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Characterizing Sediment Physical Property Variability for Bench Scale Dewatering Purposes

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Abstract

A field sampling program was undertaken to assess the variability of physical characteristics of contaminated sediments in a large (160 ha) effluent stabilization lagoon. The objective of this paper is to use this "field lab" as a basis for comparing different sampling techniques (i.e. discrete and composite) for remediation-based evaluations (i.e. sediment volume estimates and bench scale dewatering studies). The distribution of sediment thickness measured throughout the lagoon by gravity core sampling is presented for context. Selected gravity core sediment samples are evaluated with respect to physical property (water/solids content, bulk density, and particle size) variability in both the vertical (i.e. within a single gravity core) and spatial directions (among gravity cores). Composite samples created via homogenization of a single entire gravity core is performed to compare to the discrete and average physical properties of a nearby gravity core. Vacuum-based samples are also compared to gravity core samples in terms of particle size. It is demonstrated that by understanding sediment variability, composite samples can be shown to be an efficient method of obtaining representative samples. When large samples for dewatering trials are required, vacuum sampling can produce samples with similar mean particles size to discrete and composite samples.

Keywords chosen from ICE Publishing List

Contaminated material; Geotechnical engineering; Waste management & disposal

List of notations

None

Introduction

The Boat Harbour Stabilization Lagoon (BHSL) is part of an industrial wastewater treatment facility (160 ha in plan area, Tackley, 2019) located in Pictou County, Nova Scotia, Canada. This lagoon was originally a tidal estuary until it was separated from the Atlantic Ocean (i.e. Northumberland Strait) via modifications introduced by the provincial government in 1967 (Hoffman et al., 2019). These modifications were completed in order to transition the estuary into a wastewater treatment facility for predominately pulp and paper process effluent, although other industrial operations are also known to have contributed to the wastewater effluent since 1967 (Hoffman et al., 2019). During operation, up to 75,000 m^3 of wastewater was discharged to the treatment facility daily (GHD, 2018). Over 50 years of operation have resulted in the accumulation of a thin layer of organic-rich, black sediment in the BHSL (GHD, 2018). This black sediment, which is underlain by a native grey marine sediment, contains a mix of inorganic and organic contaminants (i.e. metal[loid]s, polycyclic aromatic hydrocarbons [PAHs], dioxins and furans) present above regulatory limits (Hoffman et al., 2017; Hoffman et al., 2019). BHSL has been effectively closed since January 2020; remediation to its pre-industrial state is underway (i.e. a tidally influenced estuary). It is anticipated that dredging of the BHSL will result in the dewatering of greater than 577,000 m^3 of unconsolidated sediment followed by storage in a secure containment cell (GHD, 2018). This site serves as an opportunity to compare different sediment sampling methodologies for remediation purposes, such as those explored in this paper.

Given that sediment properties are site and location specific, it is critical before establishing a dewatering/remediation approach that effective sampling protocols be developed to ensure representative samples are obtained. This is true for bench scale dewatering trials as well as estimating required volumes for future sediment containment structures. Sediment characteristics such as solids content, particle size distribution, and density must be established to prepare a basis for an effective sediment management plan (Reis et al., 2007). Past studies have also identified the need for assessing sediment properties prior to remediation efforts (e.g. Mao, 1997; Ya, 2017) as physical and chemical properties of sediment deposits in aquatic ecosystems may vary spatially (Reis et al., 2007).

Understanding the variability in sediment composition is particularly important when considering bench scale dewatering studies and sediment volume estimations, as these studies often require the use of large sample volumes from a given depth and location to represent the contaminated sediment throughout a large sampling area. The BHSL is an excellent “field lab” to assess how different sampling methods influence the determination of sediment physical characteristics; the large areal extent and potentially highly variable characteristics with depth at BHSL are typical of other contaminated waste ponds. The objectives of this paper are: 1) to present a method of comparing time-consuming discrete sampling techniques to more time-efficient composite sample techniques. This is particularly relevant for volume estimates of contaminated sediments, and, 2) to present a method of comparing composite sampling techniques to a vacuum sampling technique developed for this project. The vacuum sampling method produces large volumes of sediment for bench scale dewatering purposes but involves significant physical disturbance of the sample. To investigate these objectives, the distribution of sediment thickness measured throughout the lagoon by gravity core sampling is presented; extrusion of these gravity core samples are then performed to evaluate sediment physical properties in both the vertical (i.e. within a single gravity core) and spatial directions (between gravity cores) and provide context for the sediment’s variability. Composite samples are created by homogenization of single entire gravity cores to compare to the discrete subsamples and average discrete subsample physical properties (i.e. water/solids content, bulk density, and particle size) of a nearby gravity core and also provide some comparison to vacuum samples. Vacuum-based samples are compared to gravity core samples (both discrete and composite) in terms of particle size (i.e. a key physical parameter for dewatering).

2. Experimental Work

2.1 Sediment sampling

Figure 1 shows sampling locations (i.e. gravity core and vacuum samples) throughout the BHSL, taken over a four-year period (i.e. 2016-2019). Area A was isolated from the remainder of the BHSL in March 2017 by an earthen berm (shown in Figure 1) for pilot dewatering studies (GHD, 2018). The rest of the lagoon, which was receiving effluent at the time of sampling, has been subdivided into three regions (Area B, C, and D) in this study to assess the variability of sediment characteristics throughout the BHSL.

The majority of samples (151 cores in total) were obtained using a gravity corer (60 cm in length and 6.5 cm in diameter) (Glew et al., 2001). The device was ideal for this site, as much of the contaminated sediment was shallower than the core length. This coring method has been shown to be reliable for taking core samples sufficient for precise paleolimnology work (Dunnington et al., 2017). The device consisted of a collar, which secured the core barrel, and a spring release mechanism. The weight of the device, when secured to the core barrel, allowed it to easily penetrate the sediment (see Figure S1). During the core penetration, the top of the core barrel remained open until a weighted messenger was lowered to trigger the device. At this time, the spring mechanism was activated, and suction was maintained in the core barrel with a rubber stopper until the sample was brought to the surface. Upon recovery, the sample was then sealed at each end for transport. The method is simple, inexpensive, and does not require supplementary mechanical assistance (i.e. a winch).

151 cores were used for thickness determination to assess variability throughout BHSL. A spatial analysis of the thickness distribution in the BHSL was conducted using the ArcGIS (10.5) “Topo to Raster” interpolation method for “lake polygons”. This method is specifically designed to analyze contour and elevation inputs (Esri, 2019) and can be constrained to the limit of a given polygon (BHSL in this case). The interpolation used a 1 m x 1 m cell length (resolution), with contour lines representing each 5 cm change in thickness. The map presents a realistic interpretation of the sediment thickness, based on the data which was available at the time of publication (additional data points may alter this interpolation). This information is presented to provide an indication of the distribution of sediment throughout the BSHL.

In addition, 30 of the 151 sediment cores were selected for detailed physical testing (i.e. beyond sediment thickness determination) and were transported to Dalhousie University laboratories for analysis. Nineteen (19) of these cores were used to obtain vertically discrete samples (described in detail below), and the remaining 11 were used for depth integrated composite samples. Variability in physical properties (i.e. particle size, water / solids content) at different depths (vertically) were investigated using discrete vertical samples. Sample 19-01 was selected for discrete particle size analyses. To obtain these discrete samples, sediment in the core was sampled at 5cm intervals using an extruder (Glew et al., 2001). As can be seen in Figure S2, the extruder apparatus consisted of an aluminum rod (shaft) connected to a base and situated vertically. An extruding disk that was slightly smaller than the core barrel diameter was placed at the top of the rod. A core holder (collar) was situated below the extruding disk, which allowed for an accurate and controlled descent of the core barrel. After carefully removing the rubber stopper at the bottom of core barrel, the core barrel was mounted on top of the extruding disk. The top rubber stopper was then removed from the core barrel and a sampling stage was attached to the top of the barrel. The core barrel was moved downward to remove the top water until the top of the sediment was even with the sampling stage. A series of spacer plates (5cm aluminum cuboids) were placed on the adjuster disc, which was situated on the shaft, below the collar. The adjuster disc was carefully moved upward until the top of the aluminum cubes touched the bottom of the core holder, then was secured in place. At this time, one of the aluminum cuboids was removed, and the core barrel gently pulled downward to extrude 5 cm of sediment from the barrel. Each extruded sample was then removed from the sampling stage into pre-labeled sample bags (showing core ID, depth and date), weighed, and refrigerated at 4°C until further analysis. Although each increment was 5 cm, smaller increments were used to section the 5 cm increment near the black / grey sediment interface. After weighing each 5 cm sediment interval, the center portion of each interval was isolated for further analysis, while the surrounding sediment was trimmed and discarded to avoid portions which may have been smeared due to the sampling tube penetration.

In addition to discrete samples, 11 individual cores were homogenized to create a composite sample that simulates the mixing of the sediment that will occur during a dredging process. Composite samples were also used to compare to sediment properties at each discrete sampling location (spatially) throughout the BHSL. For each composite sample, the total thickness of sediment in one core was mixed, weighed, and then stored in sterile containers at 4°C. At the time of analysis of the composite specimens, sediments in the container were mixed thoroughly, homogenized, and a representative sample from each composite sample was selected for water / solids content, density and particle size analyses. All 11 composite samples were then evaluated for mean and variation range values of each of these physical properties.

A vacuum sampling method was used to simulate sediment sampling conditions which could arise during a dredging procedure. A barge of 4.5 m × 2 m was constructed from high density polyethylene (HDPE) pipe (sealed) to form the support for the wooden platform decking. The barge and sampling gear were then towed by a boat to the desired sampling location. Anchors were used to fix barge in position while sampling was performed. A gas-powered generator was used to power an electric submersible vacuum pump (560-watt stainless steel sewage pump), which in turn was used to recover the sediment. The pump was hand-lowered into the water, to the surface of the sediment, via a rope secured to the pump. Upon engagement of the pump, the sediment was drawn through a 50 mm diameter tube, 3 m in length, to the surface of the barge and placed in a 20L container (see Figure S3). The pump was situated at various locations on the basin bottom in order to obtain eight 20 L containers of the sediment, which were then transported to Dalhousie University in Halifax, Canada for characterization tests. Vacuum sampling results in a significantly disturbed sample with added water being entrained in the vacuum process.

2.2 Physical analysis

Physical characteristics of the black sediment were evaluated at Dalhousie University laboratories. The water / solids content (relevant ASTM standard D2216, last revised 2019), bulk density, specific gravity (ASTM D854, 2014), organic material (ASTM D2974, 2020), and particle size were measured for selected samples (i.e. discrete and composite cores). Each measurement was repeated three times for all experiments. Water / solids content and density measurements are important for remediation projects utilizing containment approaches for volume estimates of remediation projects while particle size analyses are useful when developing dewatering approaches. Specific gravity and organic carbon determinations were used for characterization purposes only.

Particle size distributions of the sediment were evaluated using a micro flow imaging technique (MFI-DPA4100/4200-Series B) (Mackie, 2010), which counts particle sizes from 2 to 400 µm. In this technique, 1 ml of sample fluid (1% dilution by volume was used for all of the samples in this study) was captured in successive image frames as the sample stream passed through a flow cell. Frame images displayed during operation provided immediate visual feedback on the nature of the particle population in the sample.

Images were also digitally analyzed using the software to compile a database containing count, size, and concentration, and to produce parameter distributions using histograms and scatter plots (Sharma et al., 2010).

2.3 Statistical analysis

A statistical analysis was performed for the physical test date collected. The mean physical properties obtained for discrete, composite, vacuum samples as well as area groupings were compared using Tukey's comparison test of one-way analysis of variance (ANOVA) in Minitab. ANOVA is used to determine whether the mean of two or more groups differ, and Tukey's method is used to formally test whether the difference between a pair of groups is statistically significant. Tukey's method also provides a range of values showing the confidence interval for the difference between the means for each pair of groups. If this range does not include zero, it means that the difference between these means is significant (Minitab express support, 2019).

3. Results and Discussion

As previously mentioned, the black sediment layer in the BHSL consisted mostly of solids accumulated from predominantly pulp and paper treated wastewater since the 1960s. Results from organic material testing showed the solid portion of black sediment contained 25% - 31% organic carbon with a specific gravity of 1.71 (± 0.13 SD).

For context of the distribution of sediment thickness throughout the BHSL, Figure 2 presents the frequency distribution of black sediment thicknesses measured in the 151 gravity core samples. For example, a 35 cm thickness of black sediment was measured in 16 samples." An average thickness of 26.6 cm (±12.2 SD) was measured in black sediment. The maximum thickness of approximately 45 cm for the black sediment was identified in core samples of BH 17-34, BH 17-33, and BH 19-82-100.

A contour map of the spatial distribution of sediment thickness determined using the methods previously described is presented in Figure 3. The results show the black sediment was not evenly distributed across the BHSL; sediment thickness is greatest in Area B (west side of BHSL, near the location of cores BH 17-34 and BH 17-33). A bathymetric survey indicates that this location is the deepest part of the basin (Spooner and Dunnington 2016). The thicker sediment in this location is likely due to its proximity to the effluent inflow point (Figure 3), and with increasing distance from that point (notably in Areas C and D), the thickness decreases.

To examine the influence of this varying distribution of sediment on its physical properties, Figure 4 shows both water and solids content, versus depth for the 19 discrete gravity core samples. Results are plotted relative to distance from the black / grey interface (dotted line). Due the large amount of data (shown in Figure 4S), data has been presented in term of mean and one standard deviation from the mean for each depth. The focus of this study was the black sediment characterization, however, grey sediment properties (water / solids content) were also evaluated in selected cores and are shown for reference. Results show that discrete samples, regardless of location, show a similar water / solids content trend. As expected, water content decreased with depth (Figure 4(a)), as self-weight consolidation of settled particles occurred. In this study, the black sediment exhibited high water contents (max 3200%) near the surface (0-5 cm) which decreased to around 500% at the black / grey sediment interface.

Water /solid content and density are key parameters to understand for remediation projects involving containment cells of dredged sediments. The self-weight consolidation process also resulted in the solids content increasing with depth from an average of 2% at the water / black sediment interface to around 12% at the black / grey sediment interface (Figure 4(b)). Likewise, the density of the black sediment increased with depth, increasing from 1.01 g/cm^3 near the surface (0-5cm) to 1.17 g/cm^3 at 45 cm below the black sediment-water contact (as presented in Table 1 and Figure S5). The density of composite samples, however, was 1.07 g/cm^3, which was close to the average density of discrete samples (1.10 g/cm^3).

Table 1. Density values of discrete and composite samples.

Depth (cm)	Density (g/cm^3) Mean + SD
0-5	1.01 ± 0.13
5-10	1.06 ± 0.03
10-15	1.08 ± 0.04
15-20	1.07 ± 0.04
20-25	1.18 ± 0.21
25-30	1.13 ± 0.08
30-35	1.10 ± 0.02
35-40	1.11 ± 0.02
40-45	1.17 ± 0.07
Average of discrete samples	1.10 ± 0.05
Composite samples	1.07 ± 0.05

Box-whisker plots (Figure 5(a) & 5(b)) present the range of water / solids content of black sediments for the cores used to create discrete and composite samples, as well as samples taken using the vacuum pump. For individual discrete samples, the plot represents data taken vertically in the core, while for composite samples, the plot represents the data analysis of a combination of all composite samples. For comparison, the data analysis of all discrete samples for each of the four areas (A, B, C, and D) are also shown. The box-whisker plot is a standard technique for presenting a 5-number summary of a dataset which consists of the minimum and maximum range values, the upper and lower quartiles, and the median (the line that divides the box into two parts). In the box plot, an outlier is an observation that is numerically distant from the rest of the data and is defined as a data point that is located outside the whiskers of the box plot. This collection of values is an effective way to summarize the distribution of a dataset (Williamson et al., 1989). In Figure 5, boxes with the same pattern show the cores taken from the same area, while grey colored boxes represent the data analysis for the collection of discrete samples from the given area. The solid black boxes represent the vacuum samples taken from Area A and B, and the solid white box shows the dataset of composite samples.

One-way ANOVA test results (using the Tukey method with 95% confidence) indicated that there was no significant difference between water / solids content of different cores representing discrete samples throughout the BHSL. In this study, Tukey's results are shown with the letters on the graphs. In Figure 5, samples attributed with identical letters are not significantly different.

As presented in Figure 5, an average water content and solids content of 957% and 9% respectively was obtained for the composite samples (over the entire depth of black sediment in a given core). These values are statistically similar to the average water / solids content of discrete samples, suggesting that composite sampling can be an acceptable method of identifying the properties of discrete samples for this site. This result is important for sediment volume estimates, as composite samples can yield higher volumes and are more readily gathered when compared to discrete samples; as a result composite samples were used for other dewatering studies by the authors (e.g. Alimohammadi et al. 2019). The locations from which the gravity core samples were taken were thought to effectively represent the entire basin. Average percent water content (corresponding solids contents are shown in brackets) were measured for Areas A, B, C, and D respectively, as follows: 1052%(11.5%), 1150%(10.3%), 1188%(8.9%), and 1153%(11.9%).Statistical analysis of this data showed no significant difference between discrete, composite or area samples. These results suggest that all black sediment samples are consistent in terms of water / solids content despite the location from which they were taken. It can be concluded that this sediment maintained spatial consistency throughout the BHSL (spatial direction), and therefore sediment gathered through composite sampling should be representative of the average found throughout the basin.

The solids contents obtained from Area A and B (sampling locations are shown in Figure 1) using the vacuum sampling technique were 0.5% and 2.8%, respectively. The solids content of vacuum samples was significantly lower than that obtained by gravity coring (discrete and composite), because of water mixing with the sediments during the procedure (Figure 5(b)). Even though the same sampling procedure was used for both Areas A and B, a lower water content and a higher solids content was measured in Area B, which can be explained by the fact that thickness of black sediment is greater at the location of sampling in Area B, allowing the intake to be more immersed in the sediment at the time of sampling. This confirms that water / solids content measurements are not comparable to gravity core methods due to the high level of disturbance in the samples.

Particle size distributions of discrete sample BH 19-01 and vacuum sample BHVP 18-01 (taken from Area B), two composite samples BH17-57, BH17-58, and vacuum sample of BHVP 18-05 (taken from Area A) are presented in Figure 6(a). Results show that the black sediment had a similar particle size distribution at various depths and locations, regardless of the sampling method. The results (Figure 6(a)) indicate that 85% of sediment particles (discrete or composite) are finer than 11 µm (D_{85} = 11 µm). However, a D_{85} value of vacuum sampling was slightly less than 11 µm as shown in this figure, indicating that sediment particles obtained by vacuum sampling were slightly finer compared to coring samples. The majority (>80%) of particles (~10^7) range between 2 µm-10 µm, in the case of gravity coring (Figure 6(b)). As the particle size increased from 10 µm to 100 µm, the number of particles decreased from ~10^6 to ~2×10^3. When obtained by vacuum sampling, however, the black sediment contains fewer particles at each certain size compared to sampling by gravity coring. For instance, the number of particles at 100 µm and 200 µm is 100 and 10, respectively, in BHVP samples, while results show almost 20 times more in coring samples (discrete and composite). These findings show that sediment / water mixing during the vacuum sampling results in dilution (a decrease in the number of particles), and perhaps a reduction in aggregation of particles during the process.

Geotextile dewatering is one feasible option for recovering and processing these sediments prior to containment based on studies related to developing remediation options for the BHSL (GHD, 2018). An understanding of particle size becomes important as it influences dewatering. Figure 7 compares the range of average (mean) size of the black sediment particles at different depths to that of the composite and vacuum samples. The average particles size ranged between approximately 6 µm and 12 µm. One-way ANOVA test (Tukey method) results indicate that there was no significant difference in particle size at various depths. Tukey's results are shown with the letters on the graph 7, and samples attributed with identical letters are not significantly different.

In addition, the average particle size of composite samples was statistically similar to discrete samples at various depths, and at different locations in the BHSL (9.3 µm, 10.0 µm, 10.4 µm, and 10.5 µm for Area A, B, C, and D respectively). The vacuum sampling method resulted in similar particle sizes distribution (slightly larger for Area A (9.9 µm) and finer for Area B (8.9 µm)) to other composite and discrete samples, indicating that sediments throughout the BHSL are consistent in terms of particle size.

4. Conclusions

This paper presents results of a field sampling program performed to assess the impact of various sampling methods (i.e. discrete versus composite versus vacuum) on the physical characteristics of contaminated sediments obtained from a large effluent stabilization lagoon. The overall objective of this paper was to use this “field lab” as the basis for assessing how different sampling techniques can be relied upon for representative samples for remediation-based evaluations (i.e. sediment volume estimates and bench scale dewatering studies). A method of comparing time-consuming discrete sampling techniques to more time-efficient composite sample techniques was presented as well as a method of comparing composite sampling techniques to a vacuum sampling technique developed for this project.

The distribution of sediment thickness measured throughout the lagoon by gravity core sampling was shown to vary substantially throughout the 160 ha site. Extrusions of these gravity core samples to obtain discrete and composite samples indicate that there was no significant difference between physical characteristics (water / solids content, density, particle size) of composite samples taken from different areas within the BHSL when compared to discrete samples. For this particular site, it appears that composite sampling would provide reasonable physical parameters when compared to more time-consuming discrete sampling methods (i.e. should reflect the overall physical characteristics of the black sediment throughout the basin for practical purposes).

The physical characteristics of vacuum-obtained samples were compared to gravity core samples (both discrete and composite). This sampling method resulted in more water entrained in the samples, lower solids content (~0.5–2.8%) and slightly finer particles in the samples. However, the mean particle size for the vacuum sampling was not statistically different than that of discrete and composite samples.

The sampling evaluation process investigated in this study provides evidence that more expeditious methods can be used to characterize sediments over large-scale, both in spatial and stratigraphic extent. The results may also provide guidance on how to choose sampling techniques for obtaining representative samples for aquatic sediment projects. .

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Figure Captions

Figure 1. Spatial coverage of sediment sampling locations in Boat Harbour (“BH 19” symbols identify multiple samples taken within a 1 m distance from each other at a specific location).

Figure 2. Histogram of black sediment thickness for 151 gravity cores.

Figure 3. Isopach map of black sediment thickness based on 151 samples presented in this study.

Figure 4. (a) Water and (b) Solid contents at various depths taken via discrete sampling of selected cores (dashed grey line shows interface between black and grey sediments, distances expressed from this interface). The symbols represent the mean values, the error bars represent one standard deviation from the mean.

Figure 5. (a) Water and (b) solids content variation of black sediment in discrete and bulk samples. Samples labelled with identical letters (i.e. a, b, or c,) were not significantly different from each other ($p < 0.05$ level). Samples labelled with different letters are significantly different from each other ($p < 0.05$ level). Vertical lines denote areas from which samples were obtained (i.e. Area A, B, C or D).

Figure 6. (a) Particle size, and (b) count distribution of discrete samples of (BH 19-01), composite core samples of (BH17-57 and BH17-58), and Vacuum samples of (BHVP 18-01 and BHVP 18-05)

Figure 7. Variation in mean particle size versus depth and location. Samples labelled with identical letters (i.e. a) were not significantly different from each other ($p < 0.05$ level).