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# Impact of Mud Aggregate Processes in Sediment Transport Studies

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**PURPOSE:** The goal of this Coastal and Hydraulics Engineering Technical Note (CHETN) is to communicate the effect of aggregated fine sediment on U.S. Army Corps of Engineers (USACE) mission areas, highlight research underway to quantify aggregate transport processes, and communicate the relevance and importance of these processes to project engineers within the USACE and other agencies.

**INTRODUCTION:** The majority of sediments located within the waterways managed by the USACE are a mixture of sand, silt, and clay. Processes involved in the erosion and transport of heterogeneous sediments have been shown to be more complex than that of pure sand (Mehta et al. 1989; Mitchner and Torfs 1996). With the addition of fine material (<63 microns [ $\mu\text{m}$ ]), the sediment matrix can become more cohesive (Mitchner and Torfs 1996; Van Ledden et al. 2004; Barry et al. 2006; Jacobs et al. 2011) and result in aggregated particles upon erosion (Jepsen et al. 2010; Schieber et al. 2010). Sediment aggregates are composed of bound particles of smaller size. Typical sediment aggregates are bound by cohesive forces of clay or organic content. They are formed by varying processes, resulting in different characteristics. Floccs, a type of low-density aggregate, are formed by colliding cohesive particles in the water column. Upon deposition and burial, the loose, open structure of floccs is destroyed and compressed into the sediment bed. Another form of aggregate is that which results directly from erosion. Through erosion processes, the consolidated bed may become exposed. When consolidated cohesive beds erode, the erosion often occurs as chunks, or bed aggregates, which have a particle density equal to the bulk density of the bed. The main concern of this report is to investigate how the size, density, and durability of these bed aggregates can significantly impact the transport characteristics of sediments.

Understanding sediment transport and deposition processes is an important aspect of many USACE projects, particularly when it comes to infilling. Approximately 700 dams are operated by the USACE, and the infilling of their reservoirs reduces capacity for water storage and flood control. Additionally, sediment infilling can be a significant issue in navigation channels. To maintain the nation's ports and channels, the USACE invests approximately \$1.4 billion annually and removes  $>1.4 \times 10^8$  cubic meters ( $\text{m}^3$ ) of material in dredging activities (USACE 2016). Discerning the sediment sources and conveyance mechanisms that lead to infilling is therefore a crucial component to effectively managing sediment within the nation's waterways. By increasing knowledge on the abundance, size, and durability of fine-grained aggregates within a system, estimations of sediment transport processes may be improved, which in turn could impact reservoir and channel infill predictions.

The potential importance of sediment aggregates to the USACE can be seen in areas beyond infilling. In recent years, beneficial usage of dredged material has been sought by managers and planners for both storm protection and environmental restoration projects (e.g., Weinstein and Weishar 2002; Yozzo et al. 2004; Bolam and Whomersley 2005; Croft et al. 2006; Erwin et al. 2007; Beck et al.

2012). However, placement of dredged material often raises questions regarding environmental impacts on surrounding areas and requires accurate methods to predict the transport and fate of these sediments. Therefore, the impacts that sediment aggregation has on sediment transport pathways and distances have clear environmental significance to projects. Further, in engineering studies where dredged material is proposed to mitigate land loss and/or create habitat (such as in wetlands, mud flats, nearshore regions, etc.), the geomorphological evolution of the sediment bed can be a critical component of the project. The presence of aggregates could govern the physical transport processes of fine sediments and influence the resulting morphology of the study site. Last, awareness of the adverse effects that reduced sediment supply can have on areas downstream of dams has increased over the last few decades. As a result, the development of methods to increase sediment bypass through dams is of growing concern. Understanding fine-grained aggregate processes can play an important role in developing accurate estimates of sediment bypassing volumes and rating curves for dams operated by the USACE.

Mathematical models are commonly utilized to predict sediment movement for project scenarios just described. Process-based numerical sediment transport modeling has advanced significantly since the mid-1990s, in large part due to improved process understanding and numerical representation. However, process-based descriptions of aggregate generation, degradation, and transport processes are presently weakly described or absent from USACE numerical models. In many applications, the lack of aggregate transport process descriptions will result in very poor and misleading estimates of project performance and impact.

Presently, little is known of the abundance, size, density, and durability of fine sediment aggregates that are either eroded from the bed or placed onto the bed in the form of dredged material. Research is required to develop a fundamental understanding of the properties and processes influencing the rate at which dense, fine-sediment aggregates are mobilized from the bed, break up, and consequently change the sediment transport potential of these sediments. With this improved knowledge, methods and parameters for aggregate transport can be developed and implemented into existing numerical models.

Currently, the DOER program is conducting research at the U.S. Army Engineer Research and Development Center, Coastal Hydraulics Laboratory (ERDC-CHL), that is focused on characterizing physical properties (abundance, size, density, settling velocity, etc.) of fine-grained aggregates upon erosion from the bed. Additionally, research is being conducted to assess the durability and transport processes of these aggregates following initial mobilization. Through collaboration with the Norfolk District (NAO), this research will also consist of a field component in the James River, where impacts of fine sediment aggregates will be evaluated in terms of channel infilling and the transport of placed dredged material.

**METHOD:** To familiarize the reader with previous studies that have examined the presence, provenance, and physical properties of mud aggregates, this CHETN will briefly present prior research describing observations of mud aggregates in both the geologic record and modern depositional environments. In addition, prior studies that evaluated fine aggregate properties in a laboratory setting will also be presented. Then, to demonstrate how these fine aggregates can significantly impact predicted sediment transport processes, a simulated case study will be presented that compares aggregated and disaggregated transport behaviors within the James River, Virginia. The findings from previous research, along with results from the simulated case study will then be

summarized and presented to highlight the potential importance of fine aggregate processes in USACE sediment management projects.

**PRIOR RESEARCH:** Robust clay aggregates have been described in the geological record, and geomorphologists have executed limited laboratory research to understand the conditions under which aggregates were preserved in the lithological record. The acknowledgement of aggregate transport processes and impact on morphology is sparse in the engineering and sediment transport literature.

**Field-Based Aggregate Observations.** Numerous studies within the geologic scientific literature report the presence of mud aggregates both preserved in the lithological record and in modern deposits across a wide variety of environments, including fluvial, lacustrine<sup>1</sup>, and coastal (e.g., Karcz 1972; Little 1982; Rust and Nanson 1989; Wright and Marriott 2007; Fettweis et al. 2009; Plint et al. 2012; Gastaldo 2013). The size of these clasts vary with environments of formation and deposition, but documented from several centimeters down to 10s–100s of micrometers in diameter (Figure 1). Natural factors involved in the formation of mud aggregates include regional soil type, mineralogy, organic matter, and availability of cementation solutes (Gastaldo 2013). A recent study investigating sedimentation processes in Cochiti Lake, New Mexico (a USACE-managed reservoir) found that the muddy bottom sediment largely existed in aggregate form (Figure 1D)<sup>1</sup>. These aggregates were believed to be sourced from local soils and mobilized from the surrounding hillsides. Erosion testing showed that these aggregates were remobilized as discrete clasts and had not been compacted or consolidated into a uniform cohesive bed. This suggests that aggregates of fine material can have sufficient durability to persist through multiple cycles of erosion and deposition following initial formation.

In addition to natural formation, mud aggregates have been found to result from anthropogenic processes such as dredging. Studies investigating sediments associated with dredged material plumes and disposal mounds have indicated that the mechanical forces used to break apart a consolidated cohesive bed do not completely disaggregate the sediment but instead generate mud aggregates (Fettweis et al. 2009; Smith and Friedrichs 2011). Figure 1C shows mud pebbles that were observed at a dredged material disposal site along the Belgium coast (Fettweis et al. 2009). Additionally, Smith and Friedrichs (2011) sampled sediment plumes resulting from dredging operations conducted in San Francisco Bay. They found that approximately one-third of the particles within the plumes were bed aggregates with densities that ranged from 1.2 to 1.8 grams (g)/cm<sup>-3</sup> and diameters ranging from 40 to 250 µm.

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<sup>1</sup> Smith, S. J., and G. Norwood. In Preparation *Physical Processes of Fine-Grained, Cohesive Sediment at Cochiti Lake, New Mexico*. U.S. Army Corps of Engineers Technical Report

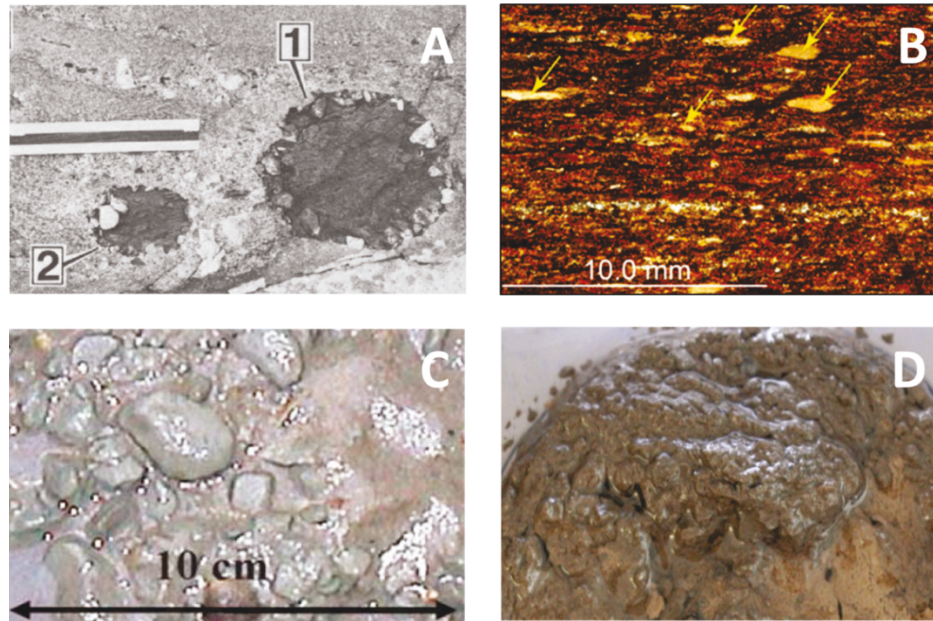


Figure 1. Photographs of mud aggregates. (A) Centimeter-sized aggregates preserved in sandstone in Connecticut (Little 1982). (B) Millimeter-sized elongated mud aggregates preserved within a mud stone indicated by yellow arrows (Plint et al. 2012). (C) Centimeter-sized aggregates on the surface of a box core collected near a dredge disposal mound along the Belgian coast (Fettweis et al. 2009). (D) Surface of a 10-centimeter (cm) diameter core taken from Cochiti Lake, New Mexico. Surface is composed largely of mud aggregates of varying size.

**Laboratory-Based Aggregate Observations.** Because mud aggregates have been commonly observed in both the lithological record and modern deposits, laboratory research into the processes involved with mud aggregate transport has been ongoing for decades. A study published in 1972 by Smith (Smith 1972) sought to examine the durability and morphological evolution of constructed mud aggregates as they were mobilized in a flume (Figure 2A). The study concluded that test clasts with higher mud and moisture contents were the most durable but that the large angular aggregates used in the study deteriorated rapidly (15–60 minutes) and only had potential transport distances on the order of 10s–100s of meters (Figure 2B).

Recently, studies have been conducted that have allowed for observation of more naturally generated aggregates that are resultant of flow being introduced over cohesive sediment beds in various flumes (Jepsen et al. 2010; Schieber et al. 2010). These studies noted that aggregate durability was greater with higher mud content and that aggregates were transported in both suspension and bedload, depending upon flume conditions. In contrast to the Smith (1972) study, Schieber et al. (2010) also observed that some aggregates persisted within their flume for periods greater than 24 hours, suggesting that transport distances on the order of kilometers were indeed possible under the right conditions.

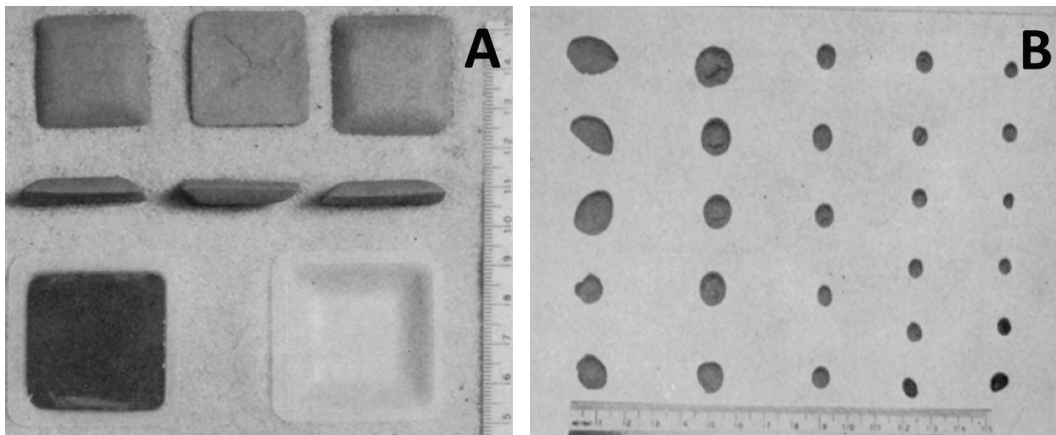


Figure 2. Images taken from Smith (1972) showing the size, shape, and construction of the test aggregates (A) and recovered aggregates after transport in flume for 60 minutes in flow velocities of 60 cm/second (B).

**SIMULATED CASE STUDY:** The potential impact of aggregation on the transport processes of fine sediment may best be demonstrated through calculations made with common sediment transport relationships that utilize measured, observed, and modeled data from a real-world environment. This section of the report presents the results of such an exercise that was performed to evaluate potential aggregate transport processes within a reach of the James River, Virginia, where channel maintenance dredging is routinely performed.

The James River federal navigation channel is approximately 90 miles in length and runs from the Chesapeake Bay to Richmond, VA. To better understand the fate of dredged sediments placed in channel adjacent disposal areas, NAO and ERDC have been working together on numerical modeling studies to simulate the transport of sediment resuspended during dredging operations and following placement at the Dancing Point-Swann Point placement site (Figure 3). Initial results of this modeling showed that placement material was not migrating back into the adjacent channel; however, current models do not include algorithms to account for fine sediment aggregate transport process.

To illustrate potential impacts of aggregation on fine sediment transport within the James River, depth-averaged hydrodynamic model data obtained from the Coastal Hydrodynamics three-dimensional (CH3D) model were utilized to estimate theoretical transport thresholds and modes of sediment transport within the Dancing Point-Swann Point study site, indicated with the yellow shaded polygon in Figure 3. These data simulate flow conditions in the river from a time period of 1–9 April 2000.

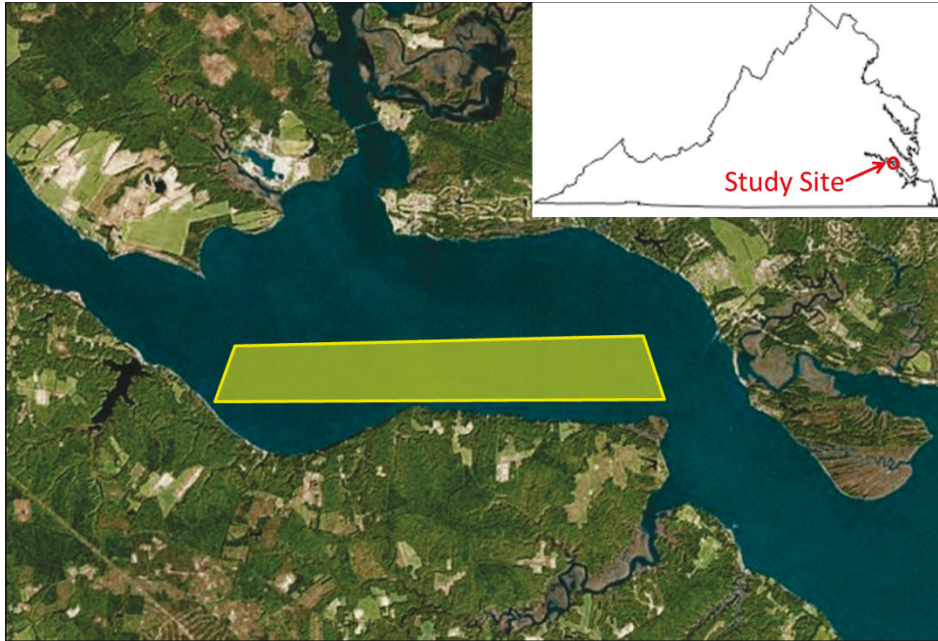


Figure 3. Map of the Dancing Point–Swann Point region of the James River. The yellow shaded region indicates the approximate location of the federally maintained navigation channel and adjacent dredge material placement areas.

Grain size data describing the sediment in the project area were obtained from a prior study (Moncure and Nichols 1968). This study found that the regional river bed was predominantly composed of mud-sized (<63  $\mu\text{m}$ ) sediments. This fine sediment bed was therefore assumed to behave cohesively. As previously discussed, erosion of cohesive beds often results in the formation of aggregates that can then be transported as discrete clasts. Transport of these discrete clasts was estimated by well-established relationships for transport of discrete sediment particles. The threshold of sediment motion (following initial cohesive erosion) was determined by the Shields (1936) criterion. The particle settling velocity was determined from the modified Stokes particle settling relationship,

$$w_s = \frac{gd^2}{18\mu} \frac{(\rho_p - \rho)}{(1 + 0.15Re_p^{0.687})}$$

where  $g$  is gravitational acceleration,  $d$  is particle diameter,  $Re_p = w_s d/\nu$ ,  $\rho_p$  is the particle density, and  $\rho$ ,  $\mu$ , and  $\nu$  are the fluid density, dynamic viscosity, and kinematic viscosity, respectively. Transport modes were inferred from the balance of gravitational settling and turbulent mixing, as expressed by the dimensionless Rouse number,  $p = w_s/\kappa u_*$ , where  $\kappa$  is the von Karman constant (taken as 0.4) and  $u_*$  is the shear velocity. For  $p \leq 0.25$ , sediment particles are maintained in suspension by turbulence. For  $p > 0.25$ , transporting particles have some bed interaction (intermittent suspension and bedload) and are described in this study as bedload. Particle size in the simulation ranged from 4  $\mu\text{m}$  to 63  $\mu\text{m}$  for disaggregated mineral particles with a density of 2.65/cm<sup>3</sup>. Bed aggregates ranged in size from 50  $\mu\text{m}$  to 10,000  $\mu\text{m}$  with a density of 1.5 g/cm<sup>3</sup>, a value representative of a moderately consolidated sediment bed.

Figure 4 presents the fraction of simulation time that particles of a particular size and aggregation state were either actively transported in bedload or suspension or were immobile on the bed. Figure 4A depicts transport behavior of disaggregated particles. These sediments are shown to be transported in suspension, with only coarser silts having limited periods of immobility for less than 20% of the model simulation. By comparison, Figure 4B presents transport behavior that would be expected for aggregated mud clasts. Mud aggregates in the 63  $\mu\text{m}$ –125  $\mu\text{m}$  size range are transported in suspension more than 80% of the time. This is similar to the transport mode results of the disaggregated mud particles. However, for aggregate sizes greater than 125  $\mu\text{m}$ , transport behavior significantly deviates from that of disaggregated particles. Bed aggregates larger than 300  $\mu\text{m}$  were no longer able to be kept in suspension and were limited to either bedload transport or were immobile. Mud clasts larger than 3,000  $\mu\text{m}$  were found to be immobile throughout the duration of the simulation.

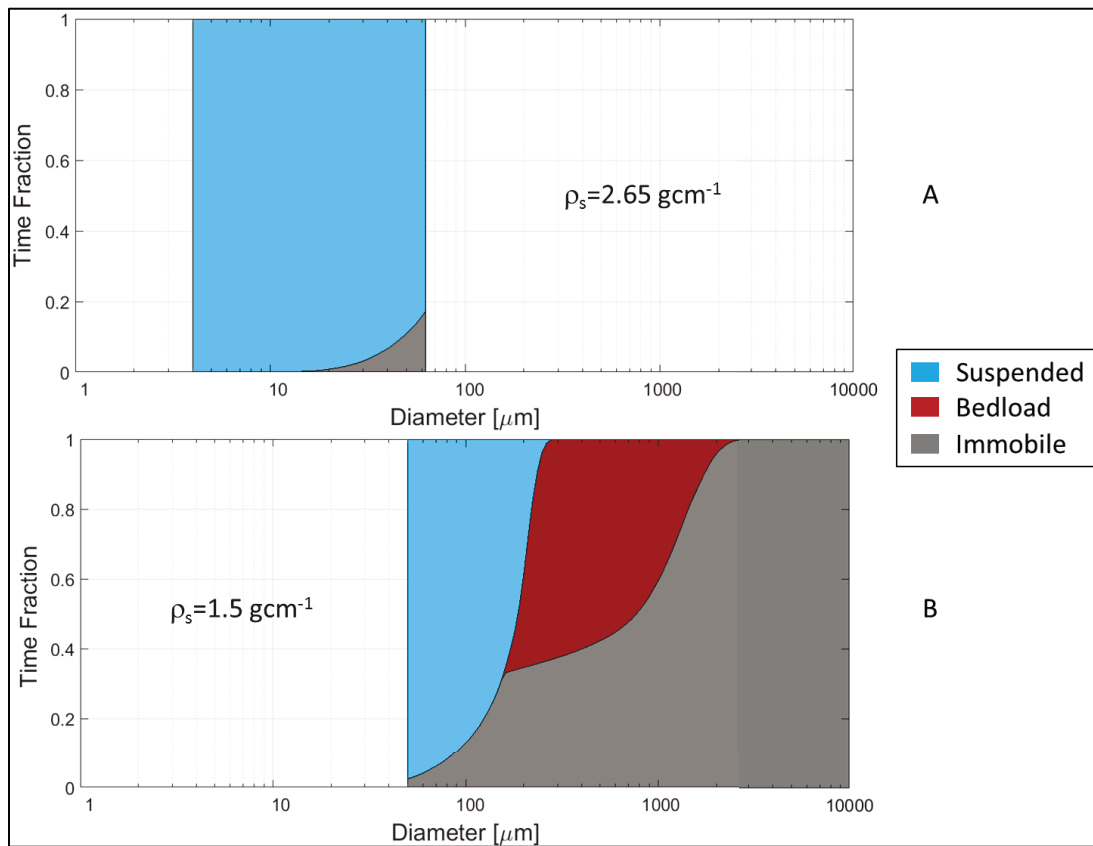


Figure 4. Estimates of transport mode by particle size for muddy sediments at Dancing Point–Swann Point for primary mineral (A) and mud aggregate (B) particles.

These results indicate that the transport characteristics of eroded mud clasts are significantly different from the transport characteristics of their disaggregated constituent particles. Since mud aggregates spanning a similar size range have been observed at other dredging related sites (Fettweis et al. 2009; Smith and Friedrichs 2011), it is likely that these mud aggregates are often present in significant quantities. Hence, an understanding of the transport behavior of these aggregates is crucial to developing reliable models of cohesive sediment transport processes for use in the evaluation of the performance of USACE projects.

The processes and sediment characteristics that influence the initiation and durability of eroded bed clasts is presently poorly understood. To help ameliorate this knowledge deficit, research is presently being conducted by the authors to examine the first-order processes related to initiation and durability of eroded aggregates.

**SUMMARY:** Whether naturally formed or as the result of dredging operations, the presence of mud aggregates can impact transport processes of fine sediment. Past research has shown the occurrence of aggregates of fine-grained material to be common in many environments. While initial research suggested that mud aggregates lacked sufficient durability to survive transport on scales significantly larger than 10s–100s of meters (Smith 1972), more recent evidence indicates that transport distances on the order of kilometers are possible (Schieber et al. 2010). As demonstrated in the simulation at the Dancing Point–Swann Point area, both the mobility and transport modes of muddy sediment are significantly influenced by the aggregation state of the particles.

In the simulation, particle size and density not only impacted how frequently sediment was mobile but also the mode in which it was transported. Aggregates smaller than 125  $\mu\text{m}$  were predicted to be mobilized directly into suspended load. This fact offers a likely explanation for the commonly held assumption that fine sediment should always be modeled as suspended load. However, prior studies have observed aggregates ranging in size from 10s of micrometers to 10s of centimeters. The bedload transport of larger aggregates of fine sediment was not only predicted to be quite common in the simulation presented but has also been observed in flume experiments (Jepsen et al. 2010; Schieber et al. 2010). While frequent contact with the bed would likely aid in breaking large aggregates apart, the rate of this decay is presently unknown but would likely depend upon flow, aggregate, and sediment bed conditions. Further, the decay of mud pebbles would likely produce multiple intermediate-sized aggregates. These aggregates may be transported in suspension more frequently, resulting in less contact with an abrasive bottom and potentially greater transport distances.

Ultimately, the differences between the observed transport pathways of disaggregated vs. aggregated particles, together with the tendency for models to only address the disaggregated transport pathways, could result in disparate predicted deposition locations from those observed in nature. For these reasons, it is important that research be conducted to gain better understanding of bed aggregate formation and durability. Recently, erosion testing of sediments from the Dancing Point–Swann Point placement area, as well as other regions of the James River, was performed. This testing included characterization of eroded aggregate size, density, and durability with the goal of inputting these parameters into sediment transport models. With better representation of these physical properties, more accurate predictions of transport processes may result. These more accurate predictions will aid project engineers in making more informed management decisions. While initial studies are occurring on the James River, the goal of this work is to demonstrate the potential importance of aggregate processes in similar locations across the country.

**ADDITIONAL INFORMATION:** This Coastal and Hydraulics Engineering Technical Note (CHETN) was prepared by David Perkey ([David.Perkey@usace.army.mil](mailto:David.Perkey@usace.army.mil)) and Jarrell Smith ([Jarrell.Smith@usace.army.mil](mailto:Jarrell.Smith@usace.army.mil)), U.S. Army Engineer Research and Development Center. The study is funded by the USACE Dredging Operations and Environmental Research Program. This technical note should be cited as follows:

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## REFERENCES

- Barry, K. M., R. J. Thieke, and A. J. Mehta. 2006. "Quasi-Hydrodynamic Lubrication Effect of Clay Particles on Sand Grain Erosion." *Estuarine, Coastal and Shelf Science* 67(1): 161–169.
- Beck, T. M., J. D. Rosati, and J. Rosati. 2012. *An Update on Nearshore Berms in the Corps of Engineers : Recent Projects and Future Needs*. ERDC/CHL CHETN-XIV-10. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Bolam, S. G., and P. Whomersley. 2005. "Development of Macrofaunal Communities on Dredged Material Used for Mudflat Enhancement: A Comparison of Three Beneficial Use Schemes after One Year." *Mar. Pollut. Bull.* 50: 40–47. <https://doi.org/10.1016/j.marpolbul.2004.08.006>.
- Croft, A. L., L. A. Leonard, T. D. Alphin, L. B. Cahoon, and M. H. Posey. 2006. "The Effects of Thin Layer Sand Renourishment on Tidal Marsh Processes: Masonboro Island, North Carolina." *Estuaries and Coasts* 29: 737–750.
- Erwin, R. M., J. Miller, and J. G. Reese. 2007. "Poplar Island Environmental Restoration Project: Challenges in Waterbird Restoration on an Island in Chesapeake Bay." *Ecol. Restor.* 25: 256–262. doi:10.3368/er.25.4.256.
- Fettweis, M., J. S. Houziaux, I. Du Four, V. Van Lancker, C. Baeteman, M. Mathys, D. Van den Eynde, F. Francken, and S. Wartel. 2009. "Long-Term Influence of Maritime Access Works on the Distribution of Cohesive Sediments: Analysis of Historical and Recent Data from the Belgian Nearshore Area (Southern North Sea)." *Geo-Marine Letters* 29(5): 321–330.
- Gastaldo, R. A., B. A. Pludow, and J. Neveling. 2013. "Mud Aggregates from the Katberg Formation, South Africa: Additional Evidence for Early Triassic Degradational Landscapes." *Journal of Sedimentary Research* 83(7): 531–540.
- Jacobs, W., P. Le Hir, W. Van Kesteren, and P. Cann. 2011. "Erosion Threshold of Sand-Mud Mixtures." *Cont. Shelf Res.* 31(S14–S25). doi:10.1016/j.csr.2010.05.012.
- Jepsen, R., J. Roberts, and J. Gailani. 2010. "Effects of Bed Load and Suspended Load on Separation of Sands and Fines in Mixed Sediment." *J. Waterw. Port, Coast. Ocean Eng.* 319–326. [https://doi.org/10.1061/\(ASCE\)WW.1943-5460.0000054](https://doi.org/10.1061/(ASCE)WW.1943-5460.0000054).
- Karcz, I. 1972. "Sedimentary Structures Formed by Flash Floods in Southern Israel." *Sedimentary Geology* 7(3): 161–182.
- Little, R. D. 1982. "Lithified Armored Mud Balls of the Lower Jurassic Turners Falls Sandstone, North-Central Massachusetts." *The Journal of Geology* 90(2): 203–207.
- Mehta, A. J., E. J. Hayter, W. R. Parker, R. B. Krone, and A. M. Teeter. 1989. "Cohesive Sediment Transport. I: Process Description." *J. Hydraulic Eng.* 115(8): 1076–1093.
- Mitchener, H., and H. Torfs. 1996. "Erosion of Mud/Sand Mixtures." *Coast. Eng.* 29: 1–25.
- Moncure, R., and M. Nichols. 1968. *Characteristics of Sediments in the James River Estuary, Virginia*. Special Scientific Report (Virginia Institute of Marine Science) No. 53. Virginia Institute of Marine Science, College of William and Mary.
- Plint, A. G., J. H. S. Macquaker, and B. L. Varban. 2012. "Bedload Transport of Mud across a Wide, Storm-Influenced Ramp: Cenomanian–Turonian Kaskapau Formation, Western Canada Foreland Basin." *J. Sediment. Res.* 82: 801–822. <https://doi.org/10.2110/jsr.2012.64>.
- Rust, B. R., and G. C. Nanson. 1989. "Bedload Transport of Mud as Pedogenic Aggregates in Modern and Ancient Rivers." *Sedimentology* 36(2): 291–306.

- Schieber, J., J. B. Southard, and A. Schimmelmann. 2010. "Lenticular Shale Fabrics Resulting from Intermittent Erosion of Water-Rich Muds— Interpreting the Rock Record in the Light of Recent Flume Experiments." *J. Sediment. Res.* 80: 119–128. <https://doi.org/10.2110/jsr.2010.005>.
- Shields, A. 1936. *Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebepbewegung*. PhD Thesis, Technical University Berlin.
- Smith, N. D. 1972. "Flume Experiments on the Durability of Mudclasts." *SEPM Journal of Sedimentary Research* 42: 378–383.
- Smith, S. J., and C. T. Friedrichs. 2011. "Size and Settling Velocities of Cohesive Floes and Suspended Sediment Aggregates in a Trailing Suction Hopper Dredge Plume." *Cont. Shelf Res.* doi:10.1016/j.csr.2010.04.002.
- Soulsby, R. 1997. *Dynamics of Marine Sands: A Manual for Practical Applications*. Thomas Telford.
- U.S. Army Corps of Engineers (USACE). 2016. *The U.S. Waterway System: Transportation Facts & Information*. <http://www.navigationdatacenter.us/factcard/FactCard2016v.pdf>.
- Van Ledden, M., W. G. M. Van Kesteren, and J. C. Winterwerp. 2004. "A Conceptual Framework for the Erosion Behaviour of Sand-Mud Mixtures." *Cont. Shelf Res.* 24: 1–11. <https://doi.org/10.1016/j.csr.2003.09.002>.
- Weinstein, M. P., and L. L. Weishar. 2002. "Beneficial Use of Dredged Material to Enhance the Restoration Trajectories of Formerly Diked Lands." *Ecol. Eng.* 19: 187–201. [https://doi.org/10.1016/S0925-8574\(02\)00077-0](https://doi.org/10.1016/S0925-8574(02)00077-0).
- Wright, V. P., and S. B. Marriott. 2007. "The Dangers of Taking Mud for granted: Lessons from Lower Old Red Sandstone Dryland River Systems of South Wales." *Sediment. Geol.* <https://doi.org/10.1016/j.sedgeo.2006.03.028>.
- Yozzo, D. J., P. Wilber, and R. J. Will. 2004. "Beneficial Use of Dredged Material for Habitat Creation, Enhancement, and Restoration in New York-New Jersey Harbor." *J. Environ. Manage.* 73: 39–52. <https://doi.org/10.1016/j.jenvman.2004.05.008>.

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