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Dewatering Contaminated, Fine-Grained Material Using Geotextiles

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DEWATERING CONTAMINATED, FINE-GRAINED MATERIAL USING GEOTEXTILES

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ABSTRACT

The ability of geotextiles to retain solids while passing liquid has lead to their use in dewatering fine-grained materials. Fine-grained materials such as dredged material from waterways, lagoon sediment or industrial waste products tend to have long and inefficient dewatering periods when allowed to dry by simply leaving the surface open to the atmosphere.

When fabricated into a tube, geotextiles act to contain the material and provide faster dewatering due to several factors. The objective of this paper is to provide basic information regarding the consolidation and dewatering of fine-grained materials within permeable tubes of various polymeric fibers and the retention of solids and pollutants within the geotextile tube.

Several laboratory tests and full scale projects have been conducted which are providing basic filtration, retention, consolidation and effluent water quality data. Additionally, these tests are verifying the efficacy of geotextile tubes and the cost effectiveness of this technology when compared to other methods of dewatering. An understanding of how dewatering occurs within a geotextile tube can be matched to specific project objectives to design the most appropriate and cost-effective application.

INTRODUCTION

The need for improved dewatering technology stems from the basic premise that saturated, fine-grained materials are typically bulky, have little or no value in their saturated state, and do not dewater efficiently on their own. For example, fine-grained cohesive dredged material consolidates to an equilibrium moisture content somewhat above the liquid limit with a relative consistency of warm axle grease (Haliburton, 1977). After reaching this state, the stress deformation relationship of the material is such that little additional settlement occurs from self-weight consolidation. In the dredging industry, this means that very large areas are required for the containment of dredged material. In other industries, sludge is the end product of a wastewater treatment system. Dealing with this sludge can be a costly problem.

Through laboratory testing and actual field use of geotextile tubes, it has been found that dewatering of fine-grained materials is enhanced when encapsulated within a permeable, woven geotextile. While this has been known for some number of years, the use of geotextile tubes for this purpose has not been widespread due to the lack of design guidance. In fact, most applications rely on trial and error. Even so, geotextile tubes provide a viable solution for some very difficult engineering problems.

This paper will present the results of field use and laboratory testing, and relate the data to the physical parameters of the geotextile tube/soil composite system. Dewatering concepts, geotextile properties and pertinent geotechnical principles are reviewed below.

RETENTION AND FILTRATION

During filtration, water in an encapsulated soil will seep through the manufactured plane of a geotextile driven by gradient and soil self weight while solid particles are retained. In traditional geotechnical filtration applications, a certain compatibility between the sizes of the soil particles and the sizes of openings through the geotextile is required when using a geotextile to retain solid particles while allowing water to escape (U.S. Army Corps of Engineers, 1997).

The method generally used to assure the retention of soils having a particular grain size distribution is based on the Apparent Opening Size (AOS) of the geotextile and is as follows (Task Force #25, American Association of State Highway and Transportation Officials (ASSHTO, 1990):

For soil with 50% or less particles by weight passing U.S. No. 200 sieve, the AOS of the geotextile must be less than 0.595 mm (AOS > No. 30 sieve).

For soil with more than 50% particles by weight passing U.S. No. 200 sieve, the AOS of the geotextile must be less than 0.297 mm (AOS > No. 50 sieve).

Apparent Opening Size is defined as the 95% opening size and is specifically measured using ASTM standard test ASTM D 4751-95. This test is conducted dry, using glass beads, and in some respects, does not replicate a wet geotextile under tension as would be the case while pumping a geotextile tube.

Several other criteria to assure retention have been developed. These often rely on the coefficient of uniformity of the soil ($CU=d_{60}/d_{10}$). It is unclear whether these have been applied to soil retention within geotextile tubes, but it is generally believed that a highly-uniform, fine-grained sediment can pipe through a tube under dynamic loads such as wave action. For filtration applications subject to cyclical loading such as in a wave or tidal environment, Schiereck (1998) provides the following criteria:

$$O_{98} < 2\ d_{85}$$

Where O_{98} = 98 percent of the grain size retained by the geotextile
and d_{85} = the 85th percentile of the soil to be retained.

Leshchinsky (1992) notes that when the soil being filtered by a geotextile is a slurry containing clay, experience shows that the escape of particles through the geotextile stops rapidly and the seepage water becomes clear. This may occur due to clogging or blinding of the geotextile, and in a tube, can result in a filter cake which increases the filtration capability and decreases the permeability.

Clogging and Blinding. Clogging is the movement of soil particles into the voids of a geotextile, thereby reducing the hydraulic conductivity (also known as permeability) of the geotextile (Koerner, 1994). Schiereck (1998) states that clogging is a time dependant process which stabilizes after a certain period of time. Blinding similarly reduces the hydraulic conductivity by blocking the openings in the geotextile. A soil/geotextile composite which has blinded will typically have permeabilities very close to the soil itself and will exhibit very small amounts of fines passing through the geotextile (Austin, et al., 1997).

When discussing dewatering with geotextile tubes, the term “clog” tends to imply that water has completely stopped passing through the geotextile. Blinding is more often the case since soil particles build up a restrictive layer (filter cake) on the inside surface of the geotextile thus reducing the permeability of the geotextile but usually not eliminating water seepage. In fact, polyester fabrics being hydrophilic, tend to wick, allowing moisture to be removed from the tube through evaporation. Sludge within a polypropylene tube on the other hand, tends to desiccate against the geotextile shell.

Filter Cake and the Importance of Viscosity. The term filter cake comes from the use of specific cake resistance, often considered to be the key factor in the characterization of sludge dewaterability (Tosun, et al., 1993). The cake filtration equation is based on an analogy to Ohm’s law for two resistances in series, one resistor being the filter and the other being the mass of solids forming the cake. Time, viscosity, pressure drops and resistance are the key parameters in the cake filtration equation. Darcy’s law, however, is not used in the derivation of the cake filtration equation, with the result that when the permeability of the cake is compared to resistance, mathematical inconsistencies are noted (Tosun, et al., 1993).

From field experience with geotextile tubes, grain size alone is not a reliable parameter to predict the filtration capability of a particular geotextile. Viscosity appears to play a role. When considering the consolidation of clay (or extremely fine-grained particles), the water surrounding the particle must deform (Dunn et. al, 1980). This deformation is viscous in nature and the speed of the deformation is a function of the magnitude of the load placed on the material. The time lag associated with viscous resistance is called viscous lag, and when acting with hydrodynamic lag, form the processes by which consolidation occurs. The Terzaghi theory of consolidation, however, recognizes only hydrodynamic lag in determining settlement.

Multiphase filtration theories, which are improvements on the cake filtration equation, indicate that the high drag which occurs at the cake-filter interface controls the filtration rate (Tosun, et. al, 1993). The newer equations include a resistance function that relates the drag force to the velocity difference and is dependent on the viscosity of the liquid and the surface area of the solids.

Background. Previous tests conducted by the U.S. Army Corps of Engineers provide a background on the ability of geotextiles to provide for filtration and retention of soils. Filtration data were collected for a geotextile tube project at Nippersink Lake, Illinois (U.S. Army Corps of Engineers, 1997). The dredged material contained volatile organics and was described as a peaty clay. The geotextile system was a composite of a nonwoven inner liner and a woven polypropylene tube. Test results showed that Total Suspended Solids (TSS) in the seepage water were a small fraction of the background water (meeting the Illinois Environmental Protection Agency regulation of no more than 15 PPM) and, that TSS decreased during the pumping process. This was reasoned to be due to blinding or clogging of the inside of the geotextile's openings.

There may not, however, be a need for an inner liner in most cases. Testing conducted by Moo-Young, et. al., (1998) indicated that a composite of geotextiles increased the filtering efficiency by, at most, 0.01%. Filtering efficiency (FE) was defined as:

$$\mathrm{FE} = \frac{\mathrm{TSS}_{\mathrm{initial}} - \mathrm{TSS}_{\mathrm{final}}}{\mathrm{TSS}_{\mathrm{initial}}} \times 100 \qquad (1)$$

Similar results were found during testing described herein using dredged material. This work will be described in more detail under the laboratory testing section.

PERMITTIVITY AND PERMEABILITY

Filtration is one of the most important functions of a geotextile. The relationships between permittivity, permeability and water flow are important in understanding filtration. To dewater fine-grained materials, the liquid must flow through the geotextile and the dewatering soil itself. Permittivity describes the cross-plane permeability (or hydraulic conductivity) and is defined as:

$$y = \frac{k_n}{t} \qquad (2)$$

where y = permittivity,
k_n= the permeability coefficient (hydraulic conductivity) normal to the geotextile, and
t = the thickness of the geotextile.

Substituting the above equation into Darcy's formula yields the following:

$$\begin{aligned} q &= k_n i A \\ &= k_n \frac{\Delta h}{t} A \\ \frac{k_n}{t} &= y = \frac{q}{(\Delta h)(A)} \end{aligned} \qquad (3)$$

where q = the flow rate,
i = the hydraulic gradient = $\Delta h/t$,
Δh = the head loss, and
A = the total area of geotextile test specimen.

This implies that water flow rate and permittivity are directly proportional assuming the head loss and area are constant (see table 1).

As with soil permeability testing, the above formula is used for constant head tests. The flow rate (q) is measured at different values of Δh, and when ΔhA versus q is plotted, the slope of the resulting straight line yields the desired value of y (Koerner, 1994).

Sample	**Type**	**AOS (Sieve No.)**	**Permittivity ($\mathbf{sec^{-1}}$)**	**Water Flow Rate (gal/min/ft2)**
A	PP, nonwoven, 12 ounce	100	1.00	75
Separation Fabric	PP, woven slit film	40	0.07	6
Filtration Fabric	PP, woven monofilament	70	0.28	18
Reinforcement Fabric	PP, woven, 400 X 400 #/in tensile strength	30	0.60	45
B	PP, woven, 400 X 600 #/in tensile strength	40	0.3	20
C	PET, woven, 1200 X 1200 #/in tensile strength	40	0.1	3
D	PET, woven, 1000 X 1000 #/in tensile strength	40	0.3	18
E	PET, woven, 1000 X 1000 #/in tensile strength	60	0.1	6

Table 1 - Minimum Average Roll Values of drainage properties of tested geotextiles

In the laboratory tests described herein, the permeability of the soil/geotextile mass was found to change both with time and distance away from the surface during the lab testing.

CONSOLIDATION WITHIN A GEOTEXTILE TUBE

Tubes achieve a natural height dependent on the pressure of pumping and the density of the fill material. For sandy materials, the tube will consolidate quickly and will retain nearly its original height. For fine-grained sludges and dredged material having a high water content (low percent solids), tubes will decrease in height as water is expelled and the material consolidates within the tube. The amount of consolidation (settlement) is typically related to the void ratio of the material. The void ratio is defined as the volume of the voids divided by the volume of the soil solids. The void ratio and load (or pressure) are two parameters typically used to calculate settlement.

Rate of Consolidation. Terzaghi and Peck (1948) presented the traditionally used theory to describe the time rate of consolidation of clay soils. A coefficient of consolidation, c_v, is calculated for each load increment based on consolidation tests, and is a function of the permeability and the coefficient of volume decrease. The rate of consolidation can be estimated using a time factor, T, which is a function of the degree of consolidation, U.

In dredge disposal studies the length of the shortest drainage path is particularly important and results in the following equation (Salem, et al., 1977):

$$c_v = \frac{T\,h^2}{4\,t} \tag{4}$$

where t = time
h = the length of the shortest drainage path
T = time factor which is a function of the degree of consolidation

Several filtration and consolidation factors are enhanced by dewatering within a geotextile tube. The filtration surface area is increased by encapsulating the material in an oval container. Drainage paths are optimized and pressure (or self weight) is maximized due to the geometry of the tube.

Tubes filled with various sludges during the field testing portion of this study decreased in height at rates and magnitudes similar to Fowler, et al. (1996) and Miki, et al. (1996). That is, height decreased rapidly during the initial hours and days and slowed with increasing time. Both lagoon waste from a pig farm and sludge from a waste water treatment facility reached acceptable levels of percent solids in two to three weeks.

The equation for predicting consolidation within a tube developed by Leshchinsky, et al., (1996) is based on the experience that the height of the tube drops while the maximum width changes very little. When plotted for various ratios of initial slurry unit weight to the unit weight of water, equation 5 provides an approximate estimate of the average drop in height:

$$\frac{\Delta h}{h_o} = \frac{G_s(\omega_o - \omega_f)}{1 + \omega_o G_s} \tag{5}$$

where Δh = decrease in the height of the tube
h_o = initial height of the tube
G_s = specific gravity of the solids
ω_o = initial water content of the fill material
ω_f = final water content of the fill material

None of the preceding theories or equations can be used to predict which style of geotextile will dewater best for a particular sludge, or help the project designer determine the optimum tube size and geometry. Laboratory testing was conducted to lend further insight into the interaction of the geotextile and fine-grained material during dewatering.

LABORATORY TESTING

Dredged material from New York Harbor was used for laboratory testing of various geotextiles. The purpose was to determine the optimum geotextile for confining this potentially contaminated fine-grained material within a tube. Filtration testing was conducted under accelerated conditions to simulate long term dewatering.

Grain size analysis was conducted on the dredged material via sieve and hydrometer. The dredged material was comprised of 85 % silt, 12 % clay, and 3 % fine sand and shell fragments (Figure 1). The dredged material was placed in a column and allowed to drain through a geotextile. Accelerated conditions were achieved by drawing a vacuum below the geotextile to collect effluent water. Water was collected for a standardized 24 hours. After this period of time, visible dewatering had ceased and the effluent was sent to a water quality lab for testing. Table 2 shows the characteristics of the dredged material before filtration and the collected effluent after the 24-hour period. All of the geotextile styles performed well, however it is important to note that the addition of a nonwoven (A+B) did not provide a significant increase in performance and may have hindered volume reduction (ie. consolidation).

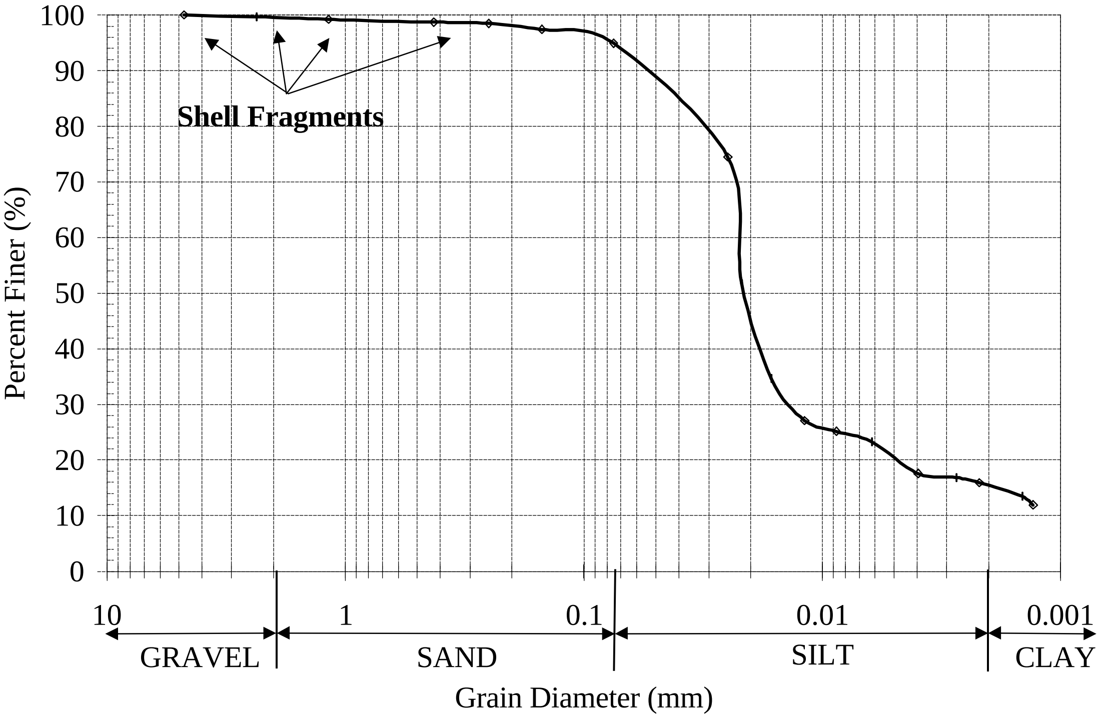

Figure 1 – Grain Size Distribution of New York Harbor Dredged Material

The retained dredged material was analyzed for its moisture content and percent solids. It was found that material closest to the geotextile had the highest percent solids. This change in void ratio with distance (i.e. dynamic vertical consolidation) is believed to result in a decreasing permeability of the soil/geotextile interface. This factor, plus probable blinding of the material, retarded further dewatering of the dredge mass.

Sample	% Solids of Contained Mat'l		Volume Reduction	TSS mg/L	Chromium ug/L	Lead ug/L
	Initial	Final				
Raw	n/a	n/a	n/a	38,541	84,800	88,700
A+B	34.0	42.3	19.0	74	Not Detected	410
B	32.8	43.0	24.3	80	Not Detected	520
C	33.6	42.5	17.5	145	250	460
D	34.1	43.6	26.2	98	Not Detected	1200
E	32.6	42.1	20.0	90	Not Detected	660

Table 2 – Characteristics of Raw Dredged Material and Filtered Effluent Water

Figure 2 illustrates the phenomena of decreasing permeability and blinding in dredged material from New York Harbor. To eliminate units in the analysis, the parameters of 'moisture content' and 'distance from geotextile/dredge interface' are divided by 'initial moisture content' and 'diameter of dredge contact area (dia_{ca})', respectively. A logarithmic increase in moisture content develops as the distance from the geotextile/dredge interface increases. If the trendline is extended, as shown in the figure, an interesting situation can be postulated. If evaporation were not to occur, the moisture content at a distance 1.3 times the dia_{ca} away from the geotextile/dredge interface, would remain constant. This would imply that smaller circumference tubes would dewater to a greater percent solids on average than larger tubes. Since the polyester continues to wick away moisture, however, dewatering is not expected to completely stop. Experience shows that given sufficient time, very-fine grained dredged material will continue to dewater to a very low moisture content.

If the data points representing the composite A+B filter are removed, R^2 increases. This may point to the added complexity of the cake-filter interface when two geotextiles are used.

The result of both the laboratory testing and field applications for some fine-grained materials used in geotextile tubes, is that dewatering results in a drier, outer layer surrounding a higher moisture content center. Miki et al. (1992) reported similar findings for fill material with a very high percentage of clay (82.4%). A schematic of this scenario is shown in Figure 3.

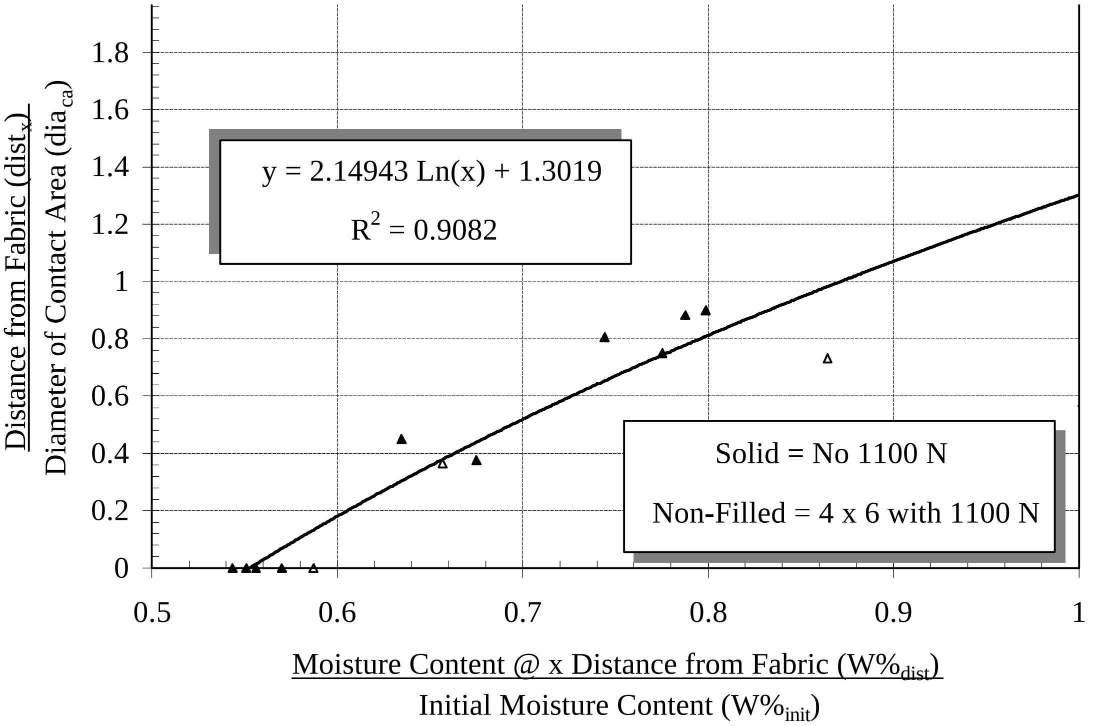

Figure 2 – Normalized Illustration of Decreasing Permeability and Blinding of Dredged Material (for moisture content above 0.87 the curve is extrapolated)

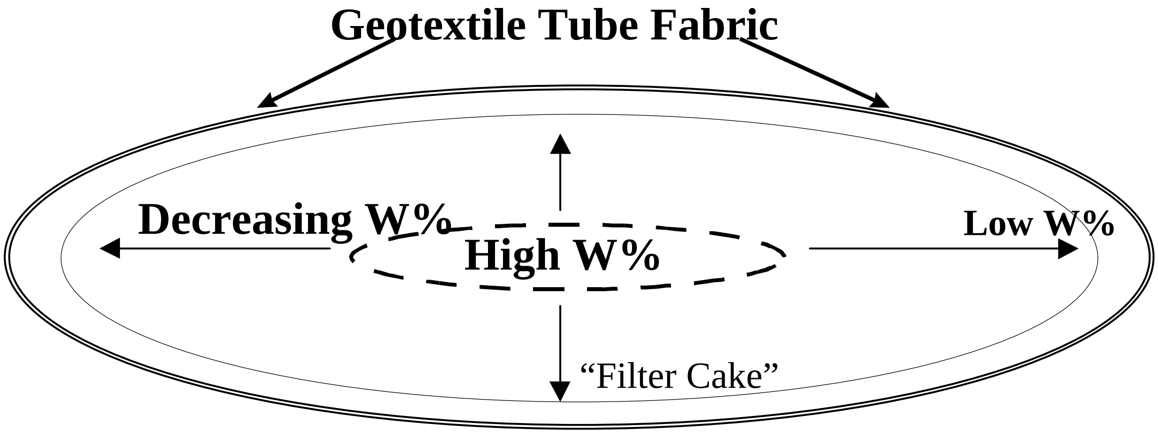

Figure 3 – Possible Dewatering Characteristic of Geotextile Tube/Dredge Material Drainage

Drainage distance (see equation 4) is therefore an important consideration. A geotextile tube will contain a certain volume (cross sectional area times a unit length) depending on its initial circumference and the height to which it is pumped (see Figure 4). A thirty-foot circumference (9.15m) tube costs more than a fifteen-foot (4.57m) tube, but will contain much more sludge. For the same unit volume however, a fifteen-foot circumference tube would have a shorter drainage distance and could be expected to dewater faster and more completely than the thirty-foot tube. For the same total volume, however, a fifteen-foot circumference tube would need to be roughly four times as long, therefore requiring more space for dewatering.

For the dredged material used in the laboratory testing, the most efficient retention and dewatering occurred with a single layer of woven polypropylene (style B). Since polypropylene does not wick, it is unknown how this fabric would compare to polyester over the long term in a field situation. Further testing of various types of fine-grained materials need to be tested and compared to field results in order to determine the relationship of accelerated testing to field dewatering in a tube.

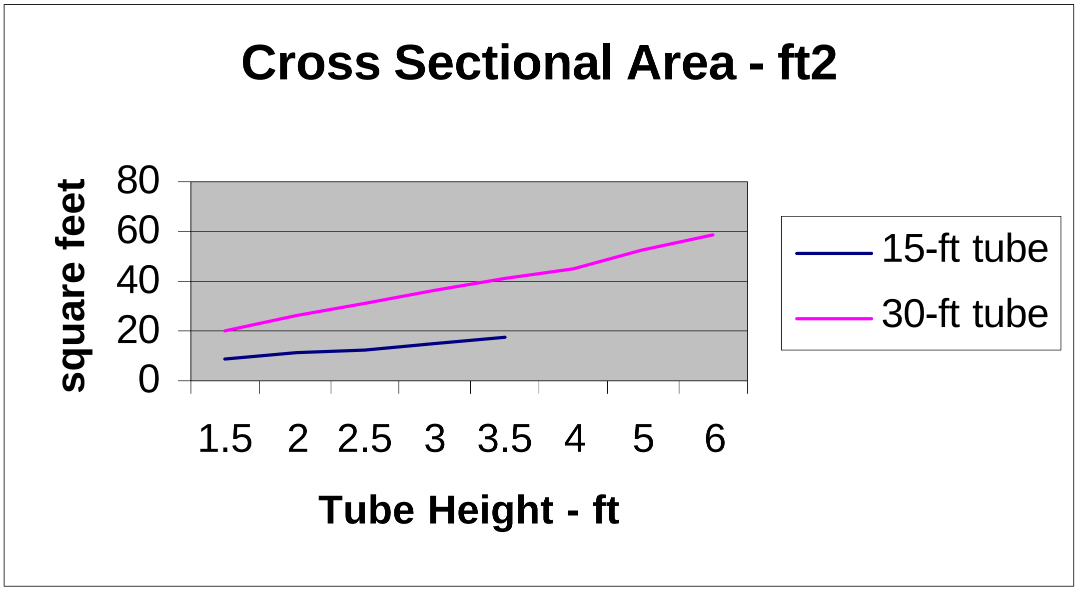

Figure 4 - Geotextile tube capacity for 15-ft (4.57m) and 30-ft (9.15m) circumference tubes

FIELD TESTING

Industrial Retention Project. Geotextile tubes were used in two recent projects which demonstrate the ability to dewater and contain contaminated materials. The first was a project in Seattle, Washington, in October of 1997, where a dewatering system was used to dewater chemically-treated stormwater to improve the overall quality of water entering the environmentally sensitive waterway. The Port of Seattle, responsible for managing the SEATAC International Airport, was having a problem meeting water quality standards from their stormwater discharge. The port was in the process of constructing a 30-acre parking lot when the fall rains started. Construction was still in the grading stages. The existing stormwater control system failed and was not capable of treating the stormwater to the desired level to meet water quality standards. Fine sediments from the site exceeded the turbidity.

A water quality criterion used by the Department of Ecology to measure contaminant concentration is based on total suspended solids measured in Nephelometric Turbidity Units (NTU). An NTU is a qualitative, rather than quantitative way of measuring turbidity. It is calculated by measuring the dispersion of a light beam passed through a water sample. Fine particles such as clay, silt, organic and other suspended matter will cause a beam of light passing through the water sample to be scattered. It has been determined that the amount of scattering is proportionate to the amount of turbidity present. The higher the NTU number, the more the beam of light is scattered. There is a direct correlation between the higher NTU value and particle size distribution within the water sample. Since clay and silt particles (<0.00195 mm and 0.047 to 0.00195 mm, respectively) remain in suspension for longer periods of time, a higher NTU value indicates a higher concentration of these particles from urban areas. The acceptable range for human consumption is 1 to 5 NTUs.

The Department of Ecology's Water Quality Standards require that the turbidity in the receiving stream not exceed 5 NTUs above background from the source. This limit translated into a treatment standard of 25 NTUs for parking lot storm water discharge. Parametrix, Inc., an environmental consulting firm, designed a treatment system to meet the criteria. During the one-month design and construction stage, stormwater was hauled to Port property and disposed of on land at considerable cost, or be faced with a potential penalty of $10,000 per day.

A batch chemical treatment system was designed and installed which included three 20,000-gallon settling tanks, one 20,000 gallon sludge storage tank, and two geotextile tubes to dewater the contents in the sludge tank. Alum and caustics were injected into the stormwater prior to the settling tanks. The sludge from the bottom of the settling tanks was pumped to the sludge tank and allowed to settle again. Sludge from the sludge tank was pumped periodically into the geotextile tubes for further dewatering.

The tubes were 15.2 m (50 feet) long and 9.15 m (30 feet) in circumference, consisting of a woven polypropylene inner tube (sample fabric B) and a non-woven outer shell. When pumped full with sludge, tube heights were about 1 m (3.1 feet) high. Two tubes were used so that they could be filled on an alternating basis. It took up to 12 hours before the tubes were filled. Analysis of the discharge water (effluent) from the tube system was measured to be less than 8 NTUs.

For a short period, before the installation of the geotextile tubes, the sludge from the sludge tanks was hauled to a landfill at a cost of $66 per ton of sludge (approximately 10% solids) plus $125 per hour handling charge.

The geotextile tubes provided a significant cost savings. The cost per tube was $900. Only three tubes were needed for the seven month operation of the treatment system. For final disposal of the tube contents, the tubes were slit open, and the dirt was used for fill at the site. The empty tubes were hauled to the local landfill for disposal.

<u>Waste Water Treatment Project</u>. In a second project, geotextile tubes were successfully used to contain and dewater approximately 1,400 cubic yards (288,800 gallons) of tannery waste. Production at the tannery had outpaced the capacity of the wastewater treatment system. Tubes were used as a cost-effective alternative to belt presses and filter presses because of their capacity, and the ability to be filled quickly. Presses can only treat small amounts of waste at a time, therefore this method did not allow adequate response time to get ahead of the problem. Rental of this equipment was proving to be very expensive when compared to material costs, mobilization and pumping of the geotextile tubes.

The tube dewatering site was prepared by grading the area and lining it with an impermeable plastic sheet. Water draining from the tubes during dewatering was to flow into a sump to be pumped back into the waste collection system.

Five permeable geotextile tubes of various fabrics and weaves were used. One tube was fabricated from polypropylene, and the remaining tubes were made of high strength polyester (see figure 5). The polypropylene tube was made from sample fabric B and was 40 feet (12.2 m) in length and 15 feet (4.57 m) in circumference. This tube was originally pumped to a height of approximately 3 feet (0.9 m). As it dewatered, the tube decreased in height and was able to be pumped full a second time.

Figure 5 – On site dewatering of sludge within polyester and polypropylene geotextile tubes

The polyester tubes were 30 feet (9.15 m) in circumference, with lengths ranging from 40 to 200 feet (12.2 to 61.0 m). Geotextiles used were sample fabrics C, D, and E. Two of the shorter tubes were pumped three times. The 200 linear foot tubes were placed in a "U" shape.

Polyester has different hydraulic properties than polypropylene. The polyester fibers are hydrophilic. During pumping, the polyester geotextile becomes wet and the weave becomes very tight. Effluent solids as small as 0.45 microns in size were retained within the tube. During dewatering, the polyester continues to weep water and lose moisture to evaporation. Polypropylene on the other hand, is hydrophobic, and apparently retains solids by forming a surface tension at the wall of the tube.

A sample of sludge pumped into the tube had a Total Suspended Solids (TSS) of 441 grams/liter. The water seeping from the tube during pumping had a TSS of 0.65 g/l. Using equation 1, a filtering efficiency of 99.998% was obtained. As one might expect, there was no significant difference in the Total Dissolved Solids. Chromium within the sludge was reduced from 3.370 mg/l to 0.8437 mg/l in the water seeping from the tube.

Two types of sludge were pumped into the tubes. Primary waste from the plant was pumped directly into the 200-foot tubes bypassing the oxidation ditch. Biological (anaerobic) sludge was pumped from the secondary clarifier into the smaller tubes. Both sludges experienced rapid dewatering of bulk water during the pumping process. Once in the tubes, however, the two sludges behaved differently. The primary effluent released water held by surface tension quicker than the biological effluent. After two weeks, the primary effluent had reached a percent solids of greater than 25%. The criteria for landfilling is 17%, therefore the primary effluent was ready to be excavated from the tube and disposed of.

Two types of dewatering occurred in the tubes. Initially, the dewatering was mechanical due to pumping, then, passive dewatering occurred over a period of weeks. Dewatering was apparently uniform throughout the tube filled with primary waste (see table 3). For the biological sludge, greater desiccation occurred near the surface of the tubes. The sludge in the center of the fifteen foot (4.57 m) circumference tube dewatered slightly better than the 30 foot (9.15 m) circumference tube, presumably due to a shorter drainage distance.

Sludge	**Geotextile Tube**	**Percent Solids (after 2 weeks)**
Original sludge pumped into the tubes		10.38%
Primary waste. Consistent density throughout tube.	Sample fabric C, polyester, 30-ft circumference. 200 linear feet.	25%
Biological sludge. Top of tube.	Sample fabric B, polypropylene, 15-ft circumference	30%
Biological sludge. Middle of tube.	Sample fabric B, polypropylene, 15-ft circumference	21%
Biological sludge. Top of tube.	Sample fabric C, polyester, 30-ft circumference. 100 linear feet.	24%
Biological sludge. Middle of tube.	Sample fabric C, polyester, 30-ft circumference. 100 linear feet.	18%

Table 3 – Dewatering results for various geotextiles and sludges

Fowler (1996) reported similar measured percent solids for dewatering sewage sludge in a geotextile tube. Of interest is that measured values were higher than calculated. Fowler suggested that the increase was due to the three-dimensional drainage and consolidation which occurs in a tube.

Geotextile tubes provided a cost-effective alternative to sludge presses when quick containment of a large volume of sludge was required. When one considers the cost of regulatory fines and a potential plant shut down, the use of tubes was far more cost effective than traditional technology which was unable to accomplish the intended purpose.

CONCLUSIONS

The results of this work, and particularly the full scale field projects successfully demonstrate the use of geotextile tubes for retaining and dewatering various fine-grained materials as well as the containment of various contaminants. In both field tests the client saved money over traditional methods. With a material cost of approximately $900.00 per tube, the Seattle system provided significant cost savings over alternative methods of treating stormwater runoff from urban environments and prevented fines of $10,000 per day.

The tannery project successfully solved a problem for which no other practical alternative existed. By containing large quantities of tannery sludge in a cost-effective manner, the plant was able to return to optimal operating conditions. This allowed the plant operator to re-establish proper waste management parameters such as odor, pH, and acceptable solids level in the oxidation ditch and the secondary clarifier bringing the company back into regulatory compliance.

When added to existing literature in this field, the data collected is clarifying how fine-grained materials dewater when contained within a geotextile tube. Typical geotextile parameters such as Apparent Opening Size were not found to be significant when compared to the permeability of the geotextile/soil system. It appears that tube dewatering will eventually be described by a combination of filter cake and Terzaghi consolidation theories. In laboratory testing, fabric style had small impacts on the ability to retain solids and contaminants. In the field, dewatering was apparently related more to the content and consistency of the fill material than to its size relationship to the geotextile. Additionally, drainage path distance and surface area were found to be related to volume reduction (consolidation). These factors are important considerations for the engineer to design the appropriate size dewatering application using geotextile containment systems.

Data supports the conclusion that an additional nonwoven layer does not appreciably improve the filtering efficiency as measured using Total Suspended Solids for static dewatering applications. Given time, fine-grained materials contained within a single-layer, geotextile tube will dewater to a low moisture content.

FURTHER RESEARCH

The relationship of *in situ* viscosity to the rate of consolidation, settlement and style of geotextile tube warrants further research. While this parameter is probably not the most important in determining final dewatered characteristics, it may hold the key to optimizing the style of geotextile for a particular material such as sludge, dredged material, or lagoon waste. Testing of a wide variety of fine-grained materials need to be continued to distinguish which data are most important to collect prior to designing a geotextile tube dewatering project.

A comparison of accelerated laboratory test results to full size tube dewatering for the same fine-grained material will provide a reality check for the test. If the test accurately replicates tube dewatering, a time correlation between testing and field dewatering can be developed.

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