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STABILIZATION OF DREDGED MATERIALS IN OHIO: An Investigation of Mechanical, Chemical and Biological Dewatering Techniques

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Abstract

Each year, materials are excavated from oceans and lakes in order to keep the waterways open so that ships can safely pass through. These excavated, or dredged, materials are then discarded, usually being returned to the body of water from which they were removed. Beginning in 2020, the Ohio Environmental Protection Agency (OEPA) will no longer allow this to occur. Therefore, the purpose of this project is to investigate beneficial uses for dredged materials in Lake Erie, and to address the best management practices for dewatering these materials, as set forth in the Lake Erie Protection and Restoration Plan created by the Ohio Lake Erie Commission. There is a multitude of ways to dewater and stabilize dredged materials, and this project will investigate three of these methods. The primary methods that will be discussed are mechanical dewatering, biological methods, and chemical treatments.

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1. Introduction

In order for dredged material or sediment to be efficiently and completely dewatered after removal from navigation channels, there are several stages through which the material must undergo. The entire dewatering process can be divided into three individual stages. The first stage of dewatering is the removal of oversized materials, also known as the solids handling stage. This stage is systematic and often easier than the subsequent stages. It involves sorting, separating, and classifying the components of the dredged material by using rugged equipment that sorts solids through a series of screens that vary in size (Englis 2007). The second stage of the process involves the settling and thickening of the dredged material. This stage usually employs a chemical treatment program in addition to mechanical methods to aid in the thickening of the dredged material. The third and final stage is the actual solids dewatering process. This stage is the most complex. The final stage of the process is the focus of this paper, but methods that can be used during the second stage of dewatering are also briefly discussed. Three methods to accomplish the final dewatering stage were researched. The research included an investigation of mechanical devices, chemical processes, and biological methods that would aid in the separation of solids and water.

Once the dredged material is dewatered, there are a variety of beneficial reuse applications for which the material may be qualified. Certain sediment characteristics are necessary in order for the dredged material to be used in subsequent civil engineering applications. Given that the material meets the criteria, some applications that the material can be used for include infrastructural works, agricultural applications and use as a building material.

2. Mechanical Dewatering

Mechanical dewatering is by far the most common method for dewatering dredged material and sediment. This process can generally be defined as the physical separation of water from sediment or soil, or in more technical terms, the reduction of the water content of a sediment (Government of Ontario 2016). Mechanical dewatering makes use of large mechanical equipment to aid in the water separation and removal process. There are several different devices, used throughout the world, to mechanically dewater dredged material.

2.1 Sludge Thickening

Sludge thickening can be defined as the process of reducing the free water content of sludges, or dredged material, in this case. This process is usually performed as the second stage in the entire dewatering process. Some important properties of dredged material that is to be thickened and dewatered include the percentage of organic matter, the grain size distribution, and the concentration, temperature, and pH of the material (Ringeling 1998). Each of these characteristics play a role in the ability of the material to be thickened and dewatered effectively. The higher percentage of organic matter a material possesses, the higher percentage of fines in its grain size distribution, and the higher concentration of mineral oils imply poor dewatering capabilities (Ringeling 1998). The temperature of the material influences viscosity and the pH of the material affects the effectiveness of the flocculating agents and chemical additives. There are many methods for sludge thickening that take into account several, if not all, of these characteristics. The most common methods are discussed below.

2.1.1 Gravity Belt Thickener

One method of material thickening is through the use of a gravity belt thickener (GBT). The gravity belt thickener uses a slow-moving fabric belt to separate solids and free water. Usually, a polymer or other chemical additive is required to precondition the sludge and promote initial separation. Figure 1 shows a schematic of a typical gravity belt thickener. Some advantages to gravity belt thickeners are that it has a smaller footprint, is fairly cost-effective, and consumes less energy than other mechanical thickening devices (Government of Ontario 2016). A few disadvantages to the gravity belt thickener include its sensitivity to the quality of the material being thickened, and its requirement of chemical preconditioning.

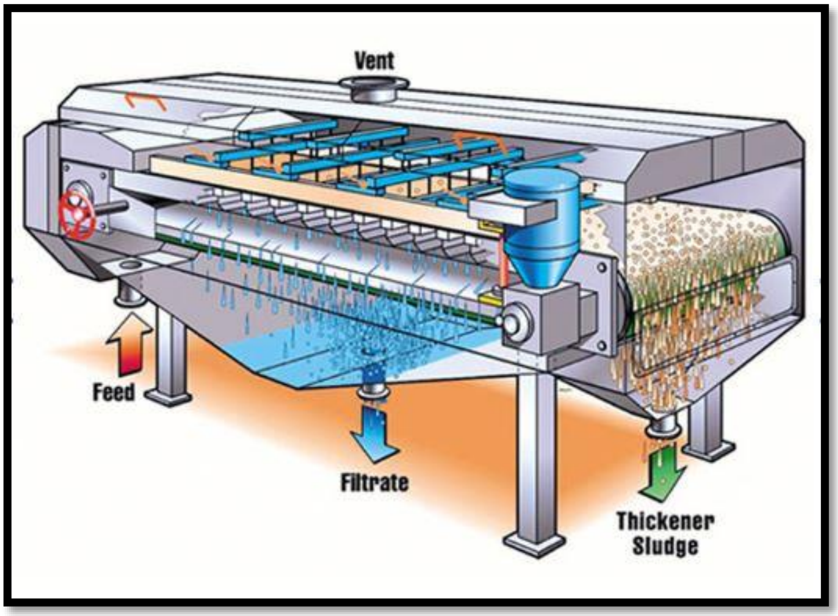

Figure 1: Gravity Belt Thickener (BDP Industries 2019)

2.1.2 Rotary Drum Thickener

Another method for sludge thickening is the rotary drum thickener. After the material has been conditioned with polymers, the machine is internally fed with sludge from a head box or flocculation tank, and then distributed into a rotating drum (Government of Ontario 2016). While in the drum, the material is physically strained to separate the free water. Additionally, this machine is equipped with a built-in spray backwashing system. There are several advantages to the rotary drum thickener, when compared to other thickening methods. The entire process is enclosed, so odor and environmental issues are reduced. The machine has a relatively small footprint, and is fairly cost-effective. Finally, the process consumes less energy than other methods such as dissolved air flotation or centrifugation (Government of Ontario 2016). A disadvantage to the rotary drum thickener is that the material entering the machine requires preconditioning with chemicals.

2.1.3 Gravity Thickener

The most basic method of sludge thickening is with the use of a gravity thickener. This process is used primarily for primary sludge and mixtures of primary sludge and waste-activated sludge (Government of Ontario 2016). This process is also usually used in conjunction with chemical conditioning, either with polymers, ferric chloride, or lime. Figure 2 shows a schematic of a gravity thickener.

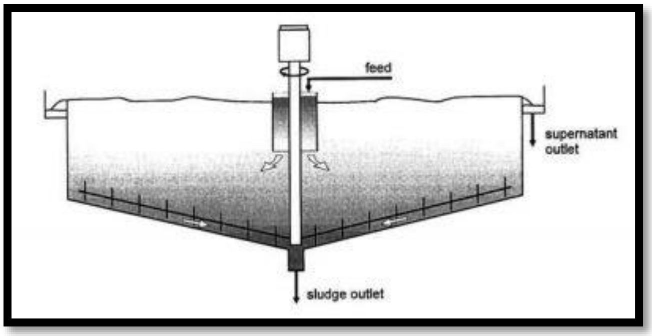

Figure 2: Gravity Thickener (Ringeling 1998)

2.1.4 Dissolved Air Flotation

The fourth and final typical method for thickening sludges is through the use of dissolved air flotation. This process is used primarily for light waste bioreactor sludges (Government of Ontario 2016). The advantages of this more advanced method is that it is reliable, and produces higher sludge concentrations, and a better solids capture rate when compared to a gravity thickener. The disadvantages of this method are that there is a need for a higher level of operating skill, and there are higher operating costs associated with this machine. This method is rarely used due to these higher costs and overall complexity (Ringeling 1998).

2.2 Mechanical Dewatering Devices

2.2.1 Geotextile Tubes

Geotextile tubes are one mechanical dewatering method that is commonly used throughout the United States. Dredged material is pumped into the tube, and the tubes are then left to drain. The tubes are usually made of woven polyester multifilament yarns or woven polypropylene (Englis 2007). This material allows the solids to be trapped in the container while the water passes through. The textiles of the tube are sewn together to create high tensile strengths, which allows for the tubes to be stacked atop one another (Englis 2007). Figure 3 shows a geotextile tube that has been filled with material, and is naturally draining. In addition to stacking to conserve space, the tubes can be used in the creation of beneficial structures, including breakwaters, shoreline protection, and island creation ("Dewatering", *Dredge America* 2019). Over time, the clean water is filtered out through several ports in the membrane and hauled away for use as topsoil, fill, or landfill cover ("Dewatering", *Dredge America* 2019). The main benefit to using geotextile tubes from a dewatering standpoint is that it is one of the faster methods for mechanical dewatering. Additionally, the tubes are easy to maintain and operate, have low maintenance and power costs, have low vapor and fumes emissions, and have a high capture rate of sediments. The main disadvantage of Geotextile tubes is that the tubes require a larger footprint than other dewatering methods.

Figure 3: Geotextile Tube and Membrane Port ("Geotextile Tube" 2007)

2.2.2 Belt Filter Press

Another common method of solids dewatering is through the use of a belt filter press. There are a variety of types of belt filter presses, but two common types include filter presses and chamber filter presses. In general, these machines use a multi-step process to promote the separation of solids and water. The belt filter press has three "Dewatering Zones" that each serve a different purpose, while continuously pressing the soil-water mixture between two woven filter cloths (Englis 2007). Figure 4 shows a schematic of the entire belt filter press, and each individual zone.

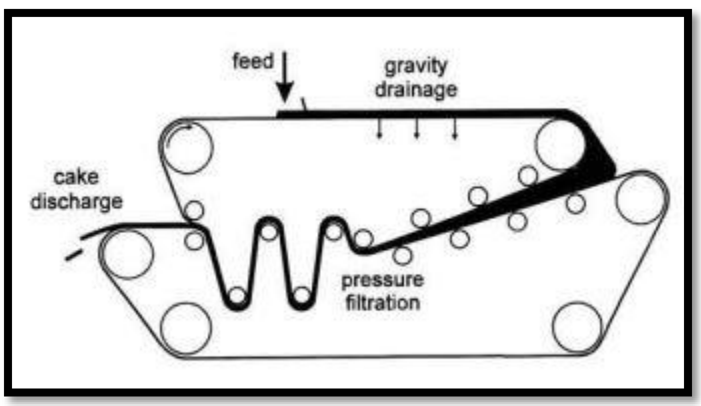

Figure 4: Belt Filter Press Schematic (Ringeling 1998)

In the first zone, the solids are evenly distributed onto the top belt of the system, and passed through rakes (also known as chicanes). This first zone is where the majority of the gravity drainage takes place, and here, around 50% of the water is drained through gravitational processes alone (Englis 2007). In the second zone, solids are dropped onto the lower filter belt cloth and conveyed to a wedge-shaped area where the material is compressed between two large rollers (Englis 2007). This area is also called the low-pressure zone, and this zone is where the initial formation of dense solids, or cake, occurs. In the third and final dewatering zone, the belt filter cloth passes through a series of small rollers that are rotating at different speeds. This zone can be seen between the pressure filtration zone and the cake discharge area in Figure 4. The rollers in this zone are situated in such a way so that the belt passes through at a steep angle. The vertical orientation of the belt and the differential speed of the belt exert

a shearing force on the solids and force additional water to be released (Englis 2007). This zone is also called the high-pressure zone. After the solids have passed through the entire belt filter press, the cake that has been formed is collected and used in a variety of beneficial reuse applications.

There are a variety of advantages to this approach of mechanical dewatering. First and foremost, with the belt filter press, most types of sludge can be dewatered (Government of Ontario 2016). This versatility is a huge advantage over other mechanical dewatering methods. Secondly, the production rate for cake formation is relatively high, meaning that each time the belt filter press is run, a large quantity of solids is formed. Thirdly, the machine is reliable and adaptable, and has a relatively small footprint. Additionally, the belt filter press has low labor costs when compared to other mechanical dewatering equipment, and has the ability to operate continuously. Furthermore, the power requirements for running a belt filter press are one-third those required to operate a vacuum filter (Government of Ontario 2016). These characteristics make the belt filter press an attractive option for the dewatering of dredged material from Lake Erie.

There are, however, some disadvantages to the belt filter press. The large machine has high vapor and fume emissions, and high energy consumption. Additionally, certain solids that enter the press, if they have a high concentration of oil and grease, can permeate the filter cloth on the belt and reduce the ability of the belt filter press to drain water efficiently (Englis 2007). Since there are so many moving parts, there is also high operation and maintenance costs associated with the belt filter press (Foged 2007). Finally, while the labor costs of physically operating the belt filter press are low, the variables that affect the output and operation of the press are controlled solely by the operator. This means that the operator is required to perform constant visual surveillance of the machine, and use his or her own judgement when the machinery is not performing at optimum conditions.

2.2.3 Filter Press and Chamber Filter Press

Both the filter press and the chamber filter press are similar in methodology. Generally speaking, in these machines the dredged material is squeezed into a chamber under high pressure. The volume of the chamber is determined as a relationship between the surface area of the filter cloths and the distance between the plates (Foged 2007). As the chamber is filled, the pressure applied to the dredged material is increased. Figure 5 below shows a schematic of a few chamber filter plates within a chamber filter press. The schematic includes the inlets for the dredged material and slurry, and the outlets for both the cake product and the filtrate. Figure 6 shows a profile view of the entire chamber filter press, made up of several chamber filter plates. In recent years, the designs of these filter presses have changed to eliminate leakage problems and improve the filter media within the plates (Government of Ontario 2016). Some units now have recessed plates within the frame and automated washing cycles for the filter media. These advancements improve the overall productivity of the filter and chamber filter press, and make them more comparable to the belt filter press.

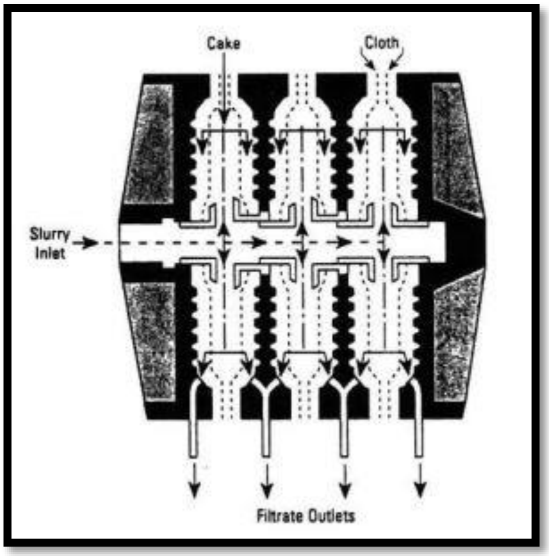

Figure 5: Chamber Filter Press Plate (Ringeling 1998)

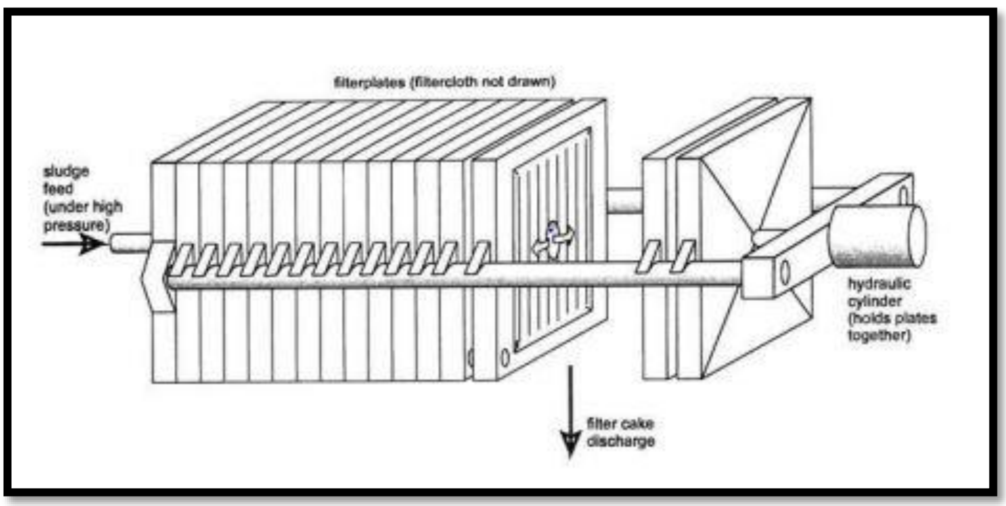

Figure 6: Chamber Filter Press (Ringeling 1998)

Because of recent advancements, these machines have several advantages over the traditional belt filter press. The end product, or cake, has good mechanical characteristics. This means that the bearing capacity of the soil is improved after dewatering, and compaction of the material, therefore stockpiling, is possible (Foged 2007). Additionally, the presses have the ability to concentrate all types of sludge to very high concentrations (Government of Ontario 2016). This ability gives the filter and chamber filter press a competitive advantage over other types of mechanical dewatering. The entire process is static, so the maintenance cost is significantly lower than that of the belt filter press. Additionally, the filter and chamber filter presses are less sensitive to abrasion, and because of their structure, have lower operating costs. There are a few disadvantages to note with the filter presses and chamber filter presses, however. The machines operate in a batch process, and in a closed system. Additionally, large quantities of chemical conditioning agents are usually required (Government of Ontario 2016). The use of chemicals in conjunction with mechanical processes can become expensive. Also, badly conditioned

sediments can only be discovered by opening the chambers, at which point there is usually little to no possibility of addressing and solving the issue of severely contaminated sediments (Foged 2007).

2.2.4 Plate and Frame Press

Another method for dredged material dewatering is through the use of a plate and frame press. The plate and frame press dewaters dredged material by trapping sediments between stacked layers of filter media and creating a pressure differential in which a cake of fine particulates is formed (Englis 2007). Figure 7 shows a schematic of a cross sectional view of one of the filter plates, and a profile view of the entire plate and frame press. The plate and frame press utilizes a four step process to dewater sediments. During the first step, known as filling, the press is closed and a chemically enhanced slurry is pumped into the press until all the air is evacuated. The second step, known as filtration, occurs at a constant pressure. Here, as cake begins to consolidate, the filtration rate begins to diminish, and the pumping process is stopped entirely when the full volume of the press is occupied (Englis 2007). During the third step, also called the blow-down, air is blown through the press drainage outlets to depressurize the press, remove the remaining filtrate still within the press, and remove solids from the core that were not able to form a cake. In the fourth and final step, also known as the discharge step, each plate is opened individually so that the cake can be dropped into a receiving bin. After the discharge step, the filter media is cleaned and the press is reassembled and readied for the next dewatering cycle (Englis 2007).

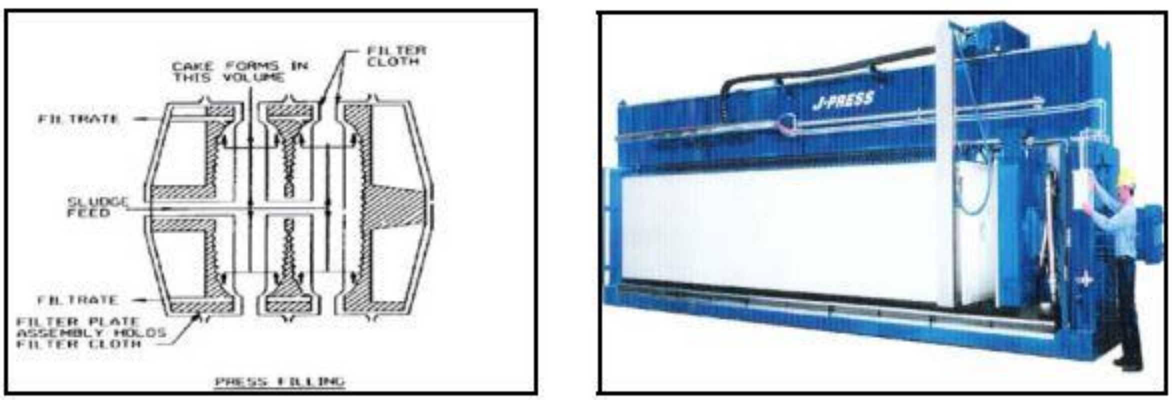

Figure 7: Plate and Frame Press (Englis, Matthew, and Dewey W. Hunter 2007)

There are both advantages and disadvantages to using a plate and frame press to dewater dredged material. Some advantages of the apparatus include: high cake solids, high solids capture rate, and low chemical dosing (Englis 2007). The plate and frame press has high production rates and does not require a large amount of chemical conditioning. Additionally, the machine is adaptive to a wide spectrum of sediment types. Some disadvantages of the plate and frame press are that the operation of the machine requires reliable and well planned thickening solids strategy, and requires continuous optimization of the chemical treatment program. Furthermore, the machine has strict operating standards (Englis 2007).

2.2.5 Screw Press

Another mechanical device that can be used to dewater dredged material is the screw press. The operation of this machine is fairly simple. To achieve dewatered materials, the press transports solids in a helical path along a tapered screw (Englis 2007). There are three processes that occur consecutively so

that the screw press can produce a cake material at the end of the cycle. In the first process, a slurry material is fed into the machine and excess free water escapes through a screen. Next, the solids travel through the low pressure zone, where compression occurs as screw blades advance the solids through the machine and void space is diminished as the screw shaft diameter increases (Englis 2007). In the third and final process, solids pass through the high pressure zone, where there is an adjustable discharge orifice that controls the opening of the machine. This small orifice opening provides a reduced rate of solids discharge, which in turn exerts a pressure onto the remaining solids in the screw press, and this then results in a higher cake production and higher dryness value (Englis 2007). There are a variety of configurations for and variables that can adjusted within the screw press. Some of these variables include screw length, taper, pitch, screen type and diameter, and selection of chemical additives. Figure 8 shows a schematic of a common configuration for a screw press. As it can be seen in Figure 8, the main components of the screw press include the inlet feed, where the slurry is first input into the press, the two pressure zones, the screen for separating free water from the solid material, and the outlet pipe where the cake is collected.

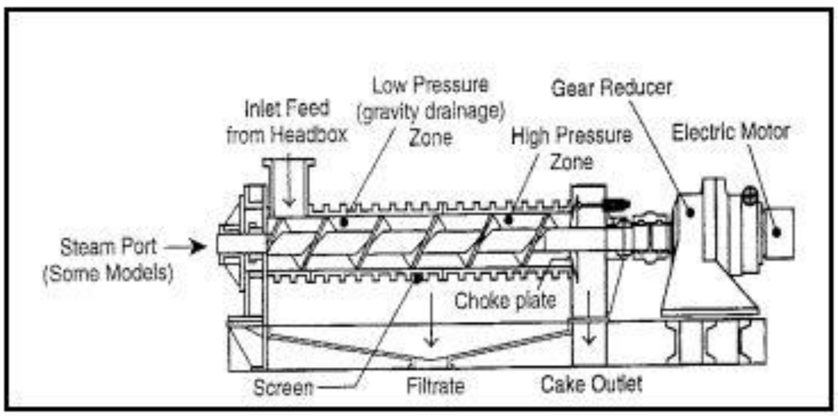

Figure 8: Screw Press (Englis, Matthew, and Dewey W. Hunter 2007)

Recently, a case study was conducted in Japan where the largest screw press system available at the time performed dewatering procedures, added solidification material and prevented leaching of pollutants from several sediment samples. The screw in the screw press was 1,350 mm in diameter and the entire system was called The Eco-Screw System (Oida 2007). The system consisted of several large pieces of equipment, including the screw press itself, a backhoe, crane, gravel pit, discharge water tank, belt conveyor, paddle mixer and several generators. Figure 9 shows a schematic of the equipment setup that was utilized during the case study. This system was designed to continuously remove water from sediment with rotating screw blades, and consisted of four main processes. The first three processes are similar to those outlined above, which involve the sediment entering the press and traveling through the varying pressure zones to separate the water and solids. The fourth and final step in the Eco-Screw system involves the collected water being transported to and treated at a facility, and dewatered sediment being removed on belt conveyors for reuse (Oida 2007). In the dewatering phase of the Eco-Screw System, the sediment was compressed via the screw press, and the water content was measured by the cone index. For fill or other civil engineering applications, the cone index for recycled material is required to be 400 kN/m^2 or higher (Oida 2007). The samples that were dewatered in this study produced a cone index of more than 300 kN/m^2.

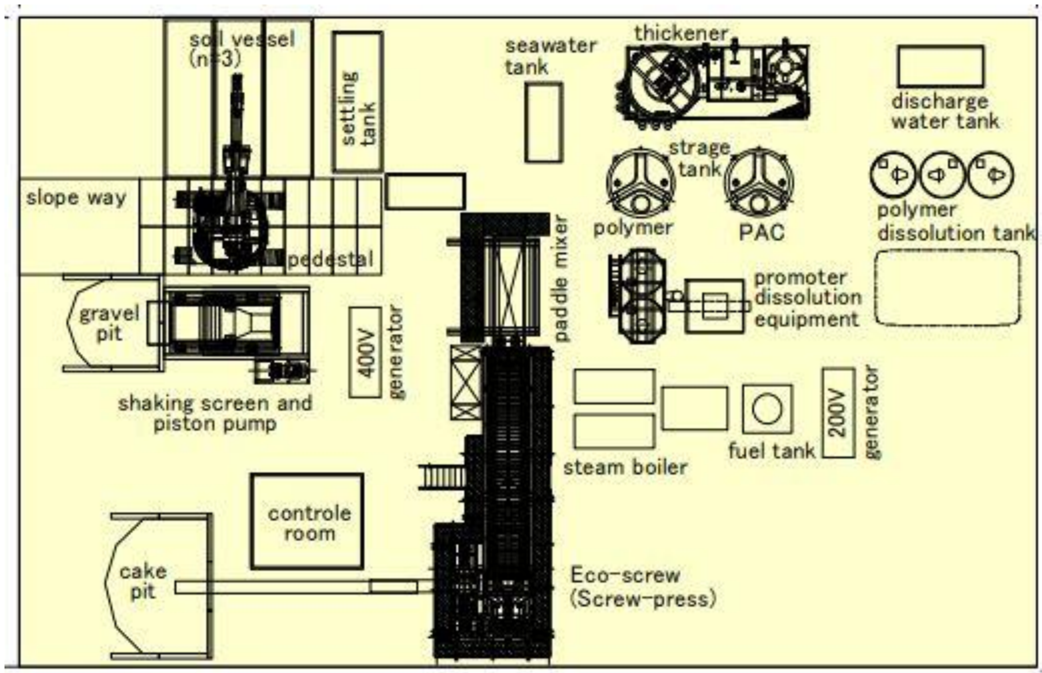

Figure 9: Eco-Screw System Equipment (Oida, Takashi 2007)

Several advantages were discovered as a result of the Eco-Screw System case study. This study proved that continuous dewatering of sediment with a screw press is possible, and because the screw press is able to continuously handle slurry, no storage tank is required (Oida 2007). This ability gives the Eco-Screw System an advantage over other batch-type dewatering methods such as filter presses. Additionally, the strength of the dewatered sediment can meet quality requirements with the adjustment of the rate of rotation of the screw blades. The screw blades usually rotate at a moderate rate, and because of this, the operation of the Eco-Screw System is quiet and consumes little electric power (Oida 2007). Moreover, the maintenance of the system is easier than other mechanical dewatering methods because punched metal is utilized in the screens as opposed to filter cloths (Oida 2007). This characteristic makes the cleaning and maintaining of the screens easier. Finally, sediments containing certain amounts of gravel can be dewatered, which is usually not possible. A major disadvantage to the Eco-Screw System is the cost and procurement of all the required equipment.

There are several other advantages to using a general screw press. Some of these include its ability to produce medium to high amounts of cake solids, its low labor costs, moderate footprint, and the ability to be operated continuously (Englis 2007). There also are a few disadvantages associated with the screw press. The configuration of the machinery requires extensive chemical additive evaluation and laboratory testing, and the screw press will most likely need to be used in conjunction with several other presses (Englis 2007).

2.2.6 Centrifuge

Another common mechanical method for dewatering sediment is through the use of a centrifuge. This complex piece of equipment is designed to use gravitational forces to separate solids and liquids by rapidly spinning material upwards of 4,500 rpm. The machine functions similarly to a clarifier, where slurry is spun and denser material is slung outward and caught on the wall of a giant bowl (Englis 2007).

There are three types of centrifuges: the solid-bowl decanter, the disc-nozzle, and the basket (Government of Ontario 2016). The components that make up a typical solid-bowl decanter centrifuge include the slurry feed pipe, where material is injected, the bowl, a scroll or screw conveyor, and both a liquid and a solids discharge port (Englis 2007). Figure 10 shows a schematic of these elements.

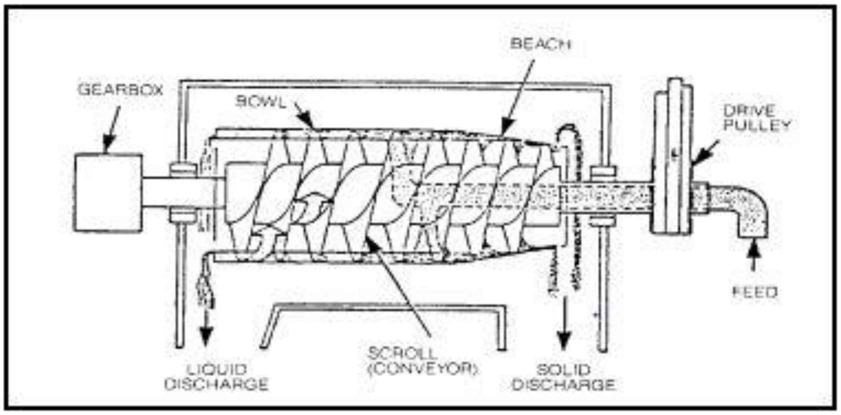

Figure 10: Centrifuge (Englis, Matthew, and Dewey W. Hunter 2007)

The mechanical separation process using a centrifuge has a number of steps. First, the dredged material enters the center of the bowl and as rotational speed of the bowl increases, the material is thrust against the outside of the bowl and centrifugal forces act to separate the solids from the water. Then, the scroll or conveyor rotates at a different speed than the bowl and moves solids away from the water (Englis 2007). During this step of the process the solids are further dewatered as they are transported to the discharge port, since the solids begin to impose resistance on the machine. As the rotational speed of the bowl continues to increase, the solids begin to exit the bowl at the end of the tapered section of the centrifuge (Englis 2007). This solids discharge port can be seen in Figure 10. Finally, as the water level builds in the centrifuge, water flows within the machine and is discharged through the liquid discharge port at the opposite end of the bowl. The results of this machine are influenced by differential rotational speeds of the bowl and the scroll, the dosage of chemical additive and the slurry feed rate.

A variable that is often modified and considered in more detail is the bowl speed. With an increased bowl speed, there are increased centrifugal forces available. However, the settled solids become more difficult to remove because there are higher G forces (Government of Ontario 2016). Additionally, the increase in bowl speed leads to an increase in abrasion damage, noise, and vibration within the centrifuge. In contrast, a lower bowl speed results in minimized internal wear, lower noise levels, and lower power requirements (Government of Ontario 2016). Additionally, with a lower bowl speed, a higher solids capture rate can be achieved, and acceleration and turbulence within the centrifuge can be minimized. However, using a lower bowl speed will require an increase in chemical additives that have to be added to the slurry (Government of Ontario 2016).

Some advantages to using the centrifuge to dewater dredged material is that the machine is capable of producing moderately high cake solids and high solids capture rates. Also, the centrifuge is a good option for solid material containing high levels of oil and grease because these two substances can be fairly easily separated using centrifugal forces (Englis 2007). Furthermore, using a centrifuge to dewater materials can be done as a continuous process and is a viable option where space limitations exist

(Foged 2007). Unfortunately, there are several disadvantages to the centrifuge that may ultimately outweigh the advantages in some applications. Skilled operators are required for the centrifuge, and maintenance can be problematic due to the machine's complexity (Englis 2007). This will result in high maintenance costs over time. There are also high power costs associated with the centrifuge. Additionally, abrasive material entering the bowl can cause excessive wear on the machine, shortening its life span and making it less suitable for heavy duty applications (Foged 2007). Finally, this machine is not ideal for very fine particles or sediments with low inorganic or fiber content (Englis 2007). Unlike most of the filter presses, this machine is not able to dewater all types of sediment.

2.3 Emergent Technologies: Soil washing

In 2017, the United States Army Corps of Engineers (USACE) conducted a variety of tests to assess the most economical methods for treatment of dredged material. These tests were performed on sediment samples that were collected from the Ashtabula River, the Buffalo River, Grand Calumet/Indiana Harbor, and the Saginaw River. Their research resulted in four emerging mechanical dewatering techniques that incorporate physical processes to promote separation of solids and water. As a whole, few processes seemed feasible for more than two different sediment types. Nonetheless, the experiments conducted are described below.

2.3.1 Froth flotation

The first method analyzed was froth flotation. For these assessments, a 1.2 L Denver Flotation machine was used. Froth flotation is a common mineral separation process used in the paper recycling and wastewater treatment industries, and recent research suggested that the process could be applied to contaminated dredged material. The goal of the experiments conducted was to achieve a high contaminant distribution and low mass distribution in the resulting dewatered material. Three chemical reagent schemes were tested. These included running the machine and analyzing flotation without a collector, flotation with a fatty acid collector, and flotation with an anionic collector and copper sulfate (Estes). In each of these schemes, several surfactants were tested. Surfactants are chemical substances that reduce the surface tension of a liquid or material in which it is dissolved or placed into contact. The surfactants tested in these experiments included phosphate ester, fatty acid sulfates, ethoxylated alcohols, and amine ethoxylates (Estes). The parameters that were measured included pH, surfactant composition, dosage, aeration rate, and slurry density. It was discovered that the best dewatering results were obtained at a lower pH and slurry density, and higher concentrations of reagents (Estes). Unfortunately, these experiments were disadvantageous in that they were difficult to control, were not particularly selective in most cases, and that they possess limited potential for application to all sediment types.

2.3.2 Magnetic separation

The second method analyzed by the USACE was magnetic separation. This process involves using a variety of magnets to separate metals in contaminated sediment samples. In this experiment, the metals were separated into four size fractions. The equipment used included a Carpco-induced roll magnetic separator, a wet high intensity magnetic separator, and a hand held magnet (Estes). The results of the study showed little correlation between metal contaminants and magnetic fractions of sediments. It was found that the process was unlikely to be feasible for three of the four sediment size fractions, with limited applications for the fourth sediment group (Estes).

2.3.3 Grain size separation

The third physical process that was analyzed was grain size separation. Through the use of wet sieving, this method attempted to physically separate a variety of metals and contaminants. The largest mesh used was the +20 mesh, and the smallest used was the -400 mesh (Estes). In this experiment, the samples were analyzed for arsenic, cadmium, chromium, copper, iron, lead, mercury, nickel, zinc, oil and grease, and total PCBs. This process seemed feasible for one sediment, with limited application for two sediments, and proved that the process would likely be unsuccessful for four (Estes).

2.3.4 Gravity separation

The fourth and final physical process that was researched in detail was gravity separation. These experiments were conducted on de-oiled sediments using two different densities of heavy filter media (Estes). Additionally, water elutriation and density separation experiments were also conducted. The process of gravity separation seemed feasible for one sediment, had limited application for two sediments, and would likely be unsuccessful for four sediments (Estes).

3. Chemical Dewatering

The second method that was investigated for dewatering solids was chemical dewatering. The processes in this category utilize chemical reactions in order to alter the chemical composition of the dredged material so that its properties are more conducive to dewatering and subsequent use. Some properties targeted in chemical dewatering are the amount of colloidal particles, net negative charges (which are responsible for making particles repulse each other) and the water content of the material (Government of Ontario 2016). Additionally, chemical processes are used in the second stage of the entire dewatering process to aid in the thickening of the dredged material. The goal of this stage is to produce homogenous concentrations of uniform solids at a constant rate and also release excess volumes of water (Englis 2007). Chemical compounds known as flocculants are frequently added to solids to promote the joining of particles and thickening of dredged material. By adding flocculants and other chemical agents, naturally occurring settling and thickening processes can be accelerated. These processes otherwise would typically require a significant amount of time and physical space. However, this accelerated process can take place in large environmentally isolated ponds, or in the mechanical thickening devices described previously (Englis 2007).

3.1 Chemical Thickening Methods

A variety of chemical compounds are used to artificially thicken solid material in preparation for dewatering. This thickening process is also known as chemical conditioning (Government of Ontario 2016). While the implementation of chemicals can be used as a singular method for thickening and dewatering, chemical methods are frequently used in conjunction with mechanical devices to promote more efficient dewatering. There are three main groups of compounds that are used in the chemical thickening process: natural organic compounds, inorganic compounds, and synthetic organic compounds. The main natural organic compound used in solids thickening is called chitin, and the main inorganic compounds used in this process are lime, ferric chloride, and aluminum sulfate (Englis 2007). With the addition of these chemicals, more rapid phase separation, higher solids concentration, and higher capture rates occur (Government of Ontario 2016). Some types of synthetic organic compounds that have been utilized in the solids thickening process include a variety of polymers, coagulants and flocculants. Coagulants are cationic, or positively charged, and are used to accelerate sedimentation rates of solids (Englis 2007). However, coagulants are not used in the dewatering phase because the

shear forces exerted can physically break the electronic bonds holding the solids together, which would cause re-suspension of the solids. Flocculants are used throughout the entire dewatering process, and will be discussed in detail below.

3.1.1 Flocculants

Flocculants are synthetic polymers that are used in both the thickening and dewatering process for dredged material. They can be anionic, non-ionic, or cationic, which means that the compound is either negatively charged, neutral, or positively charged, respectively (Englis 2007). When flocculants are added to a slurry, the solids bind to the polymer and to each other. This is possible due to the great length of the polymer molecular chain, and its ability to adsorb onto several particles simultaneously (Ringeling 1998). This process promotes thickening of the material and prevents shear forces or excessive turbulence from re-suspending the solids in the slurry (Englis 2007). Frequently, the polymers are added to a slurry to condition it, and then the slurry is fed through a mechanical dewatering device. Flocculating polymers are most commonly used with belt filter presses and centrifuges, and certain polymers with higher molecular weights are more commonly used with filter presses (Government of Ontario 2016).

In 2012, experiments were conducted in China on seven flocculating agents to determine the optimal flocculant and dosage of that flocculant that would best assist in accelerating the dewatering process. The flocculant species were all macromolecules, whose properties were affected by the mixing process, the molecular weights and distribution, pH, concentration, and electrolyte content (Hu 2012). Of the seven flocculants used in the experiments, four were industrial compounds, and three were analytical compounds. The four industrial compounds were CPAM, APAM, PAC, and PFC, and the three analytical compounds were sodium silicate liquid ($Na_2O{\cdot}mSiO_2$), N-Acetyl threonine ($(C_6H_{11}NO_4)_n$), and trisodium citrate ($C_6H_5Na_3O_7$) (Hu 2012). During the experiment, the types and quantity of the flocculants were determined by a variety of steps. First, predetermined doses of flocculant were added to beakers. Then, the mixtures were rapidly stirred, followed by a time period of slow stirring, then by minutes of precipitation. The mixtures were then added to mechanical dewatering equipment. Finally, the optimum species was selected based on the height of the settlement after 20 minutes, the flocculation group size, the appearance of the upper liquid, the water content, and the precipitation of the phenomena (Hu 2012). After the optimal species was selected, the process was repeated to test concentration in order to determine the optimal dosage. Different concentrations of the same agent were added to individual beakers, and the same parameters were measured (Hu 2012). This experiment provided a detailed method for the experimental determination of the optimal flocculating agent that could be utilized to aid in the dewatering process.

3.2 Polyacrylamides Enriched with Coagulants

There are several chemical manufacturing companies that develop a variety of products to assist with the dewatering of solids. One such company is GEO Specialty Chemicals. Several of their products combine various chemicals to produce polymeric flocculating agents that can be used in the solids thickening process. Their polyacrylamides enriched with coagulants reduce waste volume, assist with savings on sludge disposal, improve and promote water recycle, and meet environmental standards ("Dredging", *GEO*). There are four main categories of these chemicals: Polyamines, PolyDADMACs, Ultrafloc®, and Ultrapac®.

Of these four chemical categories, the two fairly common chemicals for solids dewatering that GEO Specialty Chemicals produces and markets are polyamines and polyDADMACs. Polyamines, also known as epiamines, have a very high cationic concentration in their aqueous forms, and are often used in water and wastewater treatment. PolyDADMACs have a high cationic charge and molecular weight when compared to conventional coagulants, and this chemical is also used in water and wastewater treatment ("Dredging", *GEO*). Both products have additional applications in liquids-solids separation and water clarifications. They also both can be utilized as dewatering polymers, polymeric cationic coagulants, and sweep flocculants ("Dredging", *GEO*).

The other two chemicals that have been developed by GEO Specialty Chemicals in order to assist with the process of dewatering solids are Ultrafloc® and Ultrapac®. Both Ultrafloc® and Ultrapac® consist of a blend of alum, PAC, ACH, polyamine, polyDADMAC and other additives like sulfuric acid, phosphoric acid and calcium chloride. Ultrafloc® is NSF approved for drinking water applications and Ultrapac® is primarily used for water and wastewater projects ("Dewatering", *GEO* 2019). Ultrapac® contains just enough active ingredients to achieve performance at an economical price. Both chemicals are effective in both color and phosphate removal, and other applications of these chemicals include charge neutralization, coagulation, flocculation, phosphorous removal, and TOC reduction ("Dewatering", *GEO* 2019). They can act as dewatering polymers, polymeric cationic coagulants, and sweep flocculant, similarly to polyamines and polyDADMACs.

3.3 Chemical Oxidation

In addition to the soil washing experiments that the USACE conducted, the organization also analyzed chemical dewatering techniques and further experimented with existing methods of chemical dewatering. One result of the USACE research was the implementation of chemical oxidation for use in dewatering and treating dredged material.

In the research conducted by the USACE, four primary chemical oxidants were found that were used to oxidize contaminants in soil and groundwater. The four oxidants analyzed were permanganate, persulfate, peroxide or Fenton's reagent, and ozone (Estes). For permanganate, the two compounds researched were potassium permanganate ($KMnO_4$) and sodium permanganate ($NaMnO_4$). These two chemicals are classified as strong agents, have a complex stoichiometry, and have an affinity for oxidizing compounds containing carbon-carbon double bonds and hydroxyl groups (Estes). For persulfate, the compounds researched were sodium persulfate ($Na_2S_2O_8$), ammonium persulfate ($(NH_4)S_2O_8$), potassium persulfate ($K_2S_2O_8$) and persulfate ion $(S_2O_8)^{2-}$. These persulfate compounds are more powerful than hydrogen peroxide, and through the use of heat, ferrous salt or high pH, their strength can be increased even further (Estes). Peroxide (H_2O_2) and modified Fenton's Reagent (Ca_2O_2), are typically kinetically slow, but when ferrous salt is added to them, their strength is dramatically increased. Ozone was analyzed as a reagent in the gas phase, but also exists in the liquid phase as ozonated water or ozone plus peroxide (Estes). There are two forms of ozone; one occurs in the vadose zone and one occurs below the water table. When pH is increased, the hydroxyl production is increased. Additionally, for ozone, mass transfer limitations lead to more sustained oxidation, the research found (Estes). Two case studies regarding these four chemical compound groups were examined by the USACE. One case study conducted in New Jersey using potassium permanganate proved inconclusive, but the second case study, which analyzed the chemical oxidation of PAHs, proved more beneficial. The study confirmed already recognized limitations of the oxidation process, but served to provide comparisons in

performance for the different technologies that implement each of the four chemical groups (Estes). The study found that peroxide alone proved to have the highest removal of peroxides in contaminated sediment, with 45% removal, and that chemicals in the persulfate group removed 72% of PAHs.

There are a few other common soil or sediment constituents that promote hydroxyl formation. These are alcohols, carboxylic acids, and humics (Estes). The USACE research found that there are a variety of variables affecting the effectiveness of chemical oxidants in the field. Some of these variables include the stoichiometry, thermodynamics, kinetics, including reaction and contaminant desorption/dissolution kinetics, and contact or delivery.

3.4 Chemical Extraction

Research conducted by the USACE in chemical dewatering techniques also led to a pilot scale demonstration of a chemical extraction method for sediments, using a system called the BEST system. The system incorporated four steps: extraction, solvent recovery and oil polishing, solids drying, and water stripping (Estes). Two types of extraction processes were examined: cold extractions and warm/hot extractions. Both processes were carried out at a pH greater than 10 (Estes). During cold extraction, the sediment is chilled and dewatered prior to the drying process. Warm/hot extraction occurs between 38˚ C and approximately 43˚C, and residual solvent is removed by indirect heating, and then a direct injection of steam in order to clean the sediment (Estes). Both processes are batch processes.

It was found that the entire BEST system was able to remove more than 99% of PCBs in the sediment and more than 98% of the oil and gas contained within the sediment. Additionally, the residual solvent concentrations were relatively low, at less than 150 ppm (Estes). This process showed that it is feasible to use chemical processes to treat contaminated sediment and prepare it for beneficial reuse. The demonstration concluded that full scale treatment costs could be estimated at $139-$361 per cubic yard for treatment volumes of 5,000 and 100,000 cubic yards of contaminated sediment, if the sediment is processed at 184 cubic yards per day (Estes).

3.5 Thermal Treatment and Thermal Immobilization

Two additional methods that could be classified as chemical dewatering methods are thermal treatment and thermal immobilization of dredged material. Through the use of elevated temperatures, typically around 450-650˚C, certain chemical processes that assist with dewatering solids are forced to occur. This thermal treatment process results in combustion or total destruction of organic compounds, an increase in pH, and a decrease of volatile components in sediment such as mercury and some arsenic, selenium, and cadmium (Ringeling 1998). There are several advantages to thermal treatment of sediment. Some of these include a high heat transfer rate as the combustion gases come into direct contact with the sediment, and a decrease in leachability of heavy metals (Ringeling 1998). However, there are also several disadvantages associated with thermal treatment. There is a relatively large amount of flue gases that need to be treated after the thermal treatment process is completed, and the process is limited to sediment that contains more than 5% clay (Ringeling 1998). Furthermore, using thermal treatment to dewater sediment requires that the sediment be pre-treated, and when the process is over, post-treatment is required as well.

A more intense heating process known as thermal immobilization can also be used to chemically dewater sediment. This process is performed by heating the clay-containing sediment and subsequently

cooling it. First, the material goes through a sintering stage, where it is heated to a temperature of about 1000-1200˚C, and then the material is heated even further, to temperatures greater than 1250˚C, in a stage known as melting (Ringeling 1998). Immediately following the melting stage, the material is either cooled quickly, to minimize crystallization, or cooled slowly, in order to promote a more crystalline structure within the resultant material. There are several advantages to the use of thermal immobilization as a chemical dewatering technique. Organic material is destroyed, there is an immobilization of heavy metals within the sediment, there is a large volume reduction, a small volume of waste products (less than 1%), and the final product can be reused (Ringeling 1998). Because this is such an intense heating process, however, there are usually high treatment costs, high flue gas emissions, and high energy consumption through heat loss associated with the thermal immobilization process.

4. Biological Dewatering

The third and final dewatering method investigated was biological dewatering. These processes promote water and solids separation through the use of different types of vegetation. For these processes, several case studies were analyzed, and are summarized below. Since native vegetation varies from region to region, the most appropriate way to analyze the biological dewatering methods, in an attempt to apply some of them to the dredged material that comes from Lake Erie, is on a case by case basis.

4.1 Alabama Case Study

A dredged material dewatering study was conducted in 1970 at Upper Polecat Bay Disposal Area in Mobile, Alabama. There were several demonstrations conducted in the area, one of which involved the artificial establishment of vegetation as a dewatering method. All of the demonstrations were carried out on fine-grained dredged material that was classified as a highly plastic clay (CH under the USCS) with an appreciable montmorillonite fraction (Haliburton 2002). Alabama was chosen as a test site for the biological dewatering demonstration due to the high annual rainfall the state receives and the long growing season Alabama's climate can provide (Haliburton 2002). Each demonstration conducted at Upper Polecat Bay Disposal Area was assessed on three criteria: technical feasibility, operational practicality, and cost-effectiveness. Technical feasibility was defined as the ability of the technique to accomplish the result, which in this case was the production of dewatered, densified dredged material (Haliburton 2002). A method was deemed operationally practical if the materials, equipment and operation procedures could be scaled up without loss of efficiency. Finally, the demonstration was considered cost-effective if the unit cost of creating a new disposal area storage volume by dewatering and consolidation was less than $4.00 per cubic meter (Haliburton 2002). These criteria helped the research team compare and analyze their findings, and determine the best dewatering methods for dredged materials from waterways in Alabama.

In order for dewatering via artificial establishment of vegetation to occur, the plants being utilized must have certain characteristics. In this study, the plants chosen had to be perennial and hardy, easily established at a low cost, capable of rapid growth with minimal maintenance, fast spreading with thick root mat and low profile, and have high transpiration rates (Haliburton 2002). Once plants were chosen that met these requirements, the species were transplanted from just off-site of the testing area. In addition to the plants utilized for the dewatering demonstration, pickleweed plants were collected from

salt marshes and dispersed over the surface of some of the test plots in order to address visible surface salt crusts.

After the plants used in this demonstration were allowed to grow for a reasonable amount of time, the results of the test plantings were analyzed. It was found that, as a whole, the transplanting had failed, because the transplanting had been conducted at the wrong time of year, the climatic conditions were unfavorable, and the salinity of the test plots was significantly higher than expected (Haliburton 2002). Additionally, invasive vegetative cover flourished and prevented measurable growth from the transplanted species. It was found that the demonstration was academically inconclusive, and not cost-effective (Haliburton 2002). With that being said, there were some advantages that were still able to be reported that resulted from this demonstration. It was found that the root mat support capacity can be used to allow machinery and personnel to traverse otherwise impassable areas, and that the transplanted vegetation both improved disposal area aesthetics and provided wildlife habitat (Haliburton 2002).

4.2 Iowa Case Study

In recent years, The University of Iowa experimented with a new biological approach that addresses the amount of dredged material that accumulates in major waterways. The university conducted experiments with new biological technology that would prevent sediments from entering waterways at all. This new technology, called STRIPS (Science-based Trials of Row crops Integrated with Prairie Strips), promotes soil stabilization and prevents excessive erosion of rivers and streams (Duirk 2018). This, in turn, leads to less sediment entering lakes and other major bodies of water, therefore eventually decreasing the amount of material needing to be dredged.

STRIPS were originally introduced as a farmland conservation practice to retain soil, water, and nutrients. The width and composition of the STRIPS can be determined based on flows and location. If more water is flowing down-slope, wider STRIPS can be used, and narrower plantings can be done in areas where less water is flowing downslope (“Management” 2019). The types of plants are selected based on several characteristics. Typically, the plants chosen were stiff-stemmed warm season grasses that are less prone to collapsing under a heavy rain (“Management” 2019). Some of the specific plant types chosen for experimentation included native prairie plants, tall grasses, forbs, perennial sunflowers, asters, milkweeds, coneflowers, wild bergamot, and ironweed (Duirk 2018). The root structure of these plants is important when it comes to capturing and retaining sediment and nutrients. There are two key structures that allow the plants and STRIPS to operate effectively. First, the plants in the STRIPS have about six feet of dense stems and leaves above the ground (Duirk 2018). Additionally, there is about seven feet of dense, deep roots below ground that are equipped with bacteria and fungi. About two-thirds of the plant’s biomass is underground. The root zone matrix below the surface is incredibly dense, which enables the plants to capture nitrogen and phosphorus ions (Duirk 2018). Figure 11 shows the composition of a typical plant used for the STRIPS systems.

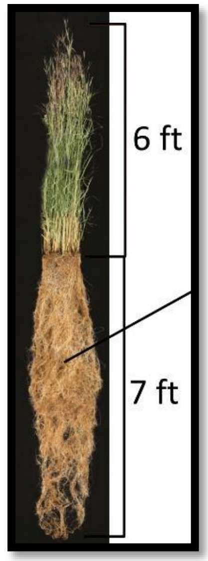

Figure 11: Typical STRIPS Root Structure (Duirk 2018)

The implementation and maintenance of STRIPS systems is fairly simple. The prairie grasses can be planted several times throughout the year, but it is preferable to plant seed in the fall after the harvest or the spring, before or after planting the crop ("Management" 2019). The fall is the best planting time for the forbs and the prairie grasses, but winter seeding can also be successful. The University of Iowa, after conducting this study, created a three year projected timeline for the maintenance of these strips. During year one, mowing is required, and plants will look like a short, vegetated buffer, since these types of plants spend their first year developing the necessary complex root system. During year two, early species may bloom, mowing is no longer required, and simple spot spraying can be used if there is an especially weedy area ("Management" 2019). In year three, the prairie plantings will resemble a diverse native tallgrass community. Beyond three years, maintenance includes spot application of herbicide as needed, bailing or prescribed burning of STRIPS, and occasional maintenance mowing ("Management" 2019). As it can be seen, the implementation of STRIPS systems is easy due to the plants' versatility and ability to germinate in almost any season, and the maintenance methods are fairly straightforward.

As a result of this case study, a 95% soil and sediment retention rate was observed where STRIPS were planted, and there was a reported 84% retention rate for Nitrogen and 90% retention rate for Phosphorus in the soils (Duirk 2018). This study showed that there is biological application for erosion control methods of sediment in the Midwest. Additionally, the STRIPS systems are cost-effective. The average annual cost of converting one acre of crop land to STRIPS ranges from $280-$390 per year ("Management" 2019). Additionally, The University of Iowa proposed a 10% solution, where one acre of STRIPS protects nine acres of crop land, and this would cost $28-$39 per year. The majority of the costs of STRIPS are associated with the upfront costs of site prep, planting, mowing, and purchase of the seed mix. There are several organizations that provide cost-share dollars to further reduce the startup costs of STRIPS. Some of these organizations include the USDA Natural Resources Conservation Service (NRCS), the USDA Farm Service Agency (FSA), and the U.S. Fish and Wildlife Partners Program ("Management" 2019). STRIPS have been proven to be an efficient and cost-effective method of erosion and sediment control; however, they are not actually being used to dewater dredged material. The

STRIPS have proven to be beneficial as a preventative method, but do not propose a solution for dewatering sediment and dredge that has already entered lakes and other bodies of water.

4.3 Lake Erie Case Study

In 2002, an erosion control study was conducted in Presque Isle, Pennsylvania that incorporated beneficial reuse of dredged material and indigenous vegetation along the shores of Lake Erie. While this study did not analyze dewatering of dredged material via biological methods, it, like the Iowa case study, incorporated a prevention plan to inhibit dredged material from entering waterways entirely. Some of the traditional erosion control methods that the study cited include breakwaters, groins, bulkheads, seawalls, and jetties, all of which are fairly costly to erect and maintain (Comoss 2002). This study investigated environmentally conscious, cost-effective methods that would produce the same erosion control results as conventional structures. A system was created for the shores of Lake Erie using downed trees, with diameters of 12-24 inches, from local parks as riprap and timber groins. The area in between the trees was filled with sand dredged from local sandbars (Comoss 2002). The sand filler was placed at a gently sloping angle, providing a back beach for turtle migration and egg hatching. Additionally, geotextiles and wattles were used to aid in vegetative rooting. Figure 12 shows a schematic of the proposed erosion control system.

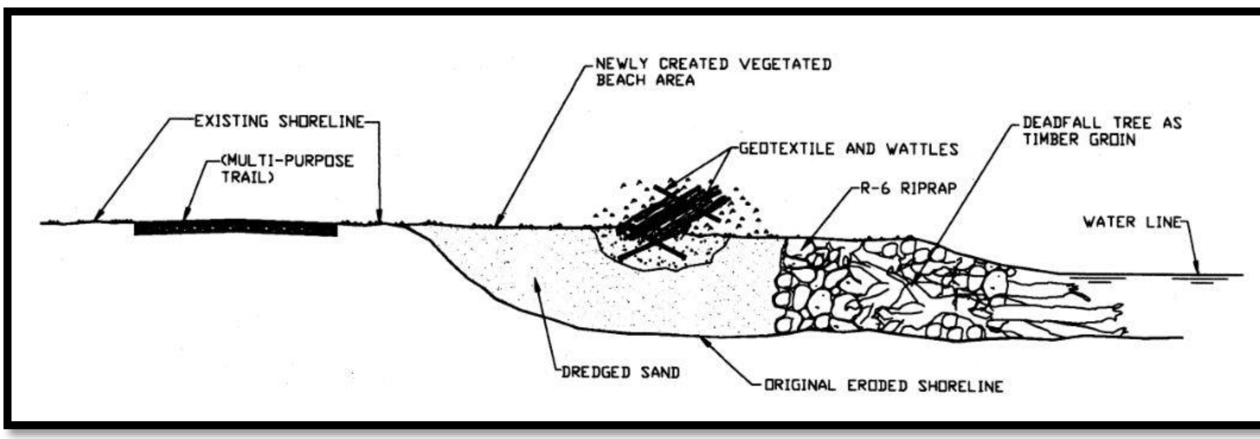

Figure 12: Erosion Control System on Lake Erie Shoreline (Comoss, Eugene J., et al. 2002)

Furthermore, several species of indigenous vegetation and aquatic plants were implemented to strengthen the erosion resistance of the shoreline. Indigenous vegetation utilized in the case study included beach grass, Indian sea oats, switch grass, choke cherry, bayberry, black oak, and driftwood, while aquatic species that were planted included branching burred, duckweed, and soft-stem bulrush (Comoss 2002). Within six months of planting this vegetation and implementing the entire erosion control system, 50% vegetative cover was achieved.

The cost of the Presque Isle study totaled $30,000. This method proved to be relatively cheap, and the native plants seemed to fare well in this system. However, erosion control of this type is limited to low energy zones, or areas with an average wave height of less than 0.5 meters (Comoss 2002). This study proved that there is promising biological applications for erosion control along Lake Erie, and that prevention of increased dredged material being deposited into waterways is possible.

4.4 South Carolina Case Study

In 2003, an ongoing research project funded by the Environmental Protection Agency was carried out in Aiken, South Carolina that investigated the feasibility of vegetative dewatering. The sediments for the experiments were collected from the Jones Island confined disposal facility (CDF), and were characterized as 22% sand, 66% silt, and 12% clay (Schwab 2003). A variety of plant species were analyzed in the study. In order to choose appropriate species, the researchers had to identify characteristics that would make them well-suited for dewatering practices. These characteristics included high water requirements, high biomass yield, high germination rates, ability to grow deep roots, and ability to adapt (Schwab 2003). Five plant species, native to South Carolina, were chosen based on these requirements. The plants used in the study were annual rye (L. multiflorum), timothy (phleum pretense), red top (agrostis alba), white clover (trifolium repens), and swamp pea (S. exaltata) (Schwab 2003). Each plant species was placed in a growth tube, and several variables were measured. The light intensities, temperature, relative humidity, wind-speed, root growth, root density, plant height and plant biomass were the variables on which the researchers chose to focus.

After a specific growing period in the tubes, each plant species was measured and analyzed. It was found that the red top had the greatest microbial bacteria population, with the swamp pea having the second highest, and the annual rye with the third highest population (Schwab 2003). The ability to sustain a high bacteria population exhibits the plant species' ability to adapt, and its resiliency. Additionally, the swamp pea exhibited the highest moisture loss, with the annual rye having the second highest, and both of these species had the greatest root growth (Schwab 2003). A deep root system increases a plant's ability to dewater the soil in which it is planted. Overall, both the swamp pea and the annual rye showed the most promising results in dewatering capabilities and sustaining high bacteria populations. These plant species are relatively inexpensive to acquire and plant, which is an advantage of vegetative dewatering over other methods. This study was completed by the end of 2003, but the final report was inaccessible.

4.5 Wisconsin Case Study

Also in 2002 and 2003, an ongoing research project funded by the Environmental Protection Agency was carried out in Milwaukee and Green Bay, Wisconsin, that investigated the ability of grasses and trees to accelerate the removal of water from sediments. The approach for this study consisted of densely planting small trees in CDFs in Wisconsin and allowing them to grow for one year (Schwab 2003). At the conclusion of the dewatering process, the trees were removed, and grasses planted in their place. The experiment to test this method of vegetative dewatering was set up in 28 control cells (Schwab 2003). These cells were constructed and lined with 36 mil polypropylene liner and filled with sediments that were removed from the Jones Island CDF.

The project was conducted in annual phases, with the first phase taking place in 2002. In this first year, the cells were planted with the following species: Poplars (varieties NM6 and OP367), hemp sesbania (sesbania exultata), eastern gamagrass (tripsacum dactyloides), common rush (juncus effuses), and smallwing sedge (carex microptera) (Schwab 2003). During the first year, all of the poplars leafed out, but the trees were unable to fully establish, and all died. Also, the eastern gamagrass, common rush, and the smallwing sedge all failed to germinate in the first year. Because of these results, two replacement species were planted: prairie cordgrass (spartina pectinate) and water sedge (C. aquatalis).

Both of these plant species fared much better, with the prairie cordgrass fully establishing in one-half of all test cells, and the water sedge establishing robustly in all cells (Schwab 2003).

In the second year of this project, five new plant species, in addition to the two that remained established from 2002, were analyzed. This phase of the project was conducted in 2003, and the same control cells were used. The new plant species included the black willow (salix nigra (SX61)), barnyard grass (echinochloa crusgalli), Italian rye grass (lolium multiflorum), red mulberry (morus rubra) and river bulrush (Scirpus fluviatilis) (Schwab 2003). In this portion of the study, the data recorded and variables measured included the moisture content of the soil, the leaf surface area and the amount of transpiration that occurred. The transpiration was measured with an Infrared Gas Analyzer IRGA (Schwab 2003).

After the species were allowed to establish and a considerable amount of time had passed, the results were collected and analyzed. The three wetland species, the prairie cordgrass, water sedge, and river bulrush, removed the greatest amount of moisture from the soil. It was also determined that the water sedge was the most effective dewatering plant, the Italian rye grass was a close second, and the black willow also had an excellent capacity for dewatering (Schwab 2003). As expected, the control cell with no vegetation was the least effective at dewatering the soil. These plant species, like those in the South Carolina study, are relatively inexpensive to acquire and plant, which is an advantage of vegetative dewatering over other methods. However, many of the species planted in the first year of this study died off, or did not survive the winter. This result shows that the planting time for certain species is crucial, and unfortunately limited, in the Wisconsin climate. The study was completed by the end of 2003, but the final report was inaccessible.

4.6 Possible Methods for Further Investigation

There are several other biological dewatering techniques that have proven worthy of additional research and experimentation, but have yet to have pilot tests or small scale demonstrations conducted on them. Some of these methods include landfarming, dewatering material through the use of bio-reactors, bioleaching, and bioremediation for the reduction of hydrogen sulfide odors. Both landfarming and treatment in bio-reactors utilize microorganisms in order to promote dewatering of sediment.

4.6.1 Landfarming

In landfarming, microorganisms are used in order to degrade organic material and reduce contamination. Landfarming is done by spreading dredged sediment on plots of land in open air (Ringeling 1998). There are two methods of landfarming: intensive and extensive. During extensive landfarming, the oxygen supply is stimulated only by planting, and during intensive landfarming, the oxygen supply is stimulated through both planting and regular plowing of the plots of land (Ringeling 1998). This process is not applicable to sediments that contain a large amount of heavy metals.

4.6.2 Bio-reactors

Another method for dewatering sediments with the assistance of microorganisms is through the use of bio-reactors. In this system, sediment is introduced as a slurry to tanks, where it is mixed and put in contact with microorganisms (Ringeling 1998). These systems are controlled by several variables, including temperature, pH, nutrient content, oxygen supply, particle size, and bio-availability. Similarly to landfarming, dewatering sediments with bio-reactors cannot be done with sediments that contain a large amount of heavy metals.

4.6.3 Bioleaching

Bioleaching is an indirect process for the leaching of metals from sulfide minerals. In this process, ferric iron and oxygen in acid solutions act as the oxidizing agents (Estes). Through the bioleaching process, ferrous iron, sulfur and other sulfur species are oxidized. The following reactions occur during this process:

$$MS + 2Fe^{3+} \rightarrow M_2 + 2Fe^{2+} + S$$

$$2Fe^{2+} + \frac{1}{2}O_2 + 2H \rightarrow 2Fe^{3+} + \ H_2O$$

$$S + \frac{3}{2}O_2 + \ H_2O \ \rightarrow SO_4^{2-} + 2H^+$$

$$MS + 2O_2 \rightarrow M_2 + SO_4^{2-}$$

This process can be important in identifying factors which must be controlled to limit metal mobilization due to acidification of sediments in beneficial reuse placement (Estes).

4.6.4 Bioremediation for Reduction of H_2S Odors

It is known that hydrogen sulfide emissions are a rising problem in confined disposal facilities. For this reason, limited research has been conducted to investigate how to reduce these emissions. In the presence of oxygen, the degradation pathway for organic material is aerobic bacterial oxidation (Estes). The process can be summarized with the following equation:

$$Carbon\ matter + O_2 \rightarrow CO_2 + \ H_2O$$

The next preferred oxidant for this process is nitrate. This reaction can be summarized as follows:

$$Carbon\ matter + NO_3^{2-} \rightarrow CO_2 + \ H_2O$$

A single study was conducted in Hong Kong using nitrate as an oxidant for the bioremediation process. In the study, liquid calcium nitrate was injected into sediments to break down organic material and reduce odor (Estes). The amount of nitrogen dosages for the study ranged from 2,900-8,400 mg/L-N. The two equations that can be used to explain the reactions that occurred can be seen below.

$$HS^- + Ca(NO_3)_2 \rightarrow CaSO_4 + \ H_2O + N_2$$

$$Carbon\ matter + NO^{3-} \rightarrow CO_2 + \ H_2O + N_2$$

After the study was conducted it was determined that the average odor removal rate was between 95 and 99%, and the amount of sediment organic matter was reduced by 16.5% (Estes). There were a few disadvantages to the process that were discovered as a result of the study. The study posed a substantial concern about eutrophication of natural systems, and there was also a concern regarding the mobilization of sulfide-associated metals (Estes).

5. Beneficial Reuse

After dredged material is adequately dewatered, either through mechanical, chemical or biological methods, the material is able to be reused. There are specific requirements that must be met by the dewatered material in order for it to qualify for reuse applications. Some of the most important factors

for cleaned and dewatered dredged material are the environmental characteristics of the material, the material properties, the national policy and public resistance regarding usage, and several economic aspects (Ringeling 1998). Environmental requirements are detailed by national legislation, and there are typically national policies regarding the reuse of materials for structural purposes. There are extra levies placed on primary materials, and sometimes contractors are obligated to use secondary, or cleaned and reused, materials (Ringeling 1998). However, the costs of secondary materials are usually higher, and the cost of dewatering dredged materials is sometimes higher than the cost of primary materials. With that being said, there are several beneficial uses for secondary materials, and several processes to create reusable material after it has been dewatered. Two of these processes include soil solidification and stabilization, and Cement-Lock Technology. Once these processes are complete, there are a multitude of reuse applications for which the material may be suited.

5.1 Solidification/Stabilization

One way to prepare previously dewatered material for beneficial reuse is through the process of soil solidification and stabilization. This process turns waste into a solid material, through the reduction of surface area of solidified materials and reduction of contaminant mobility (Estes). According to the USACE, this process is currently recognized as the best available technology for the disposal of toxic sediments. The process is typically used for sediments with high metal content, but can be effective for low level contaminants as well (Estes). The USACE cited a case study conducted in 2011 that demonstrated that Portland cement and fly ash could be used to solidify and stabilize waste material, while still maintaining soil strength. The parameters that were identified as important for solidification and stabilization of materials included cement type and dosage, soil type, mixing, curing conditions, organic content, pH, and grain size distribution (Estes).

There are several advantages to using this process to not only prepare material for reuse, but to minimize contaminant mobilization. The cost of the process is inexpensive, since it uses other industrial wastes such as fly ash and cement kiln dust (Estes). Soil solidification and stabilization also is fairly easy to implement; high water content sediments can be treated without further dewatering and mixing can occur in barges, which results in less need for staging areas and multiple unit operations. Finally, the entire process is synergistic, meaning that the materials are already alkaline in nature and further reduce the mobility of the metals naturally (Estes). There are a few disadvantages to this method though. The contaminants are only immobilized, not fully destroyed. Furthermore, oily sediments are not as readily treated due to the effects oil has on hydration (Estes).

5.2 Cement-Lock Technology

One specific beneficial use application that was recently investigated in Upper Newark Bay, New Jersey is called Cement-Lock. The goal of the full scale demonstration was to thermo-chemically transform sediments into construction-grade cement (Foged 2007). Experiments were conducted and several objectives for the experiment were outlined. The objectives included processing a bulk quantity of dredged material from harbor navigation channels through the Cement-Lock demo plant, showing that contaminants in the sediment were destroyed, showing that the sediment qualified for beneficial use applications, and showing that the sediment processing can be $35 or less per cubic yard (Mensinger 2006).

In general terms of the experiment, when the sediment arrived at the plant, it was mixed with modifiers and charged to a rotary kiln that maintains a temperature of 2500˚F. The sediment-modifier mixture was

then turned into a homogenous melt through a thermo-chemical process, and the melt then flowed through another kiln, and eventually mixed with water, which quenched and granulated the melt (Mensinger 2006). Then the product was removed by a drag conveyor, which served to further dewater the material. The actual experiment conducted at the New Jersey plant can be summarized as follows. First, the sediment was screened and dewatered to 55 percent water in a belt filter press, and the sediment was transported to the Cement-Lock site in 20 containers (Mensinger 2006). Then, the sediment was run through the demo plant, and capacity was measured during the two operating modes that the plant uses. The first mode, slagging mode, converted the sediment into a substance called Ecomelt, which is a non-crystalline remediated product that can be ground down and blended with a lime source to create construction grade cement (Mensinger 2006). The second mode, non-slagging mode, resulted in a product called EcoAggMat, which can be beneficially used without additional treatment, as fill or as partial sand replacement in mortar. During the demonstration, 20 tons of sediment was processed when the plant was in slagging mode, producing 2 tons of Ecomelt, and 80 tons of sediment was processed when the plant was in non-slagging mode, producing 53 tons of EcoAggMat (Mensinger 2006).

Both reuse materials were subjected to EPA TCLP tests, and neither material was found to have metals leaching. In the EcoAggMat, the levels of PCBs were reduced by 99.97% (Mensinger 2006). In regard to the plant as a whole, the ability for capture and destruction of organic and inorganic contaminants in the dewatered sediment was found to be significant. The emission rates of sulfur dioxide, NOx gases, and carbon monoxide were well within New Jersey Air Quality Permit limits. Within the Cement-Lock plant, 99.49% of PCBs were destroyed, 99.84% of dioxins and furans were destroyed, 99.02% of toxicity equivalency from dioxins, furans, and PCBs was destroyed, and the rate of mercury collection efficient of the activated carbon bed in the plant was 99.2% (Mensinger 2006). Furthermore, it was determined that the tipping point for operation of the Cement-Lock plant was $34.97, which was below the objective of $35 per cubic yard.

5.3 Applications

Once material is adequately dewatered, and possibly run through one of the processes outlined above, it can be put to use in a variety of applications. Some of these applications include agricultural uses, building materials, infrastructural works, expanded clay grains, and sintering.

Agricultural uses of dewatered dredged material include the use of the sediment as topsoil and in aquaculture applications (Ringeling 1998). The best topsoil is a mixture of sand, silt and clay. With this application, the dredged material can be spread over the desired area in a thin layer (Ringeling 1998). However, agricultural uses are not ideal for dredged material that was cleaned by thermal or physical treatment.

In addition to agricultural uses, there are several ways that dewatered dredged material can be used as a building material. The material can be used in gravel applications, where it is judged based on grain size distribution, hardness, absorption, and density. It can also be used as tiles or stones, where it is classified based on dimensions, stiffness, bending, and tensile or compressive strength. There are also sand applications, where the material can be used as an aggregate for concrete (Ringeling 1998). However, dredged material that was dewatered and cleaned by biological treatments does not usually meet the requirements for reuse as a building material.

Another application of dewatered dredged material is infrastructural works. This includes use of dewatered sediment in the construction of roads, landscape dikes, and isolation layers for disposal sites. Some important material properties that are considered before material is used in these applications are grain size distribution, silt percent, organic matter content, and the hardness or strength of the material (Ringeling 1998). For use in road construction, the lime content of the dredged material should be increased, and then the material can possibly be suitable for industrial parking lots (Foged 2007). For use as a landscape dike, the use of the dredged material is dependent on the properties of the clay minerals in the dewatered sediment. A high dry material content within the sediment implies that compaction of the material is possible, and that stable material can be created (Foged 2007). Finally, dewatered dredged material can be used as an isolation layer for disposal sites or as part of remediation activities if the soil properties are favorable. Some specific properties that are analyzed before material can be reused in isolation layers are strength characteristics and permeability of the material (Foged 2007). Additionally, the capping of brownfields can be done with amended dredged material. With that being said, dredged material that was cleaned and dewatered through biological treatment is not usually able to meet the material requirements for beneficial reuse in many infrastructural works.

Two other beneficial uses of dredged material can be seen through the processes of clay grain expansion and sintering. For expanded clay grains, the dewatered dredged material can act as a filler or substitute for natural clay in the production of sintered clay grains (Foged 2007). Sintering, a thermal immobilization technique, results in products like bricks (similar to those that Cement-Lock produces), tiles, and artificial gravel. The disadvantages of sintering are that the energy consumption is high and that emissions need to be limited, since some pollutants are volatile (Foged 2007).

6. Conclusions

There are a variety of methods that can be used to dewater dredged material. The three methods explored in this paper were mechanical, chemical, and biological dewatering techniques. After the dredged material is effectively dewatered using any of the above methods, the material may be tested and analyzed for use in beneficial reuse applications.

Mechanical thickening and dewatering methods were presented first. Many of the methods used to prepare the dredged material for dewatering included the use of machines called thickeners, of which there is a variety of types. Then, the mechanical devices that were investigated to efficiently dewater dredged material were presented. These included geotextile tubes and presses such as the belt filter press, chamber filter press, filter press, plate and frame press, and screw press. Additionally, emergent technologies were explored that included new, innovative mechanical dewatering methods. Some of these methods were froth flotation, soil washing, magnetic separation, gravity separation, and grain size separation.

Chemical dewatering techniques were investigated next. Some of these techniques used chemical thickening methods and well-known chemical compounds, such as flocculants, to dewater dredged material. Another technique for dewatering included the use of industry-created compounds, such as GEO Specialty Chemical’s polyacrylamides enriched with coagulants. Other methods made use of chemical processes, including chemical oxidation and chemical extraction, to effectively change the composition of the material and make it more suitable for dewatering. Other chemical dewatering processes that were investigated included thermal treatment and thermal immobilization

Biological dewatering techniques were the last dewatering method to be analyzed. Case studies gathered from around the country provided insight about plant types and planting methods that were found to be conducive to the solids dewatering process. Case studies were compiled from five states, including Alabama, Iowa, Ohio, South Carolina, and Wisconsin, and each case study presented a different biological dewatering technique. Additionally, several areas for further investigation were outlined and included dewatering of solids through the use of landfarming, bio-reactors, bioleaching, and bioremediation for the reduction of H_2S odors. Additionally, biological techniques that serve as preventative measures to prevent sediments from entering navigation channels entirely were also introduced.

Finally, beneficial reuse applications were analyzed. Two processes that were investigated included soil solidification and stabilization and Cement-Lock technology. These methods are used post-dewatering but before the material is put into use as beneficial reuse. Some beneficial reuse applications that were explored include agricultural uses, building materials, infrastructural works, expanded clay grains, and sintering.

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