Capping/Closure of Sludge Ponds

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ABSTRACT
Earthwork construction over soft polluted sludge is required in order to cap various manufacturing waste products. The soft sludge is in many cases pumped into lagoons in the ground. For various reasons, filling over these deposits is often required at some later date. High-strength geosynthetics allow access over these deposits that are typically so soft that construction equipment cannot access the lagoons. Case histories will be reviewed which examine 1) design of the geosynthetic component of the cap, 2) deployment of the geosynthetic cap over soft sludge and water and 3) filling operations over the geosynthetic.

Case histories are examined which include 1) the examination of adjacent high strength geotextile and biaxial geogrid reinforced test fills over a paper mill sludge, 2) a geotextile composed of both polypropylene and polyester fibers to effect a floating deployment scheme and 3) inclinometer, settlement platform, pneumatic pressure cell and wire extensometer monitoring of the geosynthetic reinforcement during filling.

1.0 Background

One of the fundamental uses of geosynthetics is to aid in construction of roadways and embankment fills over soft subgrades. One of the first studies of fill construction over mud flats is reported by Porter (1936). In the late 1970s, one of the first usages of geosynthetics as a construction aid over soft dredge soil was reported by Fowler and Halliburton (1980) on a United States Army Corp of Engineers project. Design and construction technique for embankments over natural soft ground including organic soil is summarized in this and many other publications including Gale (1999). Industrial sludges are another type of soft deposit which are becoming more common in the last 25 years as a substrate for construction. Industrial sludges are composed of water, chemical waste and solid by-products and in many cases are so soft that one can not walk on the deposit.

1.1 Design Protocol

Industrial sludges are soft, with undrained shear strengths less than 9.6 kPa (200 psf) in many cases. Some sludge will have a desiccated crust at the surface that can assist in the deployment of a geosynthetic reinforcement layer and of the placement of overlying fill, though the benefits of the crust may be reduced once the fill is placed. As fill is placed, most of these sludges will obey the principles of effective stress and will increase in shear strength as pore water pressures dissipate. Designs for fill placements on soft sludge typically are based on limit-equilibrium stability analyses and an evaluation of bearing capacity, lateral spreading and undrained and drained creep (Holtz et al, 1997) (Andrews and Richardson 1999). Though researchers and practitioners have debated the total stress versus effective stress analysis concept, practitioners typically prefer the total stress or undrained analysis approach. Important factors in a total stress analysis include the initial undrained shear strength of the sludge and its ability to gain strength as the normal stress increases with time.

The in-situ sludge shear strength properties, the geosynthetic reinforcement properties, the density and drainage capacity of the fill soils, the geometry of the advancing front of the fill soil placement, the staged construction lift thicknesses and the total weight and the contact pressure of the construction equipment all need to be taken into consideration in the design (Henderson and Gale, 2000). A limit equilibrium computer program such as G-slope from Mitre Software Corporation or ReSSA by Adama Engineering is used for analysis. Both programs allow for geosynthetic reinforcement strength input.

2.0 CASE HISTORY NO. 1 – ADJACENT HIGH STRENGTH GEOTEXTILE AND BIAXIAL GEOGRID REINFORCED TEST FILLS OVER PAPER MILL SLUDGE

A test fill was constructed on a paper mill sludge lagoon to obtain information for lagoon closure design. The disposal site was located in the Upper Peninsula of Michigan, USA. The sludge was derived from a groundwood mechanical pulping and paper mill and was pumped into constructed 5 meter deep lagoons that were 60 meters by 300 meters in dimension. A geosynthetic reinforcement layer, a lechate collection system, a 1 m thick sand drainage layer, a Polyvinyl Chloride (PVC) liner and then a topsoil cover was required for closure.

Figure 1. Paper Sludge Lagoon

A test section was conducted in 1995 in which the performance of both a high strength geotextile and a biaxial geogrid were compared in side-to-side test sections with all other conditions equal. The sludge in the test fill lagoon was placed 5 years prior to the time of filling. The sludge had an estimated undrained shear strength of less than 5 kPa (100 psf) with a thin desiccated crust. Each test section was 15 meters wide and extended across the shorter 65 meter distance of the lagoon. The geosynthetics were placed directly on the sludge crust.

2.1 Design of Geosynthetic Component of Cap

An extruded polypropylene "biaxial" geogrid was used for one test section and a high strength polypropylene geotextile was used for the second test section. The following properties were reported:

Table 1 – Geogrid/Geotextile Properties

Type	Machine Direction Strength by D-4595 (kN/m – Elongation %)	Cross Direction Strength by D-4595 (kN/m – Elongation %)	Seam Strength Ultimate by D-4884 (kN/m)	Permittivity by D- 4491 (sec^{-1})
Polypropylene Geogrid*	10/5%	17/5%	NR**	N/A
High Strength Polypropylene Geotextile	26/5%	79/5%	70	10

*Properties obtained from Geotechnical Fabrics Report Specifier's Guide, Dec., 1994.
**Plastic ties have an approximate strength of 22 kg each.

The geosynthetic reinforcement products were selected by manufacturers' experience with similar projects.

2.2 Deployment of Geosynthetic over Soft Sludge

<u>High Strength Geotextile</u> - The 4.5 meter wide high strength polypropylene geotextile rolls were sewn together in the field. A seam consisting of two rows of stitching was made with a Union Special 2200 B sewing machine using bonded and twisted 415 denier polyester thread. An overlap of 150 mm was required for the seam. The geotextile, because of its' weight, was deployed using ropes attached to the leading edge of the geotextile panel and then pulled across the lagoon with a small dozer. After deployment, the geotextile was placed in a small ½ m by ½ m anchor trench cut within the perimeter dike surrounding the lagoon.

<u>Geogrid</u> - The 4 meter wide polypropylene geogrid rolls were unrolled by two men pushing the roll out ahead of them. The rolls were overlapped approximately 1 meter and bound together with plastic ties. The geogrid was placed in a small ½ m x ½ m anchor trench also cut within the perimeter dike surrounding the lagoon.

Figure 2. Geogrid and Geotextile Deployment

2.3 Filling over Geosynthetic to Effect Final Cap

A medium grained sand (SP) was used as fill over the geosynthetics. A small low ground pressure dozer with a weight of 7000 kg pushed the 1m high fill in place.

The geogrid and geotextile performed "equally" as long as the crusted over sludge remained stable and minimal deformation occurred during granular soil filling.

When ground deformation did occur it was the result of a ½ meter mud wave forming ahead of a 1 meter high fill lift. Two performance differences were observed: 1) the geotextile, as a result of its ability to be sewn together, maintained its integrity through the seams (Figure 3), while the geogrid rolls split apart and kinked (Figures 4 & 5). The geotextile's tensile modulus (strength at 2 to 5% strain) was such that the geotextile elongated with the deformation of the sludge while the lack of a secure connection for adjacent rolls caused the geogrid to kink and the panels to split apart.

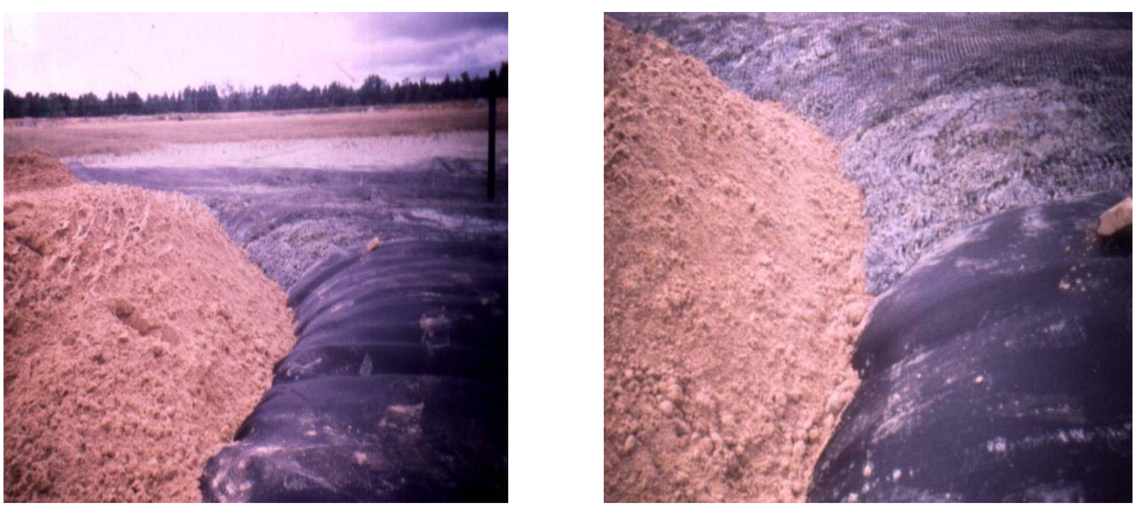

Figure 3. Fill Placement with Mud Wave

Figure 4. Geogrid Deformation

3.0 CASE HISTORY NO. 2 – GEOTEXTILE COMPOSED OF POLYPROPYLENE AND POLYESTER FIBERS TO AFFECT FLOATING DEPLOYMENT SCHEME

The closure of a fiber cellulite plant that produced a cellulose based rayon fibre occurred in 2005. The site is located within 20 kilometers of the Gulf of Mexico within the State of Alabama, USA. State environmental regulations required closure of two 180 meter by 180 meter waste treatment lagoons containing the rayon fiber. The waste treatment sludge was 4-5 meters thick and so soft one could not even walk on it. The ponds had a ½ - 1 meter deep water pool over the sludge. The sludge was estimated to have an undrained shear strength of less than 5 kPa (100 psf).

Figure 5. Cellulose Fibre Lagoon No. 1

3.1 Design of Geosynthetic Component of Cap

A design was initiated which required high strength geosynthetic reinforcement of a 1-2 meter granular fill layer and the construction equipment necessary to place the fill. The geosynthetic strength requirement was determined from limit equilibrium analyses. A 5% geosynthetic working strain was assumed for design. A specific gravity above 1.0 was also required to facilitate deployment over water. The specification resulted in the selection of a woven geotextile composed of high tenacity polypropylene yarns in the machine direction and high tenacity polyester multi-filament yarns in the cross-machine direction. The polyester yarns in the cross direction allows for a higher cross direction strength and results in a higher seam strength. The geotextile properties were:

Table No. 2 – Reinforcement Geotextile Properties

Properties	Test Method	Unit	Value	
			MD	CD
Tensile Strength – Ultimate	ASTM D 4595	kN/m	106	106
Tensile Strength @ 5% strain	ASTM D 4595	kN/m	52	58
Permittivity	ASTM D 4491	sec^{-1}	0.7	
Specific Gravity	ASTM D 792	Unitless	1.07	

3.2 Deployment of Geotextile over Soft Sludge

Closure of the first pond occurred in August, 2005. Initially, ½ - 1 meter thick of water existed over the lagoon. The lagoon was pumped down such that 150 mm of water remained.

The 4.5 meter wide panels of geotextile were sewn together in the field at the dry edge of the pond. The sewing machine used for the project was a hand held Union Special 2200 B sewing machine which made a Federal Standard 401-thread chain stitch. Initially, a bonded 207 denier polyester thread was used with a single pass resulting in a seam strength of 17 kN/m. This was unacceptable. The final seam consisted of a bonded 277 denier polyester thread sewn by forming 2 passes with a J-seam. This seam achieved a strength of 52 kN/m. One hundred twenty-five (125) spools of thread were used for the seaming of the Lagoon No. 1 geotextile.

In order to ensure that the leading edge of the geotextile remained above water as it was being pulled across the pond, 0.3 m by 0.3 m by 2.4 meter long polystyrene blocks were sewn into a pocket along the leading geotextile edge (Figure 7). Polyester webbing was sewn to the fabric to act as a strap to attach the pulling ropes (Figure 7). The pulling rope selected for the project was a 25 mm diameter nylon twisted 3 strand rope (Figure 6). This rope has an ultimate strength of 14,000 kg. The ropes were tied to the polyester webbing straps at approximately 35 meter increments. Considering that the geotextile weighs approximately ½ kg per square meter, each of the six ropes would be required to pull approximately 2500 kg of geotextile plus frictional forces. Deployment over water reduced frictional forces.

Equipment available on-site including backhoes, bobcats and dozers were used to pull on the ropes, deploying the geotextile across the pond (Figure 8). The geotextile was accordion folded at the edge of the pond (Figure 6) where it was sewn such that the material pulled out with little resistance. The Contractor pulled the geotextile the 180 meters across the pond in approximately 3 hours. The 1.07 Specific Gravity resulted in a "floating geotextile" (Figure 9). Once the geotextile completely covered the lagoon, a small key trench of ½ meter wide by ½ meter deep was dug all around the lagoon, the geotextile was placed in the trench and then the trench backfilled. The geotextile was deployed in late August, 2005 only weeks before Hurricane Katrina. The construction crew evacuated just after the geotextile was keyed into the trench. The geotextile cover survived the hurricane without damage.

Figure 6. Geotextile was sewn together on land and accordion folded. Pulling points were established 35 meters apart.

Figure 7. Polyester webbing was used for the strap to attach to the leading edge of the fabric. A 0.3 m by 0.3 m by 2.4 m long polystyrene block was sewn in a pocket along the leading edge.

Figure 8. Backhoes and bobcats were used to pull the geotextile across the water.

Figure 9. The manufactured specific gravity of the geotextile of 1.07 allowed it to float long enough.

3.3 Filling over Geosynthetic to Affect Final Cap

The Contractor remobilized after hurricane Katrina in order to place the cover fill. The granular fill soils consisted of an on-site very fine sand classified by the Unified Soil Classification System as SP. Prior to placement of the sand, 100 mm diameter PVC pipes were placed at 15 meter intervals across the geotextile and then tied to a header which drained a collected liquid to a lagoon wet well where the liquid was pumped back to the plant site. The Contractor used a 450 John Deere dozer to push the 1 meter of fill into place. A 450 G series John Deere dozer weighs approximately 7200 kg. Fill lifts of ½ - 1 meter were used over the geotextile.

4.0 CASE HISTORY NO. 3 – GEOTEXTILE REINFORCEMENT OF A 12 METER HIGHWAY EMBANKMENT OVER WATER SOFTENING SLUDGE

The extension of a 6-lane interstate freeway, I-670 into downtown Columbus, Ohio, USA was needed to eliminate a major highway bottleneck. The only alignment available was across a 1 kilometer stretch of gravel pits that had been filled with water softening sludge from an adjacent water treatment plant in the 1970s. Probes identified the sludge to be up to 7 ½ meters thick.

The sludge is a product of aluminum sulphate, lime, soda ash and alum and has the consistency of toothpaste. The sludge had an initial moisture content of 200 – 300%, a percent solids of 25% and a pH of 10. The sludge was suspected to be difficult to dewater (consolidate) because of the nature of the aluminum hydroxide. In-situ vane shear and laboratory consolidation and triaxial shear tests were performed to assess the initial strength of the sludge and the potential for strength increase with time and embankment loading. Vane shear, determined with a Nilcon Vane Borer, and a penetration device (Christopher and Wagner, 1988) identified an undrained shear strength of 5-10 kPa, increasing with depth. The Compression index, Cc, and Recompression index, Cr, was 3.1 and 0.05, respectively. Slight preconsolidation was noted. The permeability of the sludge, as determined from radial and vertically drained consolidation tests, was 1×10^{-5} to 1×10^{-6} cm/sec. Consolidated undrained (CU) triaxial shear tests identified an effective friction angle of 41° and an effective cohesion of 0.

Because of environmental concerns, the sludge could not be removed from the site. The choices were a bridge or a geosynthetic reinforced embankment over the sludge. An embankment ranging in height from 12 meters at the Scioto River crossing to 4 meters high 1 kilometer away was required. It was estimated that the embankment over the sludge would save \$5 - \$10 million US over the cost of a bridge. A fully instrumented test fill was constructed with varying wick drain spacing and varying geosynthetic reinforcement and monitored for 2 years. After analyzing all the instrumentation data collected, a final design was prepared. The embankment was constructed in 1997-98.

4.1 Design of Geosynthetic Component Cap

Taking into consideration the undrained shear strength of the sludge, the initial lift of granular soil, the weight of the specified Contractor's equipment and the ability of the sludge to gain strength with time, the geosynthetic reinforcement requirements were determined. Limit equilibrium analyses identified the required geosynthetic reinforcement strength in the machine direction of 420 kN/m at 5% strain in order to achieve a desired factor of safety of between 1.3 and 1.5 while also taking into consideration the shear strength gain of the sludge. The design allowed for three (3) layers of reinforcement to be used. Polyester based geotextiles and geogrids were excluded because of the suspected degradation effects from the high pH of the sludge.

A working platform was constructed first . A monofilament woven geotextile was designed for the initial purpose of providing a construction platform for the Contractor to work over the sludge. This geosynthetic would need to fully separate, thus a geotextile was required for this application. The geotextile would need to have a high ultimate strength, moderate elongation, a high permittivity, would need not to be affected by the high pH and would need to float. A polypropylene monofilament woven geotextile was specified. The design concept in order to construct the 12 m high embankment was to stage load the embankment such that the sludge would gain strength with time while providing embankment stability through the added inclusion of geosynthetic reinforcement in the lower levels of the embankment.

The required geotextile properties were:

Table 3 – Working Platform Geotextile Properties

Properties	Test Method	Unit	Value	
			MD	CD
Tensile Strength – Ultimate	ASTM D 4595	kN/m	35	24
Grab	ASTM D 4632	kN	1.6	0.9
Permittivity	ASTM D 4491	sec^{-1}	1.3	1.3
Seam	ASTM D 4632	kN	n/a	0.7

Table 4 – Reinforcement Geotextile or Geogrid Properties

Properties	Test Method	Unit	Value	
			MD	CD
Tensile Strength – Ultimate	ASTM D 4595	kN/m	193	70
Tensile Strength @ 5% strain	ASTM D 4595	kN/m	140	n/a
Permittivity	ASTM D 4491	cc^{-1}	0.2	0.2
Seam	ASTM D 4884	kN/m	n/a	40

A sophisticated instrumentation monitoring program was specified and then implemented during construction to identify that stability was being maintained during construction.

4.2 Deployment of Geotextile over Soft Sludge

A polypropylene woven monofilament geotextile was selected to create the working platform and 3 layers of a polypropylene woven fibrillated high modulus woven geotextile, 1/3 meter apart, was selected for the primary embankment reinforcement. The monofilament woven construction platform geotextile was unrolled perpendicular to the embankment centerline and sewn together in the field with a hand held Union Special 2200 B sewing machine. Ropes were attached to the geotextile and lead to a pulley where a small bobcat was used to run perpendicular to the embankment centerline on one of the small dikes surrounding the lagoon and pull the geotextile across the lagoon. A bonded 207 denier polyester thread was used and 2 lines of stitching were sewn. By standing on the geotextile over areas of standing water, the sewing subcontractor was able to complete the field sewing.

Figure 11. Monofilament Geotextile In Place for Construction Platform

A 1 meter thick granular drainage layer was placed and then wick drains were installed on an approximate 2 meter triangular pattern. Three layers of the reinforcement geotextile were placed with 0.3 meter of granular fill between each layer (Figure 12). The reinforcement geotextile was placed perpendicular to the dike alignment without wrinkles. The 4.5 meter wide panels of reinforcement geotextile were sewn together in the field using a hand held Union Special 2200 B sewing machine. A bonded 277 denier polyester thread was used with 2 rows of stitching to achieve the required seam strength. Wire extensometers were placed on the high strength reinforcement geotextile at various locations for monitoring during the filling process.

Figure 12. Initial High Strength Geotextile Layer,
With Wick Drains Shown In Foreground

4.3 Filling over Geosynthetic to Affect Highway Embankment

The construction platform geotextile deployment began in July 1997. Filling occurred continuously between July and December, 1997. The woven monofilament geotextile panels were placed perpendicular to the embankment alignment and filling occurred in the same direction, to reduce stress on seams (Figures 13 & 14).

Figure 13. Smaller Dozer On Leading Front Attempts to Limit Mud Wave Formation

Figure 14. Initial Fill Placement Lift is ½ m

All embankment fill, including a 1.5 meter high surcharge, was in place by September, 1998 (Figure 15). The surcharge was initially scheduled to be removed in early 2000, though it did remain in place until 2002, because of funding issues, at which time the surcharge was removed and a concrete pavement placed (Figure 16). A program was implemented during construction to identify that stability was being maintained. Instrumentation included strain gauges on the reinforcement geotextile and pneumatic pressure cells, inclinometers and settlement gauges on or in the sludge.

Inclinometers at the toe of the embankment showed that lateral squeeze was an important consideration. A maximum Inclinometer deflection of 25 cm occurred at 2/3 of the depth of the sludge at the toe of the embankment. A lateral squeeze analysis indicated that an undrained shear strength in the range of 24 kPa was required in order to raise the embankment to its final height of 12 m above the sludge surface while maintaining a minimum factor of safety of 1.5. Vane shear testing was performed regularly within the sludge in order to identify that these criteria was satisfied.

During construction pneumatic pore pressure cells were used to monitor the dissipation of excess pore pressures. Even with wick drains, the filling had to be staged in order to limit excess pore pressure development. Table 5 identifies excess pore pressures and the effects of a waiting period between 1 meter incremental lifts of the embankment.

Table 5 – Excess Pore Pressure Dissipation

Location (Station)	Highest Excess Pore Pressure (%)	Excess Pore Pressure at End of Waiting Period (%)	Number of Days Waiting Period (Days)
392+00	40	30	26
395+00	57	46	24
395+00	48	34	24
401+00	18	2	47
403+00	34	15	47
405+00	16	8	42
406+00	32	13	42
408+00	37	18	33
409+00	52	12	52
409+00	32	11	40

Figure 15. 12 m High Embankment with 2H:1V Side Slopes In Place

Figure 16. Final Concrete Pavement

A prediction of embankment settlement was based on the results from the test fill and from laboratory consolidation tests. Settlements of up to 2.8 meters occurred under the 12 meter high embankment which corresponded to 35% of the original sludge thickness.

Wire extensometers were attached to the reinforcement geotextile at the embankment centerline and at 4 equally spaced locations extending out to the toe. At full embankment height, geotextile strains of between 1 and 2% were measured.

Five (5) years after placement of the concrete pavement, the roadway section over the sludge is performing similarly to the pavement over non-sludge areas.

5.0 REFERENCES

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