homogenized by both an electric EV1P33M Lightnin mixer and a pump driven recirculation system (Figure 12). The electric mixer was mounted to the top of the tank allowing a 5 ft shaft to pass through the fill port and the impeller to be submerged to a depth 5 in. above the bottom outflow port. A gate valve at the bottom of the tank allowed for draining and filling. A 3 in. diameter suction hose connected the tank to a Honda WT30 trash pump. Discharge from the pump flowed through a wye connection which either diverted flow back into the conical tank or passed flow onto the SDP. Valterra gate valves on each leg of the wye allowed for rapid open and closure of the valves and diversion of flow (Figure 12*a*).

Figure 12. SDP mixing tank. (*A*) Schematic of the tank and recirculation pipe. (*B*) Labeled photograph of the tank and recirculation system.

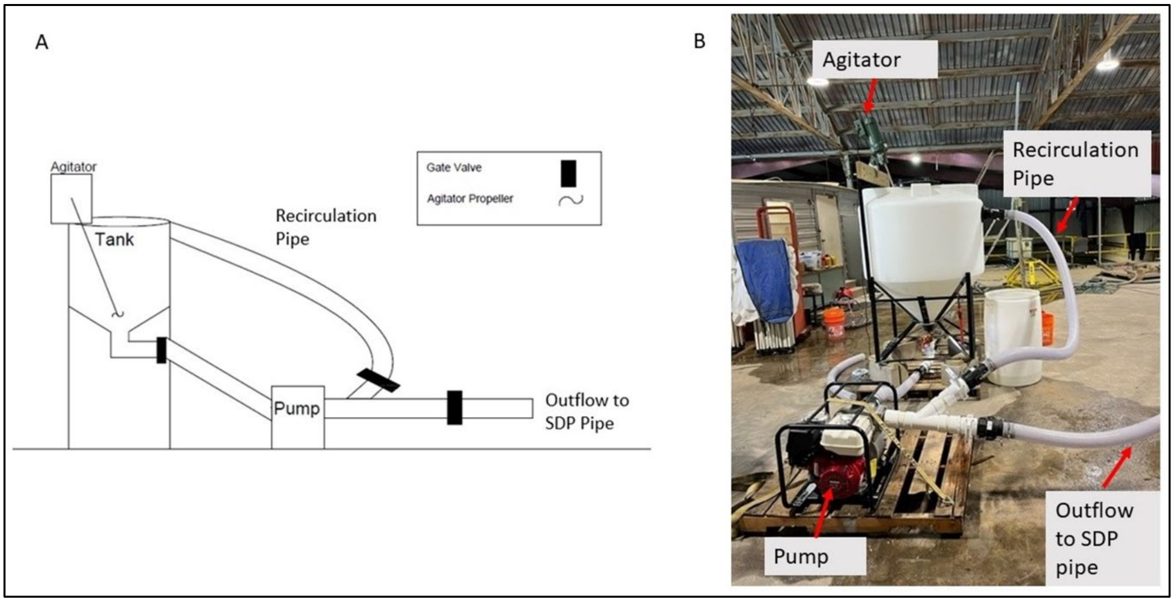
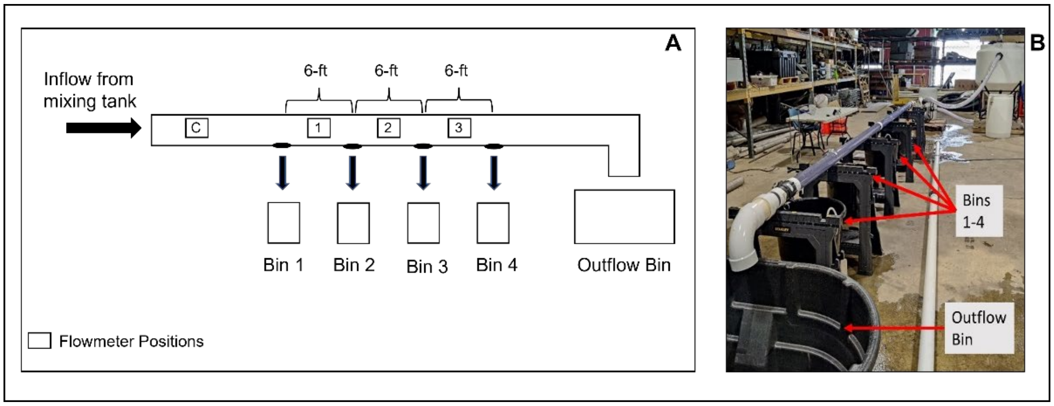


Figure 13. SDP and outflow bins. (*A*) Schematic showing the SDP and outflow points. (*B*) Photograph of the SDP outflow collection bins.



Slurry for each test run was prepared by adding 125 gal. of water to the tank. The bottom valve was then opened, and both the mixer and pump were turned on with valves positioned such that flow was fully diverted back into the tank. After the water was recirculating, 5 gal. buckets of preweighed AGSCO 50-80 and AGSCO 140-270 sediment were added to the tank until the required 488 lb of sediment had been emptied into the tank. Flow was then introduced to the SDP by opening the gate valve on the other leg of the wye. As seen in Figure 13, bins were placed beneath each hole in the SDP and at the EoP to capture the discharged slurry for grain size analysis. Once the tank and SDP were empty, the bins were moved aside and the tank was refilled with clean water. This water was pumped through the system to flush any remaining sediment from the tank, pump, or SDP prior to the setup of the next test. Figure 13 shows the schematic design of the hole spacing along the SDP pipe.

3.2.1 Laboratory Data Collection Methods

3.2.1.1 Slurry Velocity

Slurry velocity within the SDP was measured with the same greyline flow meters used during the field demonstration. Instrument settings were programed with the appropriate internal diameter, wall thickness, and pipe material. Flow data was logged every 10 seconds. All tests had a flow meter located downstream of the wye and upstream of hole 1. This position served as a control flowrate upstream of the SDP holes, as indicated in Figure 13. A second flow meter was placed between SDP holes and was moved sequentially downstream with each replicate test (Figure 13). These measurements were obtained to capture any downstream velocity changes due to the SDP outflows. Every time a transducer was repositioned, dielectric grease was applied and they were securely strapped to the SDP to ensure an airtight seal against the SDP (Figure 14).

Figure 14. Flowmeter transducer.

3.2.1.2 Slurry Sampling

Effluent from the SDP holes was collected in 18.5 gal. bins positioned under each outflow location (Figure 13). The coarse silt to medium sand particles rapidly settled out of suspension within the collection bins, allowing the overlying water to be pumped off prior to sediment collection. Subsamples of sediment for grain size analysis were collected from each bin. The volumes of wet sediment captured in the bins beneath the SDP holes were observed to be approximately 2.5 gal. or less for each test. A 1 L scoop was used to obtain a representative subsample that captured material from across the width and depth of the bin. Any remaining sediment was transferred to appropriately labeled 5 gal. buckets. Both the subsample and contents of the 5 gal. buckets were dried in an oven at 100°C and weighed to obtain a total dry mass of sediment discharged from each hole.

The volume of slurry discharged from the EoP was substantially larger than those of the SDP holes and was collected in a 300 gal. stock tank. As with the other collection bins, overlying water was pumped out after the sediment in the tank had settled. Because of the large volume of sediment in the tank, three 1 g al. subsamples were collected for grain size analysis. To account for spatial variability within the tank, subsamples encompassed the entire thickness of the sediment and were obtained from the middle, and both ends of the tank. The remaining sediment in the stock tank was placed into labeled 5 gal. buckets. These subsamples and sediments were also dried at 100°C to determine the total dry mass discharged from the EoP. The dry masses of sediment from each SDP hole and the EoP were used to calculate the percentage of total sediment mass discharged from the SDP system.

3.2.1.3 Grain Size Analysis

The grain size distributions of both the AGSCO sediments as well as the samples collected from the SDP tests were determined via dry sieving following methods described in ASTM D6913M-17 (2009). Dried sediment was sieved at 1 phi intervals from 500 µm (#35 sieve) down to 63 µm (#230 sieve). Results from replicates of each sample were used to determine a mean and SE for each size bin.

4 Results and Discussion

This section describes the results of both the field demonstration of the SDP on Sturgeon Island, New Jersey, and the subsequent small-scale laboratory testing performed at ERDC-CHL. Field data will be presented and discussed first, followed by the laboratory experiments.

4.1 Field Demonstration Data

4.1.1 Channel Sediment Grain Size

Grain size analysis conducted on the 15 sediment cores from the Atlantic Intracoastal Waterway (AIWW) found that 10 of the cores had a fines content >50% by mass, suggesting that most of the sediment to be dredged from the channel was muddy in texture. However, a wide range in percent fines was observed among the cores (13.6% to 81.4%) resulting in a mean fines content for all the cores of 53.6% with a SE of ±4.6% (Table 2). The dredged material placed on Sturgeon Island came from the area of the channel between cores S-5 and AV-7, marked with an asterisk in Table 2. Fines content of these cores ranged from 34% to 67%, suggesting that the mean percent fines for all the cores collected from the AIWW was also representative of the fines content from the region placed on Sturgeon Island.

Table 2. Mass percent fines of sediment cores collected from the Atlantic Intracoastal Waterway (AIWW).

Core Name	Percent Fines
AV-5	62.9
AV-7*	66.8
AV-9	58.6
AV-10	13.6
AV-11	50.2
AV-13	81.4
S-1	24.4
S-2	48.1
S-3	60.4
S-4	59.5
S-5*	33.9
S-6	42.3
S-7	65.2

Core Name	Percent Fines
S-8	67.9
S-9	68.8
Mean	53.6
SE	4.6

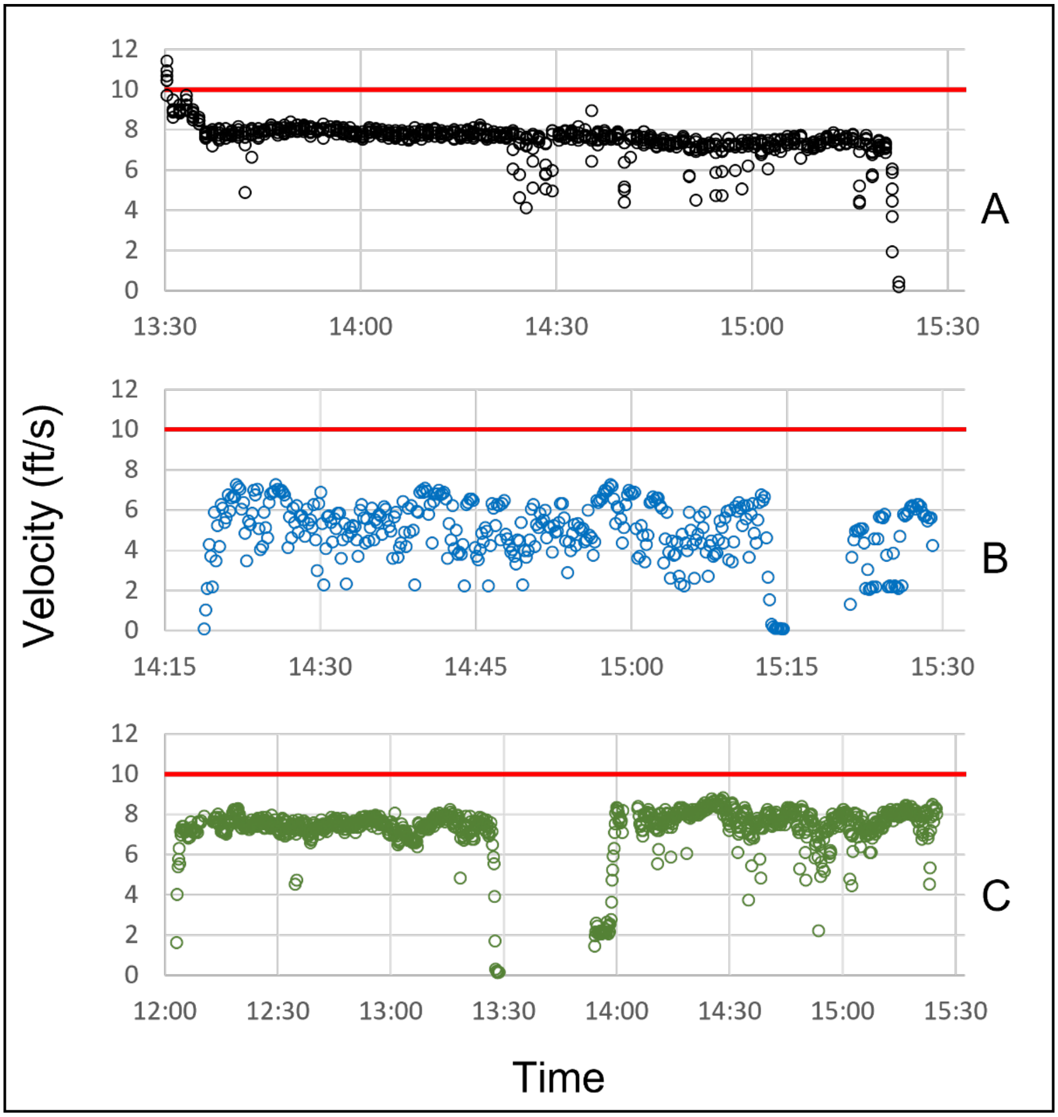
*Indicates the cores in closest proximity to dredging during field demonstration.

4.1.2 SDP Slurry Velocity and Grain Size

Upon initiation of slurry flow through the SDP on March 17th, the 2 inch × 2 inch holes immediately clogged with debris. Attempts were made to clear the holes but clogging persisted. For this reason, the holes were enlarged to 4 inch × 4 inch and no data from the 2 inch holes were collected. Partial clogging of the 4 inch holes was observed, but outflow was maintained by periodically clearing debris with a hand-held rod. Samples of the slurry being discharged from the SDP holes and the EoP were collected on the afternoon of March 17th. To reduce clogging of the outflow ports, the SDP holes were enlarged to 6 inch × 6 inch at the start of the day on March 18th.

Slurry velocity within the SDP was evaluated with data recorded by the Greyline flow meter attached to the pipeline at position 2. This data was thought to provide the best estimate of flow conditions within the SDP prior to the outflow holes due to its location (between the wye-valve and hole 1). Velocity data spanning the period of slurry collection are presented in Figure 14 for March 17–19. Using Equation (5), the transitional velocity (V_{th}) between homogeneous and heterogeneous flow for a 75 μm particle was calculated as approximately 10 ft/s. This corresponds to the needed velocity to maintain all the fines in homogenous flow and is indicated by the solid red line in Figure 15. The required V_{th} for fines was never reached during periods of slurry sampling. Instead, recorded flow during sampling was approximately 8 ft/s on March 17th and March 19th. Flow data from March 18th indicated lower and more variable velocities within the SDP that typically ranged from 2 to 7 ft/s. No issues with the dredge pump were noted during operations on March 18th, suggesting that the rapid fluctuations and inconsistencies seen in the velocity data were resultant from an issue with the flow meter. The more consistent data observed on March 19th indicates that the issue might have been associated with the seal between the transducer face and the pipe on the 18th. An airtight seal is required between the transducer face and the pipe to prevent noise in the data.

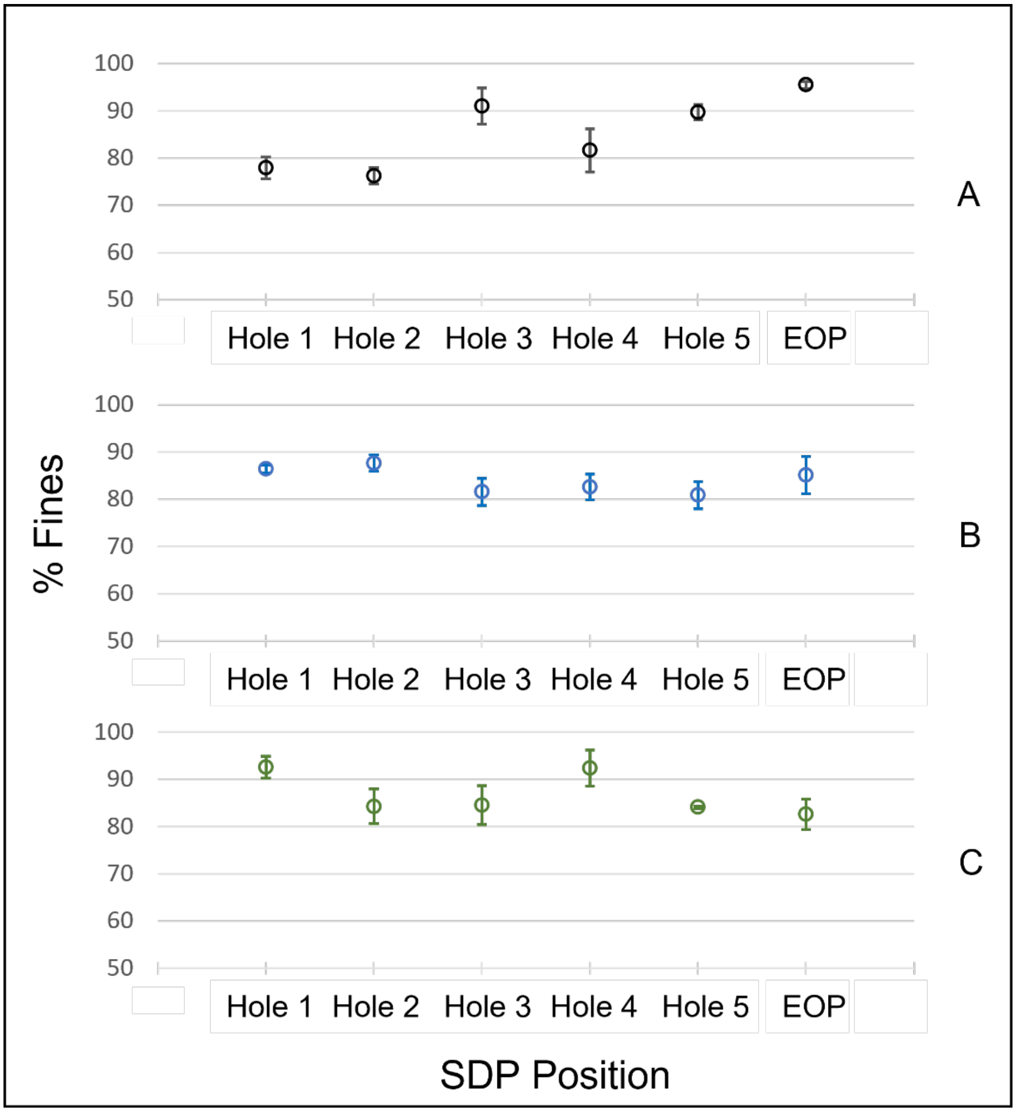
Figure 15. Slurry velocity measurements from the SDP during sediment sample collection from (*A*) March 17, (*B*) March 18, and (*C*) March 19. The *red line* in each plot presents the velocity required to maintain homogeneous flow of a 75 µm particle.



While these flow rates were not adequate to keep all the fines homogeneously mixed within the pipeline, the holes along the bottom of the SDP would theoretically still allow for a sorting of coarser material as the slurry moved through the system. The approximate 8 ft/s velocity observed on March 17th and 19th corresponds to a V_{th} adequate to maintain particles ≤55 µm in homogenous flow, but all larger particles would be in heterogeneous flow. To evaluate the level of sediment sorting occurring in the SDP, the mean percent fines content and associated SE of the slurry samples taken at each hole and EoP during dredging were calculated (Figure 16). The mean percent fines of the slurry samples was consistently observed to be >80%, indicating that the dredged slurry moving through the SDP had minimal sand content. Only samples from holes 1 and 2 from March 17th showed a mean fines content <80% at 78% and 76%, respectively. Additionally, an increase in fines content due to a loss of sand with transport through the SDP was not observed in the slurry data on March 18th or 19th. The data from March 17th does indicate a change in fines content with values <80% at holes 1 and 2 increasing to 95% at the EoP. However, this increase in fines is not consistent with all holes. The slurry samples collected from hole 3, hole 5 and the EoP had mean percent fines with overlapping standard error ranges, making them statistically indistinguishable from each other. Likewise, mean fines content of slurry samples from hole 1, hole 2, and hole 4 were also statistically indistinguishable.

In general, results from the field demonstration of the SDP were inconclusive. Additional data collection is recommended to elucidate the SDP sediment sorting capability. More comprehensive data that include a range of velocities in the homogeneous and heterogenous flow regimes for different hole sizes will be important to assess the sorting functionality provided by the SDP. Additionally, while the discharge from the holes was sampled under similar conditions (based on visual assessment of the discharge color), all the holes were not sampled at the same time, which introduces uncertainty in the data. Cores collected within the NJIWW demonstrated substantial variability of sediment texture within the channel. The assumption of constant fines content of the channel sediments being dredged is flawed, and any heterogeneity of the channel sediments would impact perceived sorting results of the SDP. Efforts were taken with the laboratory-based SDP evaluations to address some of these uncertainties.

Figure 16. Mean percent fines of slurry samples collected from each outflow port of the SDP from *(A)* March 17, (*B*) March 18, and (*C*) March 19. Error bars indicate the standard error of the mean for each sample.



4.2 Lab Demonstration Data

4.2.1 AGSCO Test Sediment Size Distribution

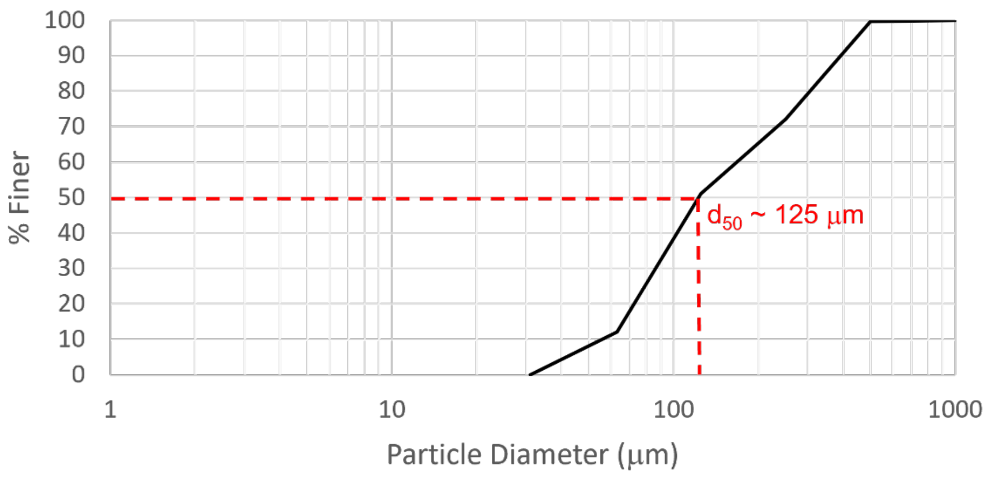
Three separate shipments of the AGSCO sediments were received during SDP lab testing. To ensure consistent texture of each sediment batch, sieve analysis was performed on a subsample from each shipment. Table 3 presents the mean and standard error of the sieve analysis performed on the AGSCO test sediments. Results showed a similar distribution to the manufacturer's specification sheet (Appendix) and minimal differences between sediment batches received. The cumulative distribution of a

50/50 mix of these sediments is shown in Figure 17 and provided the theoretical distribution for the initial test material introduced to the mixing tank at the start of each test run. The median grain size (d_{50}) of the initial test sand was found to be approximately 125 µm.

Table 3. AGSCO sieve analysis (percent by mass).

Test Material	Pan (<63 µm)	#230 Sieve (63 µm)	#120 Sieve (125 µm)	#60 Sieve (250 µm)	#35 Sieve (500 µm)
AGSCO #140-270	24 ± 2.9	72.7 ± 2.6	3.3 ± 0.3	—	—
AGSCO #50-80	0.3 ± 0.1	5.3 ± 1.6	38.5 ± 3.6	55.2 ± 4.9	0.7 ± 0.6

Figure 17. Gradation of sediments used in the experiment.



4.2.2 SDP Velocity Data

To evaluate the particle sorting efficiency of the laboratory SDP, targeted V_{th} values for analysis were required. Strategic particle sizes of 125 µm and 250 µm, which matched sieve sizes from grain size analysis, were used for calculating V_{th} with Equation (5). These calculations found that flow velocities of 8.2 ft/s and 11.7 ft/s were required to keep 125 µm and 250 µm particles homogeneously mixed within the pipeline, respectively. Figure 18 and 19 plot the compiled velocities measured along the SDP at all positions during replicate test runs for both the 1 inch hole and 0.5 inch hole experiments. Results from tests conducted with the holes in downward (180°) and 45° upward orientations are shown in Figure 18*a* and Figure 18*b*, respectively. Velocities typically ranged between 8 and 10 ft/s, indicating that conditions within the SDP were typically sufficient to maintain particles ≤150 µm in homogeneous flow. No flow velocity was observed above the V_{th} for 250 µm particles. Therefore, particles ≥250 mm would be in heterogeneous flow that would favor transport in the bottom portions of the SDP.

The velocity data at each position along the SDP was limited due to the brevity of each test run. Flow velocities of 8 to 10 ft/s within the SDP corresponded to discharge rates of 3.0–3.7 gal/s. With a starting slurry volume of 150 gal., test runs typically lasted 40–50 seconds before the tank was empty. Further, as slurry volume dropped below 30 gal., the vigorous mixing within the tank increased the amount of air introduced to the pump, which resulted in inconsistent pumping speeds. Velocity data during these final seconds of the experiments were omitted from Figure 18 and 19. The greyline flowmeters were unable to sample at a frequency higher than every 10 seconds, therefore velocity measurements at each position along the SDP were commonly limited to 3–4 data points. The number of readings at the control positions are greater because data was collected at this location for all replicate runs of a test condition.

Figure 18. Flow velocity measurements along the SDP from 1 inch hole tests: (*A*) results with holes in a downward (180°) orientation and (*B*) results from the 45° orientation.

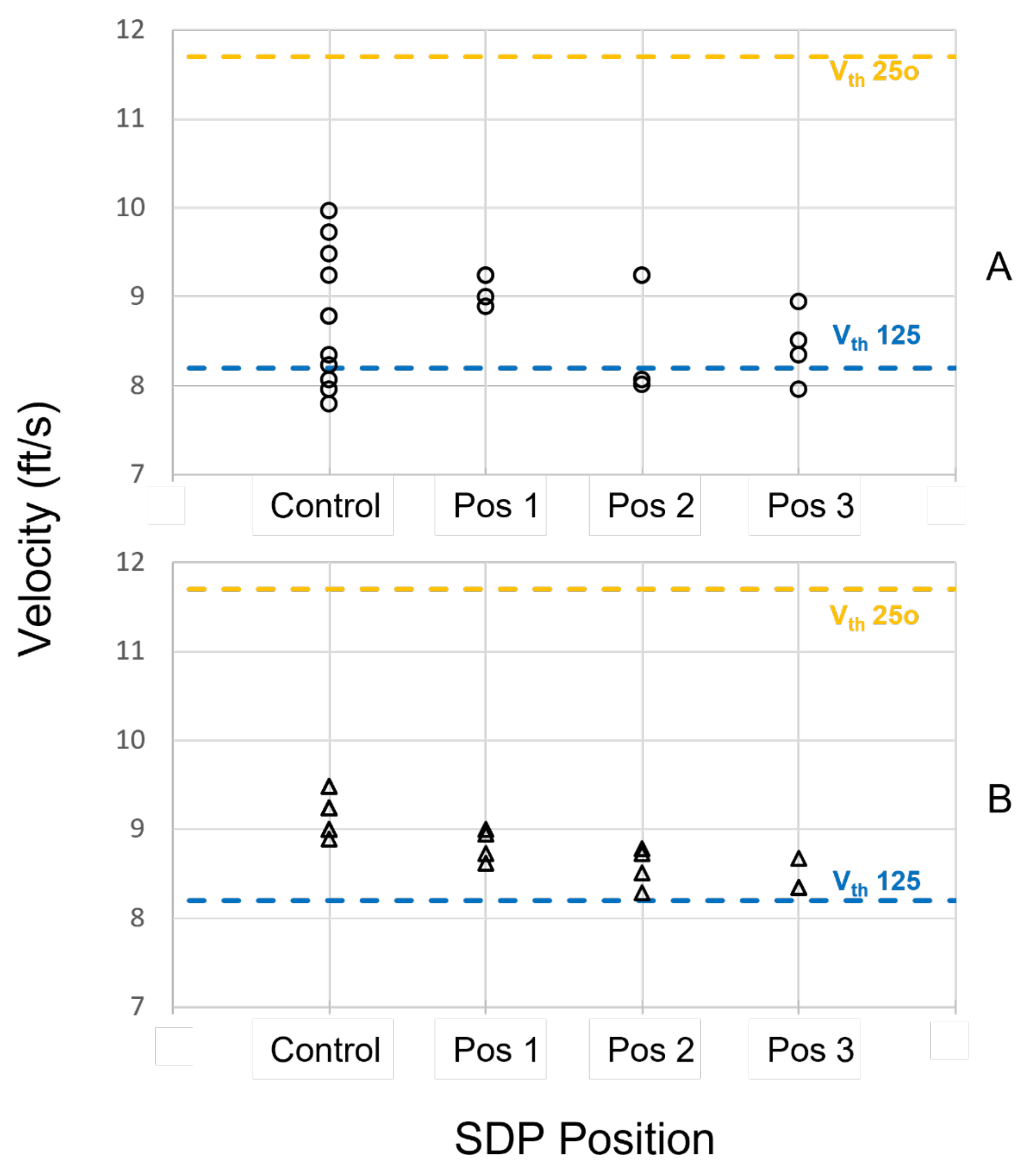
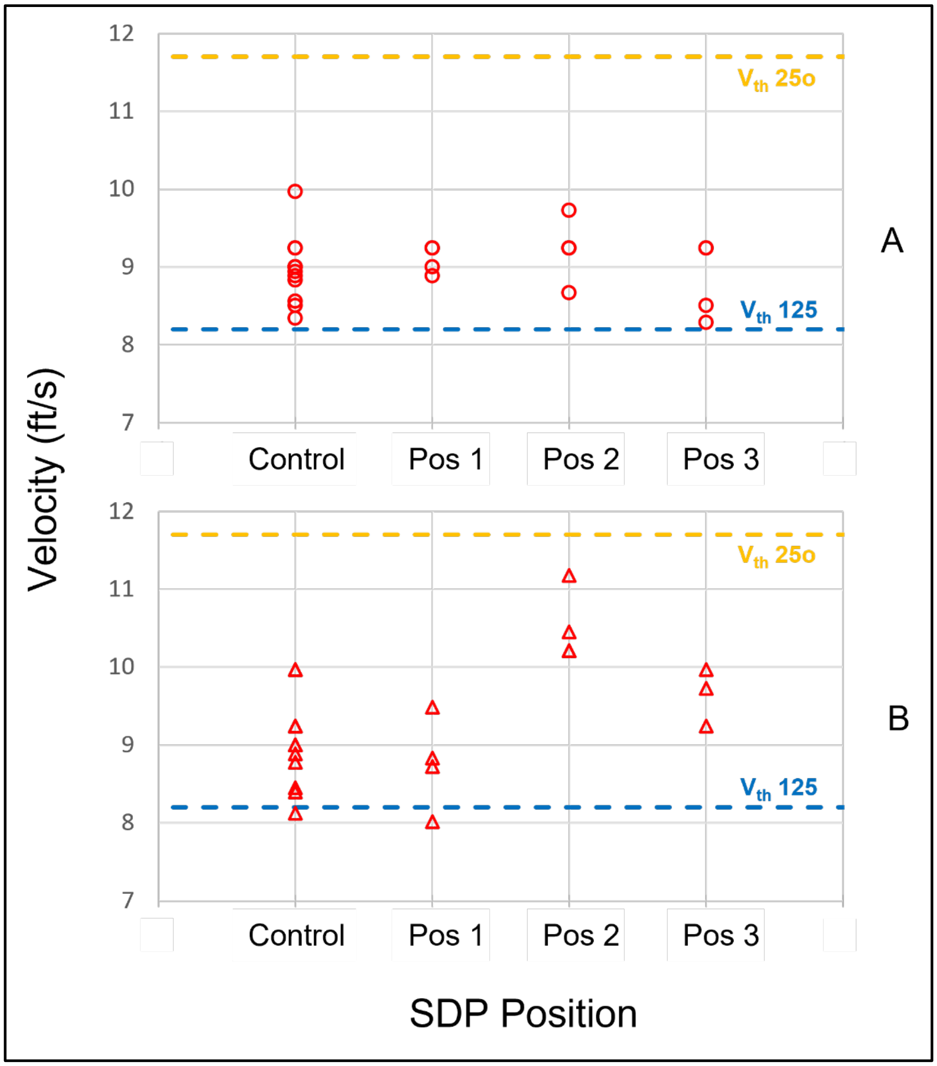


Figure 19. Flow Velocity measurements from 1/2 inch hole tests: (*A*) results with holes in a downward (180°) orientation and (*B*) results from the 45° orientation.

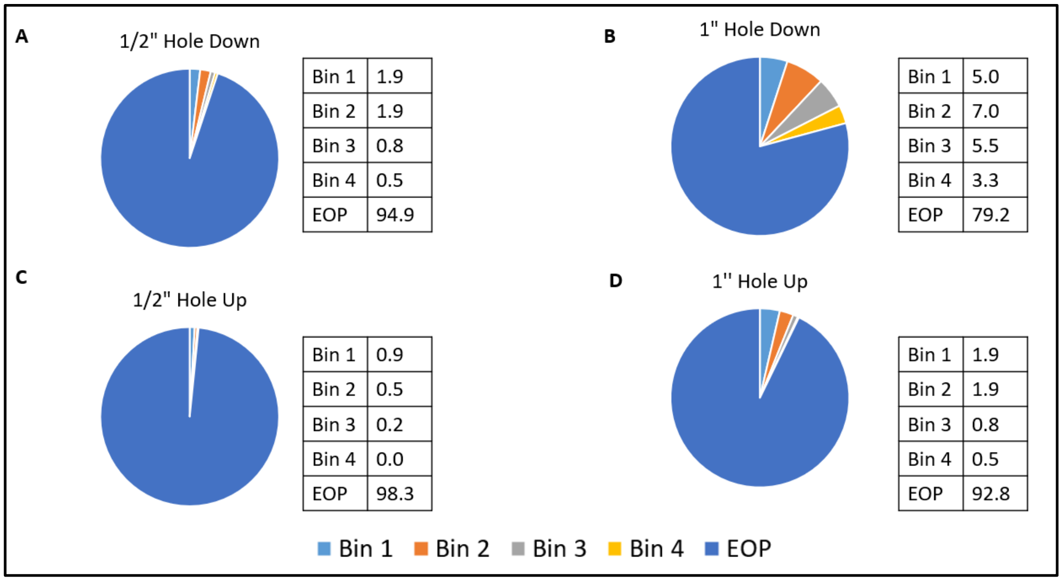


4.2.3 SDP Outflow Samples

Visual observations made during the SDP experiments indicated inconsistent discharge from holes along the pipeline throughout each test. At the start of each test, large amounts of air were observed moving through the pipe. Air within the system did appear to decrease as the pipe filled with slurry, but conditions never appeared to reach that of a full pipe with no entrained air. Instead, air was periodically observed to enter the SDP from the outflow holes configured at both the 180° and 45° orientations and 1 inch and 0.5 inch diameters. This produced inconsistent and interrupted discharge from the holes along the SDP. As described in the previous section, once volume within the tank was reduced to approximately 30 gal. or less, air was entrained from the suction side of the SDP system. In general, observations suggest that flow and discharge conditions were not consistent throughout the short duration (less than a minute) of the test runs.

Results from the slurry collected from each of the SDP outflow points showed that the overwhelming majority of the sediment mass was discharged from the EoP and that sediment mass discharged from the holes along the SDP was not uniform. Figure 20 shows the mean percentage of dry sediment mass recovered from each discharge point along the SDP for all four test conditions. Approximately 79%–98% of the slurry sediment was discharged from the EoP with the least amount of sediment reaching the EoP during testing with 1 inch diameter holes in a downward (180°) orientation. More than 90% of the sediment mass was able to bypass the SDP holes in the other tests conducted, indicating a general inefficiency of the SDP to distribute slurry from multiple points along the pipeline with the experimental hole sizes. As anticipated, the 0.5 inch diameter holes discharged less sediment than the 1 inch holes, and holes at an upward (45°) orientation discharged less sediment than holes in a downward (180°) orientation. Additionally, regardless of hole size or orientation, the sediment mass discharged from the SDP holes generally decreased downstream (Figure 20).

Figure 20. Sediment mass discharged from SDP. Percentage of dry mass from each outflow location along the SDP for (*A*) ½ in. diameter holes in downward (180°) orientation, (*B*) 1 in. diameter holes in downward (180°) orientation, (*C*) ½ in. diameter holes in upward (45°) orientation, and (*D*) 1 in. diameter holes in upward (45°) orientation.



A

Bin 1	1.9
Bin 2	1.9
Bin 3	0.8
Bin 4	0.5
EOP	94.9

B

Bin 1	5.0
Bin 2	7.0
Bin 3	5.5
Bin 4	3.3
EOP	79.2

C

Bin 1	0.9
Bin 2	0.5
Bin 3	0.2
Bin 4	0.0
EOP	98.3

D

Bin 1	1.9
Bin 2	1.9
Bin 3	0.8
Bin 4	0.5
EOP	92.8

While a limited amount of sediment mass was distributed from the SDP holes in the laboratory experiments, the primary objective of the testing was to evaluate sorting efficiency of material discharged along the pipeline. Data showing the mean percentage of sediment <125 μm discharged from each location along the SDP are presented for the 1 inch hole tests (Figure 21) and 0.5 inch hole tests (Figure 22). The initial slurry mixed in the sediment source tank was composed of 51% <125 μm material. Results from the downward (180°) oriented 1 inch holes (Figure 21*a*) showed that sediments flowing out of holes 1–4 had less than 50% <125 μm, indicating a preferential discharge of coarser sediments from the bottom of the SDP. Conversely, when oriented in an upward direction at 45°, effluent from holes 1–4 had mean <125 μm contents that ranged from 58% to 76% (Figure 21*b*).

These values were all higher than the initial test slurry, showing that sediment flowing out of the upper half of the SDP was finer in texture. These same trends in mean <125 μm content were also observed for the tests performed with 0.5 inch diameter holes (Figure 22). Effluent from the downward facing holes was coarser than the initial test slurry while effluent from the upward facing holes was finer in composition. Further, for all holes in all test configurations, the mean <125 μm content of sediment discharged from the SDP holes was found to be statistically different than that of the starting test slurry.

These observations align with anticipated results that would result from hydraulic sorting of sediment at flow conditions that allow for heterogenous flow for particles greater than 125 μm. In short, the experimental data showed that particles >125 μm were preferentially transported along the bottom half of the SDP, resulting in a finer slurry moving through the upper portion of the pipeline.

Figure 21. Mean percent <125 µm of slurry samples collected from each outflow port along the SDP from (*A*) 1 in. downward (180°) hole tests and (*B*) 1 in. upward (45°) hole tests. *Yellow square* indicates <125 µm content of the initial slurry. Error bars indicate the standard error of the mean for each sample.

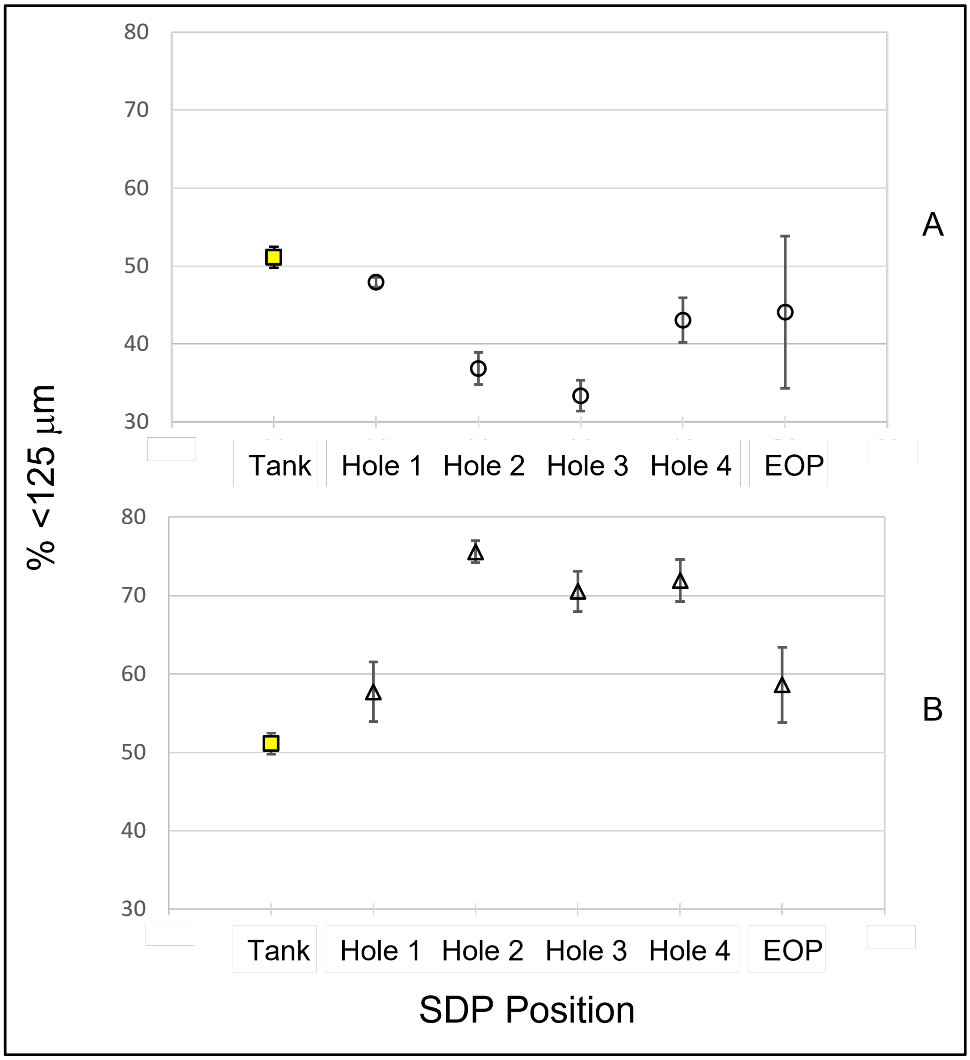
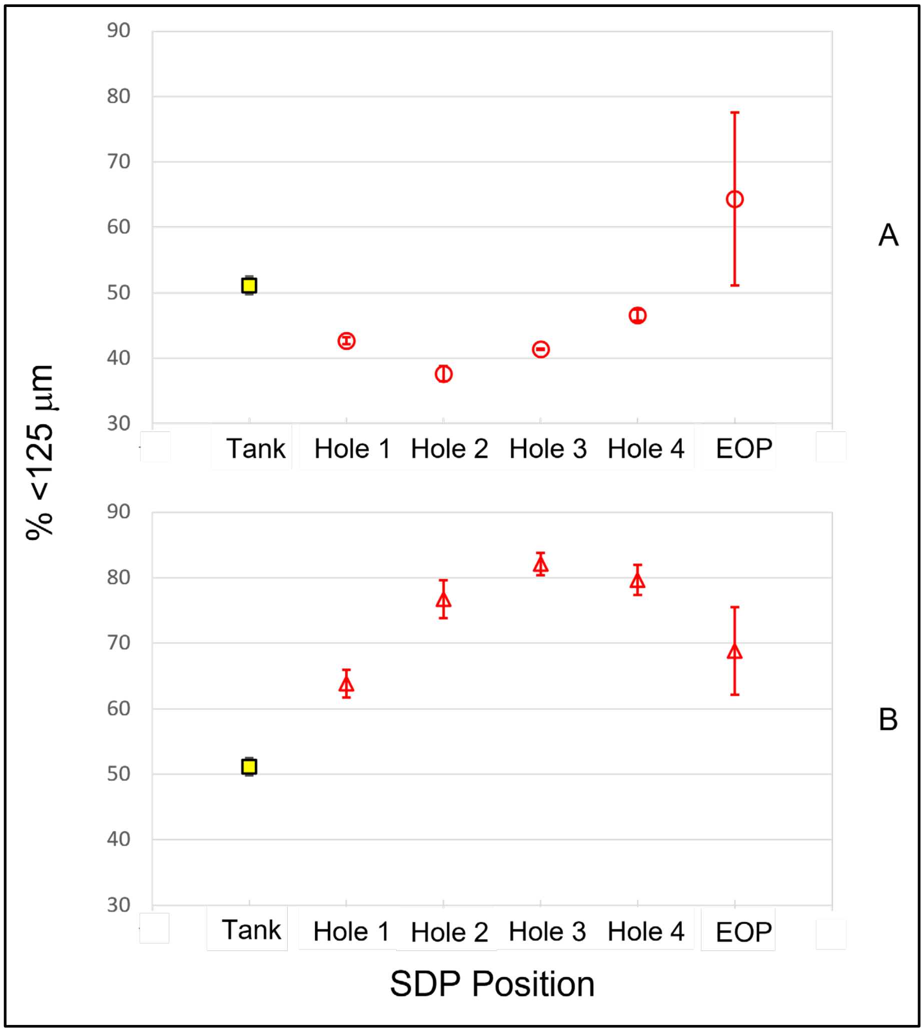


Figure 22. Mean percent <125 µm of slurry samples collected from each outflow port along the SDP from (*A*) ½ in. downward (180°) hole tests and (*B*) ½ in. upward (45°) hole tests. *Yellow square* indicates <125 µm content of the initial slurry. Error bars indicate the standard error of the mean for each sample.



The indication of hydraulic sorting that was observed in the grain size data of the effluent collected from the SDP holes was not found in the data obtained from the EoP. It was expected that EoP would have shown the opposite change in sediment texture than the effluent from the SDP holes. Thus, the discharge of coarse slurry from holes along the bottom of the pipeline should have yielded a finer slurry at the EoP while the discharge of fine slurry from holes in the upper portion of the pipeline should have produced a coarser slurry at the terminus of the SDP. However, the change in mean <125 µm content from the EoP mimicked that of the SDP holes for both 1 inch and 0.5 inch hole tests in an upward orientation (Figure 21 and 22). The EoP sediment was found to be finer in texture than the initial slurry with <125 µm contents of 59% ± 5% and 69% ± 7%, respectively.

This would indicate that all discharged material from the SDP system was finer than the starting slurry. Sediment texture from the EoP samples collected during the downward facing hole tests showed that no meaningful grain size sorting took place. Mean <125 µm content was 44% ± 10% and 64% ± 13% for the 1 inch and 0.5 inch hole tests, respectively. The SE associated with these mean values were large enough to allow for overlap with the <125 µm content of the initial test slurry (51% ± 1%).

By analyzing the grain size and total mass data together another inconsistency was found. While data from the SDP holes consistently showed changes in <125 µm content, only the 1 inch downward facing hole tests had more than 10% of the total sediment mass being discharged from the SDP holes. Thus, changes in the <125 µm content at the EoP should have been minimal (<2.5%). However, differences in mean <125 µm content between the initial slurry and EoP effluent ranged from 7%–17%. Simply put, there was not enough sediment mass discharged from the SDP holes to account for this level of change in sediment texture at the EoP.

The SE associated with the mean percent <125 µm from the EOP samples ranged from ±5%–13%, which was consistently larger than the SE of samples collected from the SDP holes (Figure 21 and 22). Values of SE from the SDP hole data were typically ≤2% and never exceeded 4%. The larger variability observed in the EoP data is likely due to insufficient subsampling of the large volume of sediment that was discharged at this location. While attempts were made to obtain subsamples that were representative of the effluent captured at end of the SDP, grain size results indicated substantial differences between the subsamples. Spatial variability of sediment texture within the collection basin may have been greater than what the three subsamples could account for. This would result in potentially biased and inaccurate grain size data for the EoP and provide a potential explanation for the apparent systematic loss of >125 µm material reported in the upward facing hole tests.

5 Conclusions and Recommendations

5.1 Conclusions

The capability of the SDP to hydraulically sort sediment particles in a slurry moving through a pipeline was evaluated in both a full-scale dredging application on Sturgeon Island, New Jersey, and in smaller scale laboratory experiments. Key findings from both sets of tests are presented in this section.

5.1.1 Field Demonstration

- During the three days of dredging and SDP sampling, flow velocities measured within the pipeline were rarely observed to be greater than 8 ft/s. These were below the theoretical velocity required to maintain homogeneous flow conditions for 75 μm particles (approximately 10 ft/s).

- Effluent samples collected along the SDP did not show a consistent change in fines content along the SDP. Significant differences in fines content were limited to the most upstream and downstream portions of the SDP during dredging on March 17, 2020, which had a consistent flow velocity that was slightly less than the transitional velocity to homogenize 75 μm particles. No change in fines content was observed with transit in the SDP during the other two days of dredging. This resulted in inconclusive data regarding the sediment sorting capability of the SDP deployed at Sturgeon Island.

5.1.2 Lab Demonstration

- Laboratory experiments were conducted with a prepared sediment slurry to evaluate the capability of a 3 inch diameter SDP system to hydraulically sort 125 μm particles. This setting allowed for the preparation of a sediment mixture and calculation of an appropriate V_{th} to test hydraulic sorting capabilities of the SDP.

- Results showed that adequate flow velocity was maintained within the SDP to keep particles ≤125 μm in homogeneous flow. Slurry discharged from holes in the SDP showed hydraulic sorting. Effluent from the bottom of the pipe was consistently found to be coarser than the initial test slurry while effluent discharged from the upper half of the pipeline was finer than the initial slurry composition.

- Flow out of the SDP holes was not uniform along the pipeline and often intermittent at holes closest to the EoP. Air entrained from both the source tank and SDP holes appeared to be a contributing factor to the inconsistent discharge along the pipeline.

- Most of the slurry bypassed the SDP holes and was discharged from the EoP. Typically, >90% of the sediment mass was discharged from the end of the SDP.

- Grain size samples from the EoP showed the highest amount of variability. Subsamples were likely insufficient to properly characterize the sediments within the final basin and resulted in inconclusive data from the EoP.

5.2 Recommendations

Results from both the field and laboratory demonstrations of the SDP were inconclusive. Much of the uncertainty associated with the data can be partially attributed to experimental design and sampling procedures. This is not due to lack of effort by those conducting the experiments, but rather due to insight gained after the fact. Key recommendations for future experiments are as follows:

- Laboratory test runs conducted in these experiments were short in duration and allowed significant amounts of air into the SDP system, which impacted flow and discharge conditions throughout the test. The development of a closed system with sediment traps may significantly reduce air in the system as well as material and labor costs associated with testing. This type of design would potentially allow for longer test runs and the acquisition of data not heavily impacted by changing flow conditions at the start and end of the test.

- Knowing the velocities within the SDP is essential to evaluating hydraulic sorting of sediments within the SDP. In both the lab and field experiments theoretical flow velocities based on pump and system specifications were used to inform decisions on both the type of sediments to use and how to analyze the sediment for grain size. This resulted in grain size data that was not informed by measured velocity in the pipeline. As a result, grain size data from the field demonstration did not align with the intended V_{th} and lab data was limited to only one V_{th} test condition. Future studies should refrain from designing sediment properties or determining sediment processing methods for size distribution until measured velocity data of the SDP system is available.

References

Allen, J. M. 1914. "Building Levees with the Hydraulic Dredge." *Engineering News: A Journal of Civil Engineering and Construction* 72 (18): 891–897.

ASTM (American Society for Testing and Materials). 2009. *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis*. D6913-04. West Conshohocken, PA: ASTM International. http://doi.org/10.1520/D6913-04R09E01.

ASTM (American Society for Testing and Materials). 2017. *Standard Test Methods for Determining the Amount of Material Finer than 75-µm (No. 200) Sieve in Soils by Washing*. D1140-17. West Conshohocken, PA: ASTM International. https://doi.org/10.1520/D1140-17.

GIW Industries (GIW Industries, Inc.). 2001. *Slurry Pipeline Design Manual*. Grovetown, GA: GIW Industries, Inc.

Herbich, J. B. 1975. *Coastal and Deep Ocean Dredging*. Houston, TX: Gulf Publishing Co.

Herbich, J. B. 2000. *Handbook of Dredging of Engineering, Second Edition*. New York: McGraw-Hill.

Huston, J. 1986. *Hydraulic Dredging: Theoretical and Applied*. Ithaca, NY: Cornell Maritime Press.

Stokes, G. G. 1847. "On the Theory of Oscillatory Waves." *Transactions of the Cambridge Philosophical Society* 8: 441–455.

Turner, T. M. 1996. *Fundamentals of Hydraulic Dredging*. Second Edition. New York: ASCE Press. https://doi.org/10.1061/9780784401477.

Appendix A: AGSCO Fine Round Grain Silica Sand Technical Data

Table A-1. Typical physical properties.

Property	Specification
Fusion Point	3135 °F
Hardness	Knoop: 820; Mohs: 7
Grain Shape	Spherical
Specific Gravity	2.65 g/cm^3
Loose Pack Bulk Density	1.60 g/cm^3 (100 lbs./ft^3)
pH	6.8 to 7.2

Table A-2. Manufacturer screen analysis showing percent mass retained of AGSCO sediments.

Test Material		
US Sieve #	AGSCO #50-80	AGSCO #140-270
40	2.7	—
50	39.3	–
60	23.8	–
70	16.2	–
80	9.1	–
100	5.4	–
120	3.5	—
140	–	27.8
170	—	---
200	–	50.9
230	–	—
270	–	19.3
325/PAN	–	2.0

Abbreviations

AIWW	Atlantic Intracoastal Waterway
ASTM	American Society for Testing and Materials
BUDM	Beneficial use of dredged material
CHL	Coastal and Hydraulics Laboratory
C_V	Concentration by volume
C_w	Concentration by weight
DM	Dredged material
EoP	End of the pipeline
ERDC	US Army Engineer Research and Development Center
NAP	USACE Philadelphia District
NJIWW	New Jersey Intracoastal Waterway
PDFM	Portable doppler flow meter
SDP	Sediment Distribution Pipe
SE	Standard error
SG_S	Solid particle specific gravities
SMIIL	Seven Mile Island Innovation Laboratory
TWI	The Wetlands Institute
USACE	US Army Corps of Engineers

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14. ABSTRACT

The US Army Corps of Engineers (USACE) recently established a goal to beneficially use 70% of material dredged from the nation’s navigable waterways by the year 2030. Most of the sediments dredged by the USACE are heterogeneous mixtures of mud and sand, which can limit beneficial use of dredged material (BUDM) applications. Innovative technologies that can sort material during the dredging process are needed to help increase BUDM practices. This investigation sought to evaluate the ability of a sediment distribution pipe (SDP) to sort particles during transport in a pipeline. Field demonstrations were conducted during dredged material placements at Sturgeon Island, New Jersey. Velocity within the pipeline was found to be inadequate for efficient hydraulic sorting of fines (<75 μm) and produced inconclusive results. Small scale laboratory SDP experiments found that effluent from the SDP holes had an altered sediment texture compared to the initial slurry and that hydraulic sorting was occurring within the pipeline. However, outflow from the SDP holes was inconsistent and typically >90% of the sediment mass was discharged out the end of the pipeline. Sorting efficiency of the SDP could not be accurately assessed in the current experimental configuration.

15. SUBJECT TERMS

Beneficial Use of Dredged Material (BUDM); Dredging; Dredging Spoil—Management; Dredged Material—Management; Innovative Dredging Techniques; Pipelines—Hydraulics; Sediments (Geology)—Size; Sediments (Geology)—Texture; Sediment Distribution Pipe (SDP); Sorting Devices

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