DESIGNER'S FORUM

Design and construction of geosynthetic-reinforced lagoon caps

By David B. Andrews and Gregory N. Richardson

RESIDUAL BY-PRODUCTS OF MANY industrial processes are stored in outdoor lagoons, some of which cover large areas. After its useful service life, a lagoon usually poses a potential liability or an environmental hazard for its owner. Increasingly, lagoons are closed with the sludge left in-place. Such closures may be selected in response to the U.S. Environmental Protection Agency's (EPA's) presumptive containment remedy for Superfund sites. Or, in-place closures may be the least risky choice among remedial alternatives.

This Designer's Forum will focus on the design of geosynthetic-reinforced-soil working platforms constructed immediately on the sludge. The design of alternative covers that can be placed on working platforms is not considered. The objective of this paper is to highlight new lessons learned from recent installations and to present a methodology for designing lagoon closures. The next Designer's Forum will focus on construction considerations for the geosynthetic-reinforced-soil working platform.

Background

Industrial processes can produce material composed of water, sediment, chemicals, wastes and solid by-products. Typically, the by-products form sludges that have a high percentage of suspended solids and are chemically flocculated.

These by-products usually are made up of a very soft, soil-like material with undrained shear strengths of less than 9.6 kN/m^2 (200 psf). Sludges generally are saturated and normally consolidate under their own weight. Prediction of anticipated settlement usually is impossible.

Some sludges crust or dessicate at the lagoon surface. Because the shear strength of a crusted section will be higher than the underlying saturated sludge, crusting can be beneficial to lagoon-cap design and construction. However, the crust will disappear once the final cover is placed. At times, vegetation can grow within the sludge at its crust.

The long-term role of the final cover must be established early in the design process. Does the final cover need to limit surface-water infiltration or the release of volatile gases from the sludge? Or, does it simply need to limit human contact with the sludge? The underlying concern is whether the cover requires a barrier and the lateral-drainage needed for such a layer.

Few technical papers focus on construction over the near-to-zero strength foundation soils that are, similar to residual industrial by-products. Published papers that focus on this subject include DeMeerleer (1993), Fowler and Koerner (1987), Guglielmetti, et al. (1996), Hoekstra and Berkout (1990), Ochiai, et al. (1996), Peterson, et al. (1990), Risseeuw and Voskamp (1993), Sandiford, et. al (1996), and Richardson (1997). Many of these technical papers include qualitative methods for selecting appropriate geosynthetic reinforcement. This article presents a quantitative approach to geosynthetic-reinforcement selection, based on geosynthetic properties, loading conditions and soil strength.

Design concept

Geotextile reinforcement provides stabilization through a "tension-membrane" effect that increases the localized- and general- (or deep-) bearing capacity of the foundation soils. Localized-bearing capacity, which is common to roadway design, refers to small, shallow failures that may result from individual wheel loads. Steward, et al. (1977) demonstrated that the presence of a geotextile increases the surface bearing capacity of weak soils by using a "separation concept." Giroud and Noiray (1981) applied a tensioned-membrane concept to arrive at the same conclusion. While the two concepts are different, they both predict an increased bearing capacity that reduces the effect of equipment loading, thus allowing initial fill placement over soft materials.

Steward expanded on Barenburg, et al.'s (1975) finding that an allowable bearing capacity, N_C, on a soft soil under limited repeated loading is equal to 3c without a geotextile, and 6c with a geotextile. Here, c is the cohesive strength of the soil. For typical sludges, this predicts a bearing capacity of less than 57.6 kN/m^2 (8.3 psi).

The tension-membrane concept is illustrated in **Figure 1**. As this figure shows, for tension to develop, the geotextile must elongate along the foundation base. It is difficult to quantify the degree to which the geotextile increases the applied load (soil plus equipment) that the soft soil can support.

Neither the separation nor the tension-membrane theory models the deep-bearing capacity of a soil-geotextile system placed over soils that do not significantly increase in strength with depth.

The initial lift of fill usually is placed with low ground pressure (LGP) earthmoving equipment. Such equipment has wider tracks, usually about 762 mm (30 in.), which reduce the applied-equipment loading to less than 34.5 kPa (5 psi). LGP equipment on typical sludge calls for a safety factor of less than 1.0 for localized-bearing capacity without the geotextile, and 1.67 with the geotextile.

For soils that are significantly softer than 50 psf, other fill-placement techniques can be used to keep the construction equipment used to deposit initial layers off of soft soils.

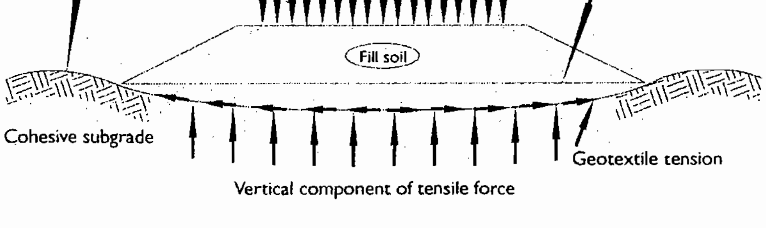

Figure 1. Geotextile-reinforcement foundation support by tension membrane.

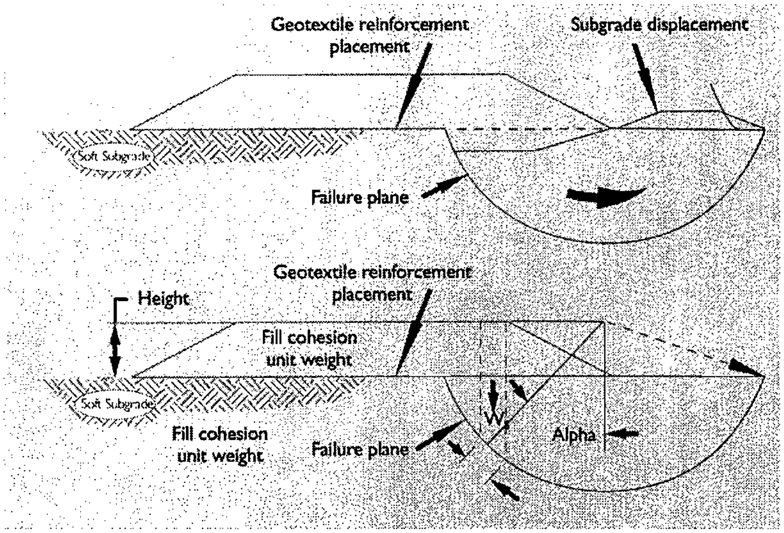

Figure 2. General slope-stability failure mode and analytical model.

These more expansive alternate-fill-placement techniques include broadcasting from hydraulic excavators, placement with draglines or clamshells, hydraulic filling, or dumping from barges. Consideration for equipment loading as it relates to bearing capacity may be minimized or eliminated with these approaches. This makes the lagoon-closure technique adaptable to viscous sludges or organic soils with very little shear strength (Fowler and Koerner 1987; Ochiai, et al. 1996).

Localized-bearing capacity concepts are adequate for roadway designs where the weak layer is relatively shallow with respect to the roadway section. However, this is not the case in most sludge lagoons; therefore, it also is necessary to verify that the bearing capacity is adequate relative to deep failures. Such analysis commonly is performed for reinforced embankments on soft soil. The geotextile localized-bearing-capacity factor of safety and design-tensile strength are determined through classical slip-circle analysis, as described in such geotechnical-engineering textbooks as Lambe and Whitman (1969). The basic failure mode and typical analysis are illustrated in **Figure 2**.

Although the final-design analysis should be verified by hand calculations, a computer program usually is utilized to find the minimum safety factor or most critical surface that incorporates geosynthetic reinforcement. Each program can account for multiple layers of geosynthetic reinforcement and the strength variations along those segments.

Because the geotextile provides construction-expedience (separation) and reinforcement functions, design procedures must blend considerations for roadway stabilization and reinforced embankments on soft soil.

Additional weight from fill placed over the soft soil causes large settlement. This decrease in soil volume is crucial to long-term stabilization because soils gain strength as they consolidate. In time, the increase in soil shear strength reduces dependence on the geotextile. Though geotextile reinforcement cannot significantly reduce total settlements, it does minimize differential settlements that could damage the cover.

Design guidelines

Step 1 Define the soil condition: Perform a geotechnical investigation to determine the sludge-material properties. The weakness of the substance precludes laboratory shear-strength testing. Field shear-strength tests, such as minature vane and large penetrometers, commonly are used.

Since sludge typically is pumped into lagoons, its shear strength can vary with distance and depth from the discharge pipe. Therefore, the minimum shear strength must be defined. The typical unit weight and depth of the sludge also should be obtained. If the water-table is not located at the surface, its depth also should be determined.

Step 2 Define the cover-foundation fill: This involves establishing the type of fill material and filling technique to be used for the working platform on which the cover is constructed. Although many different types of fill have been used successfully, a well- or gap-graded sand or gravel usually works best. This soil type compacts well during general equipment operation, provides good drainage to the underlying soft soil, and, with time, consolidates and gains strength.

The typical design thickness for the initial lift of cover soils is 0.3–0.5 m (12–18 in.), though greater thicknesses have been used. Note that the thickness of this initial soil layer, which is influenced by the strength of the geotextile, may be changed in Step 5.

The design-soil parameters for this material, including internal shear strength and unit weight, also should be defined.

Step 3 Define the construction-equipment loading: Determine or actually specify the type of equipment that will be used to spread the fill. Because design is controlled greatly by such equipment, related specifications must be adhered to firmly during construction. Typically, LGP equipment, which generates applied contact pressures near 28.7 kPa (600 psf), is specified. Note that the total weight of the construction equipment also is important and must be specified and controlled in the field.

Estimate contact pressure on the sludge from the construction equipment, q_{ae}, by assuming a 45-degree (1:1) distribution (Ochiai, et al. 1996), such that:

$$q_{ae} = q_e \left[\frac{W}{(W + 2 \bullet T)} \right] \bullet I_f$$

where:

q_e is the equipment load at fill surface, typically 28.7 kPa (600 psf) for LGP equipment

W is the equipment-track width, ft, typically 762 mm (30 in.)

T is the thickness of fill soil, m (ft)

I_f is the impact factor for dynamic loading of equipment, which typically is 1.2 (Ochiai, et al. 1996).

Note that all construction equipment, including trucks that supply the fill, must be evaluated in this manner.

Step 4 Calculate the localized-bearing-capacity safety factor: Check to ensure that the fill-soil/geotextile system has sufficient bearing capacity to support construction-equipment loading during placement of initial lift of soil. This can be done quickly by applying Steward's recommendation, as shown below:

$$FS_{LocalBC} = \frac{6_c}{q_{ae} + \gamma T}$$

Typically, the minimum acceptable bearing-capacity safety factor is 1.5. However, the designer may recognize that because the consequences of failure are small (e.g. pulling the dozer out of sludge), lower safety factors may be acceptable.

TABLE 1. MARV INDEX-PROPERTY CRITERIA FOR SOFT-SOIL STABILIZATION

Property	Test method	Minimum value
Ultimate Wide-Width Tensile Strength	ASTM D-4595	70 kN/m (4800 lbs/ft)
Wide-Width Tensile Strength @ 5% Strain	ASTM D-4595	35 kN/m (2400 lbs/ft)
Puncture Strength	ASTM D-4833	620 N (140 lb)
Mullen Burst	ASTM D-3786	8270 kPa (1200 psi)

Step 5 Determine the geotextile deep-bearing-capacity safety factor and design-tensile strength: Evaluate the potential for a deep-bearing-capacity failure with a slope-stability computer program that incorporates circular failure surfaces. The calculated bearing capacity will be influenced by the assumed tensile strength of the geotextile. The required design geotextile tension, T_{req}, is selected based on its anticipated service life. If the reinforcement only needs to be effective during and immediately after construction, safety factors may be lower (1.1–1.25).

However, if the reinforcement will be necessary for long-term stability, the safety factors should be higher (1.3–1.5), and the embankment should be analyzed for long-term conditions (i.e, full height, no equipment loading, with creep-reduction factors). Note that the maximum tensile strength of the geotextile typically is limited by seam strength.

Step 6 Limiting elastic deformation: To minimize soil-cap movement, the maximum strain that the high-strength geotextile will experience while developing the required reinforcement tension, T_g, must be limited. Fowler, et al. (1986), used finite-element methods to determine a maximum desirable strain of 10%. To be conservative, design strains of 5% typically are used (U.S. Army Corps of Engineers 1989).

Step 7 Establish longitudinal and latitudinal strength requirements: Although capping the lagoon by spreading fill soil perpendicular to the geotextile seams is recommended, this method cannot always be accomplished during construction. Therefore, it is recommended that the adjacent geotextile-roll-lengths be sewn together to provide a continuous tensile element.

During lagoon-cap construction, major and minor principal-stress directions, which are found in some soft-soil applications, may change with the method and direction of fill placement. Hence, the reinforcement should have equal (or biaxial) seam strength in both the machine and cross-machine direction.

Step 8 Select the high-strength woven geotextile: Geotextile reinforcement is selected based on tensile strength, installation survivability, and filtration criteria.

Tensile Strength: GRI-GT7 defines the general formula used to calculate the design strength, T_{allow}, as shown below:

$$T_{allow} = \frac{T_{geo}}{RF_{cr} \bullet RF_{id} \bullet RF_{d} \bullet RF_{jnt}}$$

where:

T_{geo} is the Wide-Width Tensile Strength (MARV, ASTM D-4595)

RF_{cr} is the reduction factor of safety for creep

RF_{id} is the reduction factor of safety for installation damage

RF_{d} is the reduction factor of safety for durability

RF_{jnt} is the reduction factors of safety for joints (seams)

The influence of the creep-reduction factor must be evaluated carefully. For short-term events, the creep-reduction factor is not included in the T_{allow} calculation. In such cases, the reinforcement-design strain is controlled by the wide-width tensile strength at 5% strain.

On the other hand, for long-term events, the maximum allowable strain is accounted for by the creep-reduction factor. In these cases, the ultimate wide-width tensile strength is used to determine T_{allow}.

Seams also can have a significant influence, typically reducing design-strength by as much as 50% (Diaz and Myles 1990, Fowler and Edris 1987, Koutsourais, et al. 1997, Sprague 1992). Therefore, it is beneficial to maintain biaxial tensile strength in the geotextile after seaming. Recommended seaming procedures are detailed in many published reports (e.g., Koutsourais et al. 1998, Diaz & Myles 1990, Sprague 1992).

Survivability: Construction stress on the reinforcement can be severe. In addition to conventional survivability concerns of subgrade softness and equipment loading, the reinforcement must endure the rigors of deployment, which can cause concentrated stresses on the edge being pulled. This situation is beyond the scope of such survivability guidance as AASHTO M288-96.

Table 1 (p. 23) includes minimum MARV index-property criteria for candidate geotextiles used in soft-soil stabilization,which are developed from a review of successful projects reported by DeMeeleer (1993), Fowler and Edris (1987), Fowler and Koerner (1987), Fowler, et al. (1986), Fritzinger and Koerner (1990), Guglielmetti et al. (1996), Hoekstra and Berkout (1990), Ochiai, et al. (1996), Paulson (1989), Risseeuw and Voskamp (1993), Sandiford et al. (1996), Schimelfenyg et al. (1990), Sprague and Koutsourais (1992), U.S. Army Corps of Engineers (1989), and Uibel (1987).

Filtration: The reinforcing geotextile should have sufficient permeability to permit water to escape from underlying soft soils to the drainage layer above the geosynthetic. The material also should meet filter criteria to prevent clogging and a resulting reduction in permeability. Design procedures for these conditions are provided in the FHWA manual (Holtz, et al. 1995) and Luettich, et al. (1992). Many high-strength geotextiles used on these types of stabilization projects have the following minimum-MARV filtration characteristics.

Permeability (ASTM D-4491): 0.009 cm/sec

Apparent Opening Size (AOS—ASTM D-4751): 30-60

Step 9 Determine a geotextile-anchorage scheme: To fully develop a tension-membrane effect, the geotextile must be anchored on two opposite sides, as a minimum, and sometimes continuously around the entire perimeter of the lagoon. This stabilization may be created with an anchor trench or a runout length covered by a nominal (0.3–0.6 m, [1–2 ft]) soil depth. Design procedures for both were presented by Koerner (1994).

If there is sufficient room around the perimeter, use of a runout length is the preferred anchorage method. This approach provides a more uniform distribution of tensile stress across the geotextile. The following equation is used to determine an adequate anchorage runout length, L_a.

$$L_a = \frac{(T_{req} \bullet FS_{min})}{2 \bullet T' - \gamma_f \bullet \tan\phi_f - C_i}$$

where:

T_{req} is the required tensile strength, kN/m, (lb/ft)

FS_{min} is the minimum safety factor for anchorage, (usually 1.5)

T' is the Thickness of fill at anchorage, m (ft)

γ_f is the unit weight of fill soil, kN/m^3 (pcf)

ϕ_f is the internal-shear angle of fill soil in degrees

C_i is the coefficient of shear-stress interaction

A coefficient of shear-stress interaction, C_i, is used to relate pullout capacity to the available soil-shear strength on both sides of the geosynthetic. C_i values can be determined from laboratory pullout testing performed with the GRI-GT 6 Geotextile Pullout method. This coefficient also can be calculated through direct-shear testing with ASTM D-5321, Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method, modified to account for soil on both sides of the geosynthetic reinforcement (Koutsourais, et al. 1998).

For high-strength polypropylene geotextiles, a typical C_i is 0.8–0.95 for sands and 0.6–0.7 for clays. High-strength polyester geotextiles typically have a C_i of 0.8–1.0 for sands and 0.7–0.9 for clays (Koutsourais, et al. 1998). Using a C_i of 0.7 instead of 0.9 yields minimal variations in the required anchorage length. Hence, geotextile design-tensile strength is the governing factor in soil reinforcement design, not "interlock" or the frictional interaction between the geosynthetic and the soil.

Summary

Design of a geosynthetic-reinforced-soil working platform over sludge is unique, in that it cannot be performed without knowledge, or definition, of the construction equipment to be used and the initial soil-lift properties. In practice, the nine design steps detailed above can be performed quickly to determine the specific geotextile required for a given set of field and construction considerations.

The design engineer must clearly identify the variables important to the design in project plans and specifications. While a designer normally must resist the urge to restrict construction practices or equipment, it is essential to do so in these projects. The next Designer's Forum will review construction considerations for lagoon closures.

The authors would like to acknowledge Michael Simac's assistance with the initial development of Synthetic Industries' lagoon-closure technical note. GFR

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