DESIGN OF A GAS PRESSURE RELIEF LAYER BELOW A GEOMEMBRANE COVER TO IMPROVE SLOPE STABILITY

Richard Thiel
Thiel Engineering, USA

ABSTRACT

Pore pressures generated by landfill gas underneath a geomembrane final cover can significantly reduce the effective normal stress on the lower geomembrane interface to the point of creating a cover veneer instability. An estimation of gas flux from the landfill surface can allow a gas-relief layer to be designed using Darcy's law for gas flow through a porous medium. The methodology incorporates knowledge of the gas transmissivity of a chosen medium to design a spacing for highly-permeable strip drains. The strip drains in turn would discharge the gas either to vents or an active gas collection system. The gas-relief layer typically consists of sand or a geonet-composite. Limited testing of nonwoven-needlepunched (NWNP) geotextiles indicates that these materials may also be acceptable for gas relief in some designs. However, more testing is recommended before using NWNP geotextiles alone in this application. A failure case histories is presented that supports the design theory recommended in the paper. The greatest assumption in the proposed methodology concerns the estimation of gas flux. More work is needed in this regard. However, the basic concept of providing a gas-relief layer with intermittent highly-permeable strip drains is recommended as a prudent engineering measure for landfill final covers incorporating geomembrane barriers.

INTRODUCTION

Recent landfill cover slope stability failures have been attributed to excess gas pore pressures below the geomembrane. Soil mechanics methods provide all the tools necessary to address this issue. However, what has been lacking to date are recognition of gas pressures as a design issue, and a design methodology to account for gas pressures and gas relief. The primary steps recommended in this paper to incorporate gas pressures in a landfill cover design are: (1) estimate the maximum gas flux that may need to be removed from below the landfill cover; (2) perform slope stability analyses to estimate the maximum allowable gas pressure; and (3) design a vent system below the cover that will evacuate the assumed gas flux under the estimated maximum allowable driving pressure. Each of these three steps are described in detail in this paper.

ESTIMATING GAS FLUX

The mass flux of gas from the surface of a landfill will be site specific. It will also vary spatially and temporally at a given landfill. The amount of gas will depend on the waste type, age, temperature, moisture, other avenues of gas extraction or venting, barometric pressure, etc. For purposes of slope stability design, estimates of the maximum gas flux, rather than the average, are recommended. One way to estimate the gas flux is to use a computer model for landfill gas generation, such as the EPA's Clean Air Act model. The upper bound estimate of landfill gas generation should be used. The gas flux would then be calculated as the estimated gas generation rate divided by the landfill area under consideration.

An alternate, simplistic method to estimate gas flux (for example, see Richardson, 1998) is to assume a gas generation rate per unit mass of waste, multiply by the mass of waste under consideration, and divide by the area. The literature reports landfill gas generation rates up to 0.6 standard cubic feet per wet pound of waste per year (ft^3/lb/yr) (0.037 m^3/kg/yr) (Pacey, 1997). However, this value is exceptionally high and is reported for controlled landfills in an enhanced decomposition mode. For closures at municipal solid waste landfills on the west coast of the United States, where cell closure occurs at the end of a cell's life, the author has used a gas generation rate of 0.1 ft^3/lb/yr (6.24×10^{-3} m^3/kg/yr) for purposes of cover design. However, estimation of the gas generation rate is very site specific, and the designer is encouraged to consult someone experienced in landfill gas considerations for estimates of gas flux for a particular project.

SLOPE STABILITY CALCULATIONS INCORPORATING GAS PRESSURES

Several papers describing landfill cover veneer slope stability have been presented in the literature (for example Koerner and Soong, 1998; Kavazanjian, 1998; Giroud et al, 1995; Thiel and Stewart, 1993). In these papers different considerations for cover slope stability are presented and developed, including infinite slope approaches, seepage forces, seismic forces, toe buttressing forces, tapered slopes, and slope reinforcement. It is left to the individual practitioner to select the model most appropriate for a given situation to develop the design. In the interests of brevity, the slope stability equations used in this paper for the development of gas pressure considerations will be limited to non-reinforced, static, infinite-slope conditions. However, the principles developed herein to include gas pressures in a stability analysis could easily be combined with other models as well.

Because of the hydraulic break provided by the barrier geosynthetic (assumed to be a geomembrane), seepage forces that may occur in the cover soils above the geomembrane have no influence on the stability of the interface below the geomembrane. Therefore, separate slope stability analyses are required for the geomembrane's upper and lower interfaces. The stability analysis presented herein would only be for the lower interface, where the gas pressures would potentially occur.

The general equation for the factor of safety of an infinite-slope section experiencing pore pressures from below (gas or water) can be formulated as (see Giroud et al, 1995, Eqn 38, for derivation of similar equation):

$$FS = \frac{\bar{a} + [h\gamma \cos\beta - u_g] \tan\bar{\phi}}{h\gamma \sin\beta} \quad (1)$$

where: h = cover soil thickness above the geomembrane and perpendicular to the slope; γ = average unit weight of cover soil above geomembrane; β = slope angle; u_g = gas pore pressure on lower side of geomembrane; $\bar{a}$ = effective adhesion parameter for the lower geomembrane interface; $\bar{\phi}$ = effective friction parameter for the lower geomembrane interface.

Presuming that the material properties and geometry are fixed for a specific design, the designer must then select a minimum allowable factor of safety, FS_{allow}, and calculate a maximum allowable gas pressure, $u_{(g\text{-}allow)}$. Note that the most common unit for measuring landfill gas pressures in the United States is "inches of water column," where one inch of water = 5.2 psf = 0.036 psi (249 Pa).

DESIGNING THE GAS PRESSURE RELIEF SYSTEM

For purposes of the model proposed in this paper, the surface gas relief layer is assumed to be composed of the following three primary elements:

- a blanket gas-relief layer
- a series of parallel trenches or strip drains (the term 'strip drains' is used in the remainder of the paper), at a regular spacing (*D*), that collect gas from the gas-relief layer, and are more permeable than the gas-relief layer to allow the gas to be conveyed to the outlets
- outlet points for the strip-drains

Figure 1(a) shows a typical landfill slope cross section, with an emphasis on the gas collection layer below the barrier layer. In the cross section two benches are shown (which could just as well be the crest and toe of slope for short landfills). Strip drains, which could be perforated pipes, gravel filled trenches, or geosynthetic highway edge drains, are shown running longitudinally along the benches. The distance *D* is defined as the slope distance between the strip drains. Figure 1(b) shows a schematic plan view of the strip-drain layout for this situation, and also indicates that outlet points (in this case vents to the atmosphere) would be intermittently located along the strip drains to relieve the collected gas.

In the event that the strip-drain spacing between benches is found to be inadequate, additional strip drains could be connected in the slope direction between benches. This is illustrated in Figure 1(c) where the spacing *D* is now defined as the distance between the drains running up and down the slope. In this case the strip drains along the benches would serve as headers.

The derivation of the relationship between the strip drain spacing (*D*), incoming gas flux rate, gas transmissivity of the gas-relief layer, and pressure in the gas relief layer is similar to the design of the drainage layer and drainage layer outlets in the cover above the geomembrane as presented by Thiel and Stewart (1993). The derivation is based on Darcy's law, which applies to fluid flow in porous media where the flow is laminar. A discussion of the applicability of laminar flow to the gas-relief layer is presented in Thiel (1999). The derivation steps are as follows:

1. Consider a unit-width surface area between strip drains, as shown in Figure 2(a). Figure 2(b) illustrates a cross-section between two strip drains, showing the gas flux coming uniformly into the gas-relief layer from the waste below. Ideally, the gas flow is symmetric about the centerline between the strip drains, and we need only consider the half-distance, L, where $L = D/2$. The figure identifies the variable distance 'x' beginning at one of the strip drains, and increasing towards the centerline.

2. Figure 3 illustrates how the volume of gas being carried in the gas-relief layer would vary linearly from zero at x=L, to a maximum value at x=0. The volume of gas per unit width can be written in terms of the gas flux as

$$Q_x = \phi_g (L - x) \tag{2}$$

where Q_X is the gas discharge flow rate per unit width at any point x in the gas-relief layer.

3. The flow of gas in the gas-relief layer can be assumed to follow Darcy's law, which can be written in terms of the pressure gradient as follows:

$$Q_x = \left(\frac{k_g}{\gamma_g}\right) \cdot A \cdot \left(\frac{\mathrm{d}u}{\mathrm{d}x}\right) = \left(\frac{k_g}{\gamma_g}\right) \cdot (t \times 1) \cdot \left(\frac{\mathrm{d}u}{\mathrm{d}x}\right) = \left(\frac{k_g \cdot t}{\gamma_g}\right)\left(\frac{\mathrm{d}u}{\mathrm{d}x}\right) \tag{3}$$

where k_g=gas permeability of the gas-relief layer; γ_g=the gas unit weight; A=cross-sectional flow area which is the thickness of the layer (t) times a unit-width; and du/dx is the pressure gradient.

4. Since we can define the gas transmissivity (Ψ_g) of the gas-relief layer as the permeability times the thickness:

$$\Psi_g = k_g \cdot t \text{ (gas transmissivity of the gas relief layer)} \tag{4}$$

we can combine equations (2), (3), and (4) as:

$$\phi_g (L - x) = \frac{\Psi_g}{\gamma_g}\frac{\mathrm{d}u}{\mathrm{d}x} \tag{5}$$

5. Equation (5) can be rearranged to solve for 'u' by integrating in terms of 'x' as:

$$u_x = \frac{\phi_g \gamma_g}{\Psi_g}\int_0^x (L - x)\mathrm{d}x = \frac{\phi_g \gamma_g}{\Psi_g}\left(Lx - \frac{x^2}{2}\right) \tag{6}$$

where 'u_x' is the gas pressure at any distance 'x' from a strip drain.

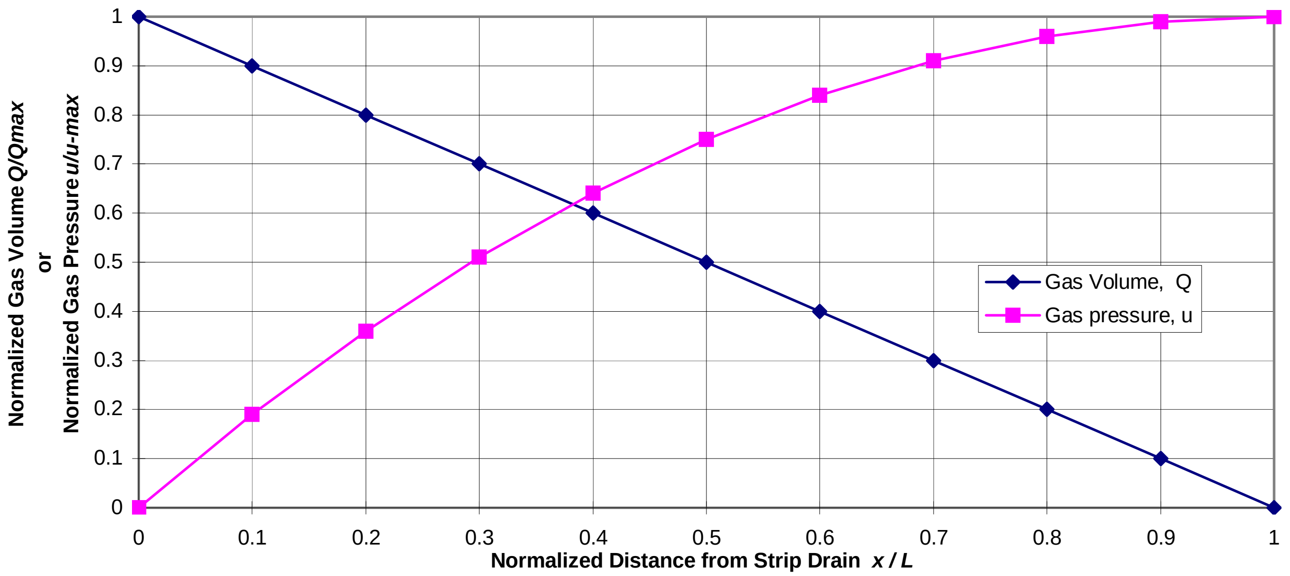

Figure 3. Normalized Gas Pressure and Volume vs. Distance From Strip Drain

The gas pressure is plotted in Figure 3 as a function of distance from the strip drain. From Figure 3, and Equations (5) and (6), we can observe the following:

- The pressure gradient, d*u*/d*x*, varies linearly with distance *x*. It is a maximum at *x*=0 (where the gas volume is greatest), and is zero at *x*=*L* (where there is essentially no gas flow).
- The pressure varies as a polynomial function of distance. It is zero at *x*=0 (that is, it is at the backpressure value in the strip drain). The maximum pressure at *x*=*L* is:

$$u_{max} = \frac{\phi_g \gamma_g}{\Psi_g}\left(\frac{L^2}{2}\right) \quad (7a)$$

or in terms of the strip-drain spacing, *D*:

$$u_{max} = \frac{\phi_g \gamma_g}{\Psi_g}\left(\frac{D^2}{8}\right) \quad (7b)$$

Using Equation (7b), the distance *D* can be written in terms of the maximum pressure as:

$$D = \sqrt{\frac{8 u_{max} \Psi_g}{\phi_g \gamma_g}} \quad (8)$$

It is important to note that the gas pressure calculated in the above equations would be additive to whatever back-pressure exists in the strip drain system. The backpressure value would be the pressure relative to atmospheric pressure that exists at x=0. The author estimates that the back pressure should be no more than 1 inch water column (249 Pa) for well designed passive vent systems. If the vents are connected to an active (suction) gas collection system, a negative value may exist for the backpressure, depending on the suction pressure.

USING INTRINSIC PERMEABILITY TO COMPARE AIR AND WATER TRANSMISSIVITY

Use of Equations (7) or (8) requires the designer to select, or back-calculate, the value of transmissivity, Ψ_g, of the gas-relief layer. However, little if any testing or manufacturer data are available regarding the gas transmissivity of soils or geosynthetics. Therefore, the design will usually have to resort to assuming or specifying an equivalent hydraulic (water) transmissivity. In theory, the gas transmissivity can easily be calculated from the water transmissivity using the concept of intrinsic permeability.

Intrinsic permeability is characteristic of the medium in question, and entirely independent of the nature of the fluid. The principle of intrinsic permeability is considered valid for granular soils, and probably most geosynthetic drainage layers, but would not hold for silts and clays where the polarity of the fluid and electro-osmotic potentials begin to have a significant influence on the measured flow rates. (See, for example, Lambe and Whitman, 1969, pp 287-289; McWhorter and Sunada, 1977, pp 65-71; or for an excellent analytical and historical discussion Muskat, 1937). The formulation of Darcy's law in terms of intrinsic permeability is:

$$Q = K \cdot \frac{\gamma_f}{\mu_f} \cdot i_f \cdot A \qquad (9)$$

where Q = flow rate; K is the intrinsic permeability with units of L^2; γ_f = unit weight of the fluid; μ_f = dynamic viscosity of the fluid; i_f = the fluid gradient, and A is the cross-sectional area of the flow medium. The relationship between the standard civil engineering coefficient of permeability and the intrinsic permeability can be written as:

$$k_f = K \cdot \frac{\gamma_f}{\mu_f} \qquad (10)$$

where k_f is the standard civil engineering coefficient of permeability for a given fluid.

Since K is a constant independent of the fluid, the ratio between the coefficients of permeability for two different fluids (denoted by subscripts 1 and 2) can be determined as

$$\frac{k_1}{k_2} = \frac{\mu_2}{\mu_1} \cdot \frac{\gamma_1}{\gamma_2} \qquad (11)$$

Using Equation (11), the design of a gas-relief layer can now be accomplished by converting the required gas transmissivity to a required hydraulic (water) permeability. All that is required are physical properties of density and viscosity for the fluids of concern. These are easily obtained from published literature.

GAS PERMEABILITY IN PARTIALLY SATURATED SOILS

If the gas-relief layer is a granular soil, it is reasonable to assume that the soil will be holding a certain amount of capillary water either due to rain during construction, or from condensate underneath the geomembrane. Note that condensate water will be prevalent under landfill covers due to landfill gas, which is generally saturated. Since the bottom of the gas-relief layer is not a water table (hopefully!), a sand in this application would probably be at or above its field capacity. Guidance on the field capacity for typical sands can be found in the reference documents for the HELP computer program (Schroeder et al, 1994).

The reduction in gas permeability due to partial saturation of the sand layer can be estimated using the Brooks and Corey (1964, as reported by Fredlund and Rahardjo, 1993) relationship:

$$k_g = k_d \left(1 - S_e\right)^2 \left(1 - S_e^{(2+\lambda)/\lambda}\right) \qquad (12)$$

where: k_g= gas coeff of permeability under given moist conditions

k_d = coeff of permeability to air for a dry soil (S=0)

λ = pore size distribution index (typical values range from 2 for porous rocks, 4 for natural sand deposits, to infinity for uniform spheres)

S_e = effective degree of saturation = $\dfrac{S - S_r}{1 - S_r}$ (13)

S_r = residual degree of saturation at which point an increase in matric suction does not produce an appreciable change in the degree of saturation (S). Typical values for residual saturation are presented by Schroeder et al (1994, pg 13, Figure 2).

For example, the author investigated the air transmissivity of a moist fine sand that was used as the gas-relief layer for a cover system that failed (see Failure Case History, later). The water permeability had previously been measured as $6\text{x}10^{-3}$ cm/s. Using the Equations (11) and (12) with appropriate input values for the field-exhumed sand sample, the author calculated that the air permeability of the moist sample would be $7.2\text{x}10^{-5}$ cm/s. The laboratory-measured value of the air permeability was found to be $8\text{x}10^{-5}$ cm/s, which is in excellent agreement with the theoretically calculated value. It is worthwhile noting that the ratio of k_g/k_d was 0.18. That is, the gas permeability of the sand was reduced by over 80% due to the presence of field moisture!

Using typical values of moisture field capacity for sands presented by Schroeder et al (1994), and going through the same calculations above, indicates that the gas permeability of a typical sand would be reduced by 25-50%. The example described above, derived from actual field data, showed a considerably greater reduction because the field moisture content was greater than the static-drained field capacity. This was probably due to rains during construction, and the constant presence of moisture due to saturated landfill gas. Coarser sands will be less saturated and retain better gas permeability. Based on the limited field experience discussed in the preceding paragraph, and the limited data presented by

Schroeder et at (1994), the following preliminary recommendations are put forward until more data is available:

1. For fine sands containing less than 10-15 percent fines, the field-gas permeability can be taken as the dry-gas permeability reduced by a factor of 5 to 10 to account for the presence of field-moisture.

2. For clean medium and coarse sands, the field-gas permeability can be taken as the dry-gas permeability reduced by a factor of 2 to account for the presence of field-moisture.

FAILURE CASE HISTORY

A sliding failure occurred during construction of a 15-acre (6 ha) final cover project. The slope on which the failure occurred was inclined at 4H:1V (25%, or 14 degrees), and was 60-feet (18 m) high with no benches. The cover system design consisted of the following elements, from bottom to top:

- Foundation soil over waste
- 1-foot (30 cm) thick gas relief layer consisting of a fine sand with a measured hydraulic conductivity of 0.006 cm/s.
- Geosynthetic clay liner (GCL) (needlepunched type, with slit-film geotextile carrier against geomembrane, and nonwoven geotextile carrier facing down)
- PVC geomembrane
- 1-foot (30 cm) drainage layer sand
- 1-foot (30 cm) vegetative soil
- 0.5 feet (15 cm) topsoil

The design also included vertical gas vents on a 200-foot (60 m) spacing each way. The wells consisted of 18-inch (45 cm) borings 15 to 60 feet deep (4.6 to 18.3 m), with 6-inch (15 cm) dia. slotted PVC pipe, backfilled with pea gravel around the pipe. Failure occurred after the following elements had been constructed:

- gas vents
- sand gas-relief layer
- GCL
- geomembrane
- 8 acres (3.2 ha) had just been covered with 1-2 feet (30-60 cm) of drainage sand

The observed failure mode was the geomembrane stretching and then tearing at the top of the slope. The sand on top of the geomembrane, and the geomembrane, slid downslope along the geomembrane/GCL interface. The GCL did not appear to be distressed. However, a thin film of bentonite had extruded from the slit-film side of the GCL at the geomembrane interface.

As the failure progressed, and rain eroded portions of the top sand drainage layer, large gas bubbles formed in the geomembrane. Even the exposed GCL appeared to be uplifted by gas pressures. Subsequent installation of 12 gas probes monitored over a period of two months revealed an average gas pressure in the gas-relief layer of 6.8 inches of water (35.4 psf, or 1.7 kPa) in the nine most critical locations. Two of the probes reported average readings of over 10 inches of water column (2.5 kPa). The probe with the highest pressure averaged over the two months was 13.3 inches of water (69 psf, or 3.3 kPa), and had a single high reading of 16 inches of water (83.2 psf, or 4 kPa).

Shear strength testing was conducted on the PVC geomembrane/hydrated GCL interface over a normal load range of 50-250 lb/ft^2 (2.4-12 kPa). The samples were recovered from the field. The measured Mohr-Coulomb shear strength parameters were 16 degrees friction, and a y-intercept of 11 lb/ft^2 (0.5 kPa). The peak and post peak values were the same. Using the moist sand unit weight of 107 lb/ft^3 (17.3 kN/m^2), a gas pressure of 10 inches of water column (52 psf, or 2.5 kPa), and a sand layer thickness of 1 foot (30 cm) the factor of safety can be calculated from Equation (1) as:

$$\mathrm{FS} = \frac{11\,\mathrm{psf} + \left[1\,\mathrm{ft} \cdot 107\,\mathrm{pcf} \cdot \cos(14) - 52\,\mathrm{psf}\right] \cdot \tan(16)}{1\,\mathrm{ft} \cdot 107\,\mathrm{pcf} \cdot \sin(14)} = 0.9999$$

This factor of safety is marginally less than one, which implies potential localized failure. It is useful to note that the factor of safety is extremely sensitive to the shear strength parameters, and assumed pore pressure. A discussion of these sensitivities is provided by Liu et al (1997). For example, ignoring the very small y-intercept of the Mohr-Coulomb envelope reduces the factor of safety to 0.57! Note that the practice of ignoring the y-intercept is a common practice and is often recommended in the literature (e.g. Koerner and Soong, 1998).

In this case history, no strip drains were provided in the gas-relief layer. We can use this opportunity, in hindsight, to calculate the improvement in factor of safety by installing strip drains. The original designer assumed a gas generation rate of 0.1 ft^3/lb/yr (6.24x10^{-3} m^3/kg/yr), which resulted in an estimated gas flux of 0.001 cfm/ft^2 (5x10^{-6} m^3/s/m^2) for this site. The air-permeability of the moist gas-relief layer was measured in the laboratory as 8x10^{-5}cm/s. The equivalent landfill gas permeability and transmissivity can be calculated from Equations (11) and (4) as:

$$k_g = k_{air}\frac{\mu_{air}}{\mu_{gas}} \cdot \frac{\gamma_{gas}}{\gamma_{air}} = 8(10)^{-5}\frac{cm}{s} \cdot \frac{1.79(10)^{-5}\mathrm{N-s/m^2}}{1.32(10)^{-5}\mathrm{N-s/m^2}} \cdot \frac{12.8\,\mathrm{N/m^3}}{11.8\,\mathrm{N/m^3}} = 1.2(10)^{-4}\frac{\mathrm{cm}}{\mathrm{s}}$$

$$\Psi_g = k_g \cdot t = 1.2(10)^{-4}\frac{\mathrm{cm}}{\mathrm{s}} \cdot 30\mathrm{cm} = 3.6(10)^{-3}\frac{\mathrm{cm}^2}{\mathrm{s}} \quad \left(3.6(10)^{-7}\frac{\mathrm{m}^2}{\mathrm{s}}, \mathrm{or}\, 2.32(10)^{-4}\frac{\mathrm{ft}^2}{\mathrm{min}}\right)$$

Using Equations (1) and (7b), the variation in factor of safety with strip drain spacing (*D*) is graphically presented in Figure 4. The figure indicates a variation in FS from 1.4 with back-to-back strip drains (i.e. no gas pressure buildup), to *FS* = 1.0 with a strip drain spacing of 29 ft (8.8 m). The close strip-drain spacing required by this case history is caused by the poor transmissivity of the sand. One of the lessons learned in this case is that fine sands that may demonstrate relatively good hydraulic conductivity lose a lot of their gas permeability due to the presence of field moisture.

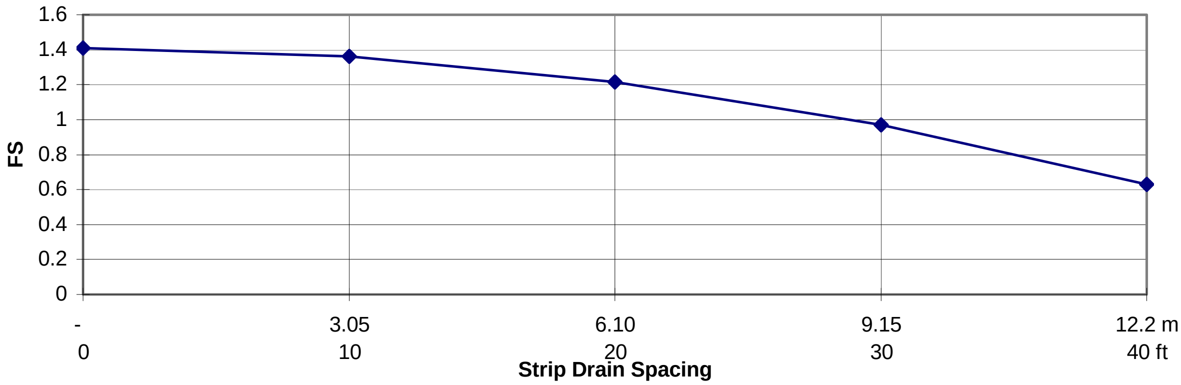

Figure 4. Solution for Case History

LABORATORY STUDY OF GAS TRANSMISSIVITY OF NWNP GEOTEXTILES

In specifying a gas-relief layer, it is tempting to consider use of a NWNP geotextile. However, there is very limited test data available regarding the in-plane air transmissivity (or permeability) of geotextiles. Koerner et al (1984) presented their interpretation of water and air transmissivity testing using a radial flow device. However, the data interpretation appears to have been flawed in that the authors did not take into account the gradient for the air testing. Therefore this reference is not able to be used without further evaluation of the raw data, which was not provided in the paper.

Weggel and Gontar (1993) used the same radial flow device as Koerner et al (1984) to study in-plane air flow through eight NWNP geotextiles. They provided a substantial amount of raw experimental data, and a relatively thorough derivation of the flow analysis. Their testing appears to have been outside of the laminar flow region as indicated by the trends in the test data. Their empirically derived relationship results in a dry-air transmissivity of a geotextile with a thickness of 145 mils (0.37 cm) (presumably a 16-oz/yd^2, or 540 g/m^2 material) of approximately $1x10^{-4}$ cfm/ft ($1.5x10^{-7}$ m^2/s). This is about one-half the gas-transmissivity of the fine sand described in the failure case history.

Thiel (1999) provides radial air testing data on a suite of three NWNP polyester geotextiles, under both dry and wet conditions, all at a normal load of 1,000 psf (47.8 kPa). The tests were conducted at an average gradient of approximately 750. The tests results indicated the following:

- The wet specimens lost 25-33% of their transmissivity, compared to the dry specimens.
- Going from a 6 denier (6d) -16 oz/yd^2 (540 g/m^2) material to a 45d-32 oz/yd^2 (1,100 g/m^2) material resulted in an order-of-magnitude increase in transmissivity. The average dry transmissivity of the 6d-16 oz/yd^2 (540 g/m^2) material was found to be $6x10^{-4}$ cfm/ft ($9x10^{-7}$ m^2/s). The average dry transmissivity of 45d-32 oz/yd^2 (1,100 g/m^2) material was found to be $6x10^{-3}$ cfm/ft ($9x10^{-6}$ m^2/s).

- Using the theory of intrinsic permeability, the estimated in-plane water transmissivity of the 45d material is equivalent to that of a 1-ft (30 cm) thick layer of sand having a permeability of 4.7×10^{-2} cm/s.

The author is currently coordinating radial air and water testing of a 45d-32 oz/yd^2 (1,100 g/m^2) NWNP polyester material and a 6d-16 oz/yd^2 (540 g/m^2) NWNP polypropylene material. The testing purposes are (a) to verify that the theory of intrinsic permeability is valid for these geotextiles, and (b) to determine the materials' air transmissivity under dry and wet conditions. The tests are being conducted and analyzed in a fashion similar to that described by Weggel and Gontar (1993) and Thiel (1999). Typical preliminary results are summarized in graphical form on Figure 5. Preliminary conclusions from these test results are:

- The theory of intrinsic permeability appears to be valid. That is, the intrinsic permeability calculated from air and water tests on the same material is nearly the value. The graph shows this by illustrating that the dry-air transmissivity back-calculated from a water test is approximately the same value as the dry-air transmissivity determined from an air test. The dry-air transmissivity for the 45d-32 oz/yd^2 (1,100 g/m^2) material is approximately 8×10^{-3} cfm/ft (1.2×10^{-5} m^2/s). The dry-air transmissivity of the 6d-16 oz/yd^2 (540 g/m^2) material is approximately one-order of magnitude less, or 8×10^{-4} cfm/ft (1.2×10^{-6} m^2/s).

- The air transmissivity of a 45d-32 oz/yd^2 (1,100 g/m^2) material that has been wetted to field-capacity and stabilized under the air flow is approximately one-order of magnitude less than its dry-air transmissivity.

- The air transmissivity of a 6d-16 oz/yd^2 (540 g/m^2) material that has been wetted to field-capacity and stabilized under the air flow is approximately one-half order of magnitude less than its dry-air transmissivity.

It is the gas-transmissivity of a wet material that would be of primary interest to the design subject of this paper, since the field condition of a gas relief layer would generally be expected to be moist. The wet-air transmissivity of the 45d-32 oz/yd^2 (1,100 g/m^2) material is preliminarily estimated to be between 5×10^{-4} cfm/ft (1.2×10^{-6} m^2/s) and 1×10^{-3}cfm/ft (6×10^{-6} m^2/s). This is 3-6 times the wet-air transmissivity of the fine sand discussed in the case history.

The author advises caution in using any of the geotextile air-transmissivity values presented in this paper for actual designs. The test methodologies and data interpretations are non-standard at this point. The data is presented to illustrate the potential for using these materials, and the direction that laboratory testing studies need to go.

CONCLUSIONS

Slope stability of landfill covers incorporating geomembrane barriers can be compromised by pore pressures caused by landfill gas. This has been demonstrated by field failures in which gas pressures appeared to play a significant role.

Standard geotechnical and fluid mechanics engineering principles can be used to design final cover systems to accommodate potential landfill gas pressures. However, as is typical with many geotechnical problems, the basic input of field parameters to the analysis, in this case an estimation of the field gas pressures and volumes, is not an exact science, and involves educated assumptions and experience.

Calculations and experimental evidence from the literature suggests that landfill gas flow rates expected in gas-relief layers are generally expected to be laminar, and Darcy's law applies. The fluid-mechanics principle of intrinsic permeability can allow estimations of gas transmissivity and permeability to be made based on more well known, or more easily obtained, values for water.

Limited laboratory test data suggests that coarse, heavy (e.g. 45d-32 oz/yd^2 (1,100 g/m^2)) NWNP geotextiles may have adequate gas transmissivity under field conditions for many typical situations. However, industry testing and design experience in this regard is sparse.

RECOMMENDATIONS AND DISCUSSION

The theoretical solution to gas flow presented in this paper is undoubtedly more developed than the profession's ability to provide the basic input parameters to the model. To that extent, it may be found that the theoretical assumptions presented herein are incorrect when a more accurate understanding of landfill gas generation, flux, and flow mechanisms is attained. However, in lack of any other procedures available, the model presented in this paper is meant to serve as a starting point.

The key input parameter that needs more development is the assumed gas flux that might cause pressures below a landfill cover. To that end, additional gas flow measurements below installed covers would be useful. Gas pressure measurements, as described for the failure history, would also be very useful.

The industry is also in need of good, well documented test data for in-plane gas transmissivity. The testing should be performed at relatively low pressure gradients representative of landfill gas collection requirements, where the flow is laminar. However, higher gradient tests with non-laminar flow would be conservative in that they would result in lower transmissivity values. The testing should be performed not only for dry geotextiles, but also on wet geotextiles at a simulated field moisture capacity obtained from soaking the geotextile and then letting it drain. When possible, it would be useful to provide side-by-side testing of air and water transmissivity in the laminar flow region to verify that the concept of intrinsic permeability can be applied to geotextiles. The geotextiles being tested should be fully described in terms of their mass per unit area, fiber size, initial thickness, and polymer type.

The model presented herein is probably conservative since many successful landfill covers have been constructed without explicit considerations for gas pressures. However, the author has witnessed several cover construction projects that, even though successful in the end product, experienced significant landfill gas problems during construction. Whether the design procedures presented in this paper are used, or some other method, the author believes that all parties involved with a landfill final cover will be well served if some degree of highly permeable strip drains and gas-relief layer are constructed below the barrier layer system.

ACKNOWLEDGEMENTS

The author is indebted to Mr. Ron Marsh of Geocomp, Inc. for providing air transmissivity testing data for geotextiles.

REFERENCES

Fredlund, D.G., Rahardjo, H. (1993) Soil Mechanics For Unsaturated Soils, John Wiley & Sons, Inc., New York.

Geocomp, Inc. (1998) Personal communication with Ron Marsh, 1996-1999.

Giroud, J.P., Bachus, R.C. and Bonaparte, R. (1995) "Influence of Water Flow on the Stability of Geosynthetic-Soil Layered Systems on Slopes", Geosynthetics International, Vol. 2, No. 6, pp. 1149-1180.

Koerner, R. M., Bove, J.A., and Martin, J.P. (1984) "Water and Air Transmissivity of Geotextiles", Geotextiles and Geomembranes, Elsevier Applied Sciences Publishers, Inc., Vol. 1, pp 57-73.

Koerner, R.M., Soong, T.Y. (1998) "Analysis and Design of Veneer Cover Soils", Proceedings of the Sixth International Conference on Geosynthetics, Roseville, MN, IFAI, pp 1-26.

Kavazanjian, E. (1998) "Current Issues in Seismic Design of Geosynthetic Cover Systems", Proceedings of the Sixth International Conference on Geosynthetics, Roseville, MN, IFAI, pp 219-226.

Lambe, T.W., Whitman, R.V. (1969) Soil Mechanics, John Wiley & Sons, New York.

Liu, C.N., Gilbert, R.B., Thiel, R.S., Wright, S.G. (1997) "What Is An Appropriate Factor of Safety for Landfill Cover Slopes?", Proceedings of Geosynthetics '97, Roseville, MN, IFAI, pp 481-496.

McWhorter, D., Sunada, D. (1977) Ground Water Hydrology and Hydraulics, Water Resources Publications, Highlands Ranch, CO.

Muskat, M. (1937) The Flow of Homogeneous Fluids Through Porous Media, McGraw Hill, New York.

Pacey, J.G. (1997) "Insights to Enhanced Landfill Gas Generation", Proceedings to Sardinia '97 Sixth International Landfill Symposium, CISA, Vol. 1, pp 359-368.

Peck, R.B., Hanson, W.L., Thornburn, T.H. (1974) Foundation Engineering, 2nd Ed., John Wiley & Sons, Inc., New York.

Richardson, G.N., and Zhao, A. (1998) "Composite Drains for Side Slopes in Landfill Final Covers", Geotechnical Fabrics Report, Volume 16, No. 5, June/July 1998, pp. 22-25.

Schroeder, P.R., Dozier, T.S., Zappi, P.A., McEnroe, B.M., Sjostrom, J.W., and Peyton, R.L. (1994) The Hydrologic Evaluation of Landfill Performance (HELP) Model - Engineering Documentation for Version 3, USEPA.

Thiel, R.S., Stewart, M.G. (1993) "Geosynthetic Landfill Cover Design Methodology and Construction Experience in the Pacific Northwest", Proceedings of Geosynthetics '93, Roseville , MN, IFAI, pp 1131-1144.

Thiel, R.S. (1999) "Design Methodology for a Gas Pressure Relief Layer Below a Geomembrane Landfill Cover to Improve Slope Stability." Accepted for publication in Geosynthetics International. To be published in 1999.

Weggel, R., and Gontar, W.A. (1993) "In-Plane Air Flow Through Needle-Punched Nonwoven Geotextiles Under Normal Loading", Geotechnical Testing Journal, ASTM, Vol. 16, No.2, June 1993, pp 207-215.