ABSTRACT: Economic and safe capping of high water content waste disposal lagoons or ponds is required for environmental protection. Geotechnical problems include handling and disposal, dewatering, stabilization, hydraulic performance, settlement, stability, in situ testing, and construction. This paper highlights the geotechnics of capping such very soft wastes with specific reference to a case of capping large lagoons of contaminated wastewater sludges.

RÉSUMÉ: Des solutions économiques et fiables pour la couverture des dechets semi-fluides sont nécessaires pour la protection de l'environnement. Il y a des problèmes geotechniques associés à la mise en place, le sechage, la stabilisation, la performance hydraulique, les affaissements, la stabilité, les tests et la construction. Cet article décrit les aspects geotechniques de cette méthode de couverture avec un exemple de la couverture d'un grand lagon contenant des boues polluées.

1 INTRODUCTION

The retirement of large industrial waste storage facilities in accordance with environmental regulations has become a critical cost issue for industry and a challenge to a geotechnical community. Many facilities were constructed prior to the emergence of modern environmental regulations and contain variety of contaminated high water content materials. Some examples are PCB (polychlorinated biphenyls) containing wastewater treatment sludges, contaminated harbor dredgings, waste pickle liquor sludges, asbestos-containing sediments, and contaminated river bottom sediments. These materials are contained typically in surface impoundments such as lagoons, ponds or old quarries. Some of the remediation alternatives include beneficial reuse, in situ chemical stabilization, ex situ treatment, landfill disposal, and capping. The last one is typically the least costly, though not always, and the subject matter of this paper.

Capping, if practical, offers often the least expensive solution to remediation of contaminated sludge facilities. In this approach, sludge is left in place and isolated so that accidental falling of humans and animals and ingestion of contaminated sludge is prevented and if required infiltration of rain and surface water is impeded. Caps can be impervious if infiltration of water and generation of leachate is to be limited or pervious when leachate generation is not a concern such as in natural attenuation sites and/or with certain type of contaminants (e.g., PCBs and asbestos are quite insoluble and do not transport with water). Pervious caps include vegetative root mat, constructed composite cap, floating cap, and subaqueous cap. Composite caps consist of geosynthetics for reinforcement, separation, and filtration functions and soil for the purpose of containment, surcharging (to consolidate the sludge), and supporting vegetation. The emphasis in this paper is on constructed composite cap. Soft and highly compressible nature of sludges gives rise to a variety of technical and environmental challenges for cap design and construction. Some of these challenges will be described in the context of capping PCB-contaminated wastewater treatment sludge lagoons in Madison, Wisconsin, U.S.A. The lagoons, as shown in Figure 1, covered an area of 52 ha with about 18.4 ha already having a vegetative cover and requiring no further action. The remaining lagoon areas consisted of 25.6 ha of uncontaminated sludge that was removed for land application and 8 ha of sludge (1.2 to 1.5-m deep) with a PCB concentration of 50 mg/kg or higher that required capping. A composite cap, consisting of a woven slit-film geotextile and an approximately 0.45-m thick mixture of soil and wood chips, was selected. The cap was intended to isolate the sludge and provide a base for vegetation and development of a root mat.

![Figure 1. Air photo of the lagoons](image)

The physical and geotechnical properties of the sludge are summarized in Table 1. The low strength of the sludge made construction a challenge. It was determined to be the most economical to construct the cap in two-winter seasons by taking advantage of an ice platform to support construction equipment. Alternatively, high-strength geosynthetics (e.g., a bi-axial geogrid) could be used to support the construction equipment and carry out construction during any time of the year.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Content (%)</td>
<td>300-470</td>
</tr>
<tr>
<td>Solid Content (%)</td>
<td>18-26</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.85</td>
</tr>
<tr>
<td>Organic Content (%)</td>
<td>25</td>
</tr>
<tr>
<td>Atterberg Limits (%)</td>
<td>Nonplastic</td>
</tr>
<tr>
<td>Fines Content (grains &lt; 0.075 mm) (%)</td>
<td>21-31</td>
</tr>
<tr>
<td>In Situ Strength* (kPa)</td>
<td>1.1-2.6</td>
</tr>
<tr>
<td>In Situ Hydraulic Conductivity ** (m/s)</td>
<td>0.9-8 x 10^-4</td>
</tr>
</tbody>
</table>

*From plate load tests **From two-stage borehole permeameter

Table 1. Properties of Wastewater Treatment Plant Sludge.
Stability during construction is the single most important challenge to construction of caps over very soft sludges. Unlike embankments, typical cap thicknesses are in the range of 0.3 to 1 m, i.e., much thinner than typical embankment heights. Furthermore, cap geometry is mostly areal (equi-dimensional) in contrast to longitudinal embankments. These traits set cap stability apart from embankment stability. Small thickness and use of lightweight fill materials (such as wood chips, tire chips, and their mixtures with soils) result in much smaller bearing pressures and make support by very soft sludges possible. However, this situation makes equipment weight significant relative to fill weight, which has to be considered in bearing capacity analysis. Once construction is completed, the areal configuration of the cap obviates the problem of a general bearing failure in a transverse direction observable in the longitudinal embankment fills.

There are several modes of failure for caps:

- General bearing capacity failure, i.e., inability to support the weight of cap fill material and construction equipment on it and local bearing capacity, i.e., formation of excessive rutting under tires to allow hauling truck trafficalbility.
- Edge instability, i.e., mud waving in front of the filling advance.

Presence of a geotextile provides a localized restraint (separation between the sludge and the cover material). Localized restraint prevents sludge from intruding into the cover material especially if the cover material is coarse-grained. Burst strength of the geotextile provides this restraint and it is easily met within the survivability strength required during installation.

Local bearing capacity (rutting) design historically followed the procedure proposed by Steward et al. (1977) based on theory presented by Barenberg et al. (1975) which employs reduction of tire pressures on the sludge by the cover material and the empirically modified bearing capacity equation accounting for the presence of geosynthetic (geotextile or geogrid) reinforcement. Cap thickness and/or tire contact pressure can be controlled to allow sufficient stress reduction to meet the safety factor for bearing capacity. Bearing capacity factors used are 6.0 with geosynthetic reinforcement and 3.3 without geosynthetic reinforcement (Henry 1999). Geosynthetic is selected essentially by survivability requirements and its tensile modulus is not taken into account explicitly. Alternatively, the method proposed by Giroud and Noiray (1981) can be used. This method accounts for the load support and soil confinement provided by the geosynthetic itself and incorporates geosynthetic tensile modulus.

General bearing capacity analysis is appropriate to investigate the stability of hauling trucks transporting capping materials to the filling front over the already constructed cap. A modified form of the bearing capacity equation for foundations with limited depth such as the sludge layer is available (Bonaparte et al. 1987, Mandel Salencon 1969) and can be used. For winter construction, if an ice layer is formed to provide a working platform, general bearing capacity can be analyzed by treating the ice layer as the upper stiff layer and the sludge the lower weak layer and using the bearing capacity formulation provided by Meyerhof and Hanna (1978) for layered soils.

Edge stability is analyzed for both summer and winter construction by a global stability calculation, which determines the safety factor against sliding under the weight of the cap material and the weight of the dozer (Richardson 1997). Geosynthetic tensile strength or ice shear strength is incorporated to the analysis. Cap material thickness should be considered both as it is spread as well as when it is unloaded as a pile from a truck at the filling front. Tensile strength of the geosynthetic can be determined to achieve an acceptable safety factor. Sliding is assumed to take place perpendicular to the general filling front, which is kept wide in cap construction.

### 1.1 Bearing Capacity

Because of the climatic conditions in Madison, Wisconsin, an ice layer could be formed over the sludge lagoons to provide a support platform for construction. Thickness of the ice layer depends on water depth and freezing index. If the water depth is excessive to allow freezing all the way down to the surface of the sludge, an ice layer floating on water is created which results in ice breaking and instability. By trial and error, it was determined that a 0.3-m ice layer can be formed in this locality over the sludges in average winters. Bearing capacity analyses resulted in a design where a 56-kN dozer and 170-kN tri-axle trucks could be supported over a cover material with a minimum thickness of 0.45 m taking advantage of a 0.30-m thick ice layer with a safety factor of 1.3 (Figure 2). Safety factors with respect to local bearing failure (punching through the ice) were significantly higher under individual tires or tracks. A woven slit-film geotextile with a tensile strength of 20 kN/m was placed over the ice primarily to function as a separator, filter and reinforcement when the ice melts and a safety net during construction in case the ice broke.

### 1.2 Edge Stability

Global stability analyses were performed using the modified Bishop method to achieve an adequate safety factor against edge sliding at the filling front (Figure 2). Both winter and summer construction were considered and the effect of several variables on safety factor was evaluated. Placement of a geotextile over the ice and under the cap fill does not contribute initially to stability because of the vast difference in deformation modulus of ice and geotextile. Once the ice breaks and large deformations begin to take place, the geotextile is engaged and provides stability against loss of fill material and sinking of equipment. Table 2 gives the relative impact of the various factors on safety factor. These factors were varied one at a time in a range that was practical for this case while keeping the other factors fixed at the levels used in the final design. It was assumed that wood chips/soil mixture (cap) had a friction angle of 46° and unit weight of 11 kN/m³, ice had a cohesion of 29 kPa and unit weight of 9.8 kN/m³, and sludge had a cohesion of 1.2 kPa (2.6 kPa if frozen) and unit weight of 11.3 kN/m³. A conservative shear strength was assumed for the ice layer based on field plate load tests. It is clear that ice thickness is important, however, there is limited ability to specify it. Equipment weight provides the major control on safety factor for a given ice thickness in winter construction.

![Figure 2. Cross Section Considered in Stability Analyses](image-url)
A long-term function for the geotextile is to provide satisfactory filtration to the sludge. The sludge lagoons were in a wetland subject to groundwater recharge. Additionally, the area receives significant rainfall and surface water. Therefore, the water management practices required a pervious cap allowing unhindered movement of water through it. Construction of the cap would also involve consolidation of the high water content sludge, again requiring a filter to allow pore water to escape through the cap. A satisfactory filter should provide for long-term retention of the contaminated sludge solids without clogging.

Extensive laboratory and field tests were conducted to investigate the filtration behavior of the sludge with a variety of geotextiles (Aydilek, 2000). Comparisons were made with a silty sand having a grain size distribution same as the sludge. These investigations showed that the filtration characteristics of the sludge are different than those of natural soils like the silty sand. Presence of organic mass and clod-like structure of sludge results in a more complicated filtration behavior. Its structure reduces piping of the solids but also promotes clogging. This situation limited the use of the existing filtration criteria, which are based on tests involving natural soils and the direct application of standard filtration tests such as gradient ratio test (ASTMD 5101). For instance, gradient ratio (the ratio of hydraulic gradient in the soil-geotextile contact zone to that in the soil) was a misleading indicator of clogging because of the measurement artifacts arising from gas generation in the sludge. On the other hand, permeability ratio (the ratio of soil permeability to stabilized system permeability, i.e. the permeability of the soil plus the contact zone) was an effective indicator of clogging behavior.

Clogging ratio (expressed in terms of permeability ratio) decreases and piping increases with increasing percent open area (POA) for woven geotextiles used in filtering sludge as shown in Figure 3. The shaded area represents the zone of acceptable filter behavior. The maximum acceptable piping rate is set at 1,900 g/m² (lower than 2,500 g/m² limit set by Lafleur et al. (1989) for natural soils) because of the contaminated nature of the sludge solids. Also a minimum POA limit of 2% was set because geotextiles with POA < 2 have quite high clogging ratios approaching 3. The lower limit was set at a clogging ratio of one.

Based on extensive tests, limiting values of retention and clogging were examined in terms of the ratio of various geotextile opening sizes and sludge grain sizes. The following characteristic ratios were found to relate to retention and clogging limits, thus providing sludge retention and clogging criteria with woven geotextiles.

- **Retention criteria (for all POA)**
  \[
  \frac{O}{D} \leq 1.0 \\
  \frac{O}{D} \geq 1.0
  \]

- **Clogging criteria for 1< POA<8**
  \[
  \frac{O}{D} \geq 1.0 \\
  \frac{O}{D} \leq 1.0
  \]

- **Clogging criteria for POA>8**
  \[
  \frac{O}{D} \leq 1.0 \\
  \frac{O}{D} \geq 1.0
  \]

where O is the geotextile opening size and D is the grain diameter and the subscripts represent the percent of opening sizes or grain sizes that are finer.

![Figure 3. Determination of acceptable filtration zone](image-url)

Based on these considerations, a woven geotextile with the following properties was chosen for filter over the sludge: slit film, mass per unit area of 291 g/m², thickness of 0.603 mm, apparent opening size (O₃₅) of 0.425 mm, percent open area of 2%, and permeativity of 0.10 s⁻¹.

### Table 2. Effect of Different Parameters on Global Safety Factor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Winter Construction</th>
<th>Summer Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice Thickness (m)</td>
<td>0.06 to 0.2</td>
<td>+0.58</td>
<td>NA</td>
</tr>
<tr>
<td>Cap Thickness (m)</td>
<td>0.3 to 0.6</td>
<td>-0.25</td>
<td>-0.60</td>
</tr>
<tr>
<td>Equipment Contact Pressure (kPa)</td>
<td>10 to 18</td>
<td>-0.48</td>
<td>-0.35</td>
</tr>
<tr>
<td>Geotextile Tensile Strength (kN/m)</td>
<td>175 to 1750</td>
<td>NA</td>
<td>+1.17</td>
</tr>
<tr>
<td>Thickness of Dumped Pile (m)</td>
<td>0.3 to 1</td>
<td>-0.37</td>
<td>-0.81</td>
</tr>
</tbody>
</table>

* Geotextile tensile strength is ignored. ** Ice strength is ignored. Note: + and – indicate increase and decrease, respectively, in safety factor as the parameter increases within the range. NA=Not applicable.
A cap constructed over a high water content sludge is subject to considerable settlement that needs to be assessed at the design stage. The consolidation characteristics of sludge were investigated using laboratory and field tests and found to be different than those of natural clays (Aydilek et al. 2000). Large-scale slurry consolidation tests were more effective for measurement of the compression of the sludge during the first load increment, which typically corresponded to the load applied by the cap in the field. Both the void ratio and the hydraulic conductivity varied with applied consolidation stress in a manner comparable to the behavior generally observed for high water content materials.

Field test cells indicated a compression of 30 to 33% over a period of 2 years for a sludge with an initial thickness of 1.5 m and initial water content of 300% under an applied stress of 8 to 11 kPa. Conventional consolidation (Terzaghi) theory is an infinitesimal strain formulation. However, high water content materials, such as the wastewater treatment sludge, experience large strains during consolidation, thus invalidating this assumption. To investigate these effects, settlement estimates obtained from conventional theory and a piecewise-linear finite strain model (CS2) developed by Fox and Berles (1997) were compared with measured values from the field. The required input parameters for CS2 are the initial thickness of the sludge layer, initial and final overburden effective stress conditions, initial void ratio at the top of the layer, specific gravity of solids, and void ratio-effective stress (e-σ') and void ratio-hydraulic conductivity (e-k) relationships. The output file gives the settlement and excess pore pressure profile for specific values of time.

The decrease in void ratio (Δe) with increasing stress is given by the following approximation based on the large-scale slurry consolidation tests:

\[ \Delta e = 1.40(\log(\sigma'_{v}) - 0.058) \]  

where \( \sigma'_{v} \) is vertical effective stress (kPa). The decrease in field hydraulic conductivity with decreasing void ratio was characterized based on slug tests conducted in piezometers inserted in the sludge by:

\[ \log k = 0.78e-10.86 \]  

where \( k \) is in m/s.

Figure 4. Settlement behavior of the sludge

CS2 successfully estimated the time required for a given average degree of consolidation in the field using these relationships as shown in Figure 4. Conventional infinitesimal-strain (Terzaghi) theory underestimated the elapsed time for a given average degree of consolidation. CS2 also provided a satisfactory estimate of the total settlement.

5 SUMMARY

Construction of an engineered cover or capping system is an efficient and economical component of in situ containment strategies for contaminated sludges and other high water content waste materials. Low strength, high compressibility, and contaminated and organic nature of such sludges present short and long-term geotechnical challenges. Stability during construction and filtration and large-strain consolidation in the long-term are some of the important design considerations. Filtration and consolidation characteristics of wastewater treatment sludge were found to be different than those of natural soils requiring special considerations. These considerations were applied to successful construction of a lightweight cap over contaminated wastewater treatment sludges covering an area of 10 ha in Madison, Wisconsin, U.S.A.

6 ACKNOWLEDGEMENT

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7 REFERENCES


