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LINER DESIGN FOR LATERAL AND VERTICAL EXPANSIONS

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SUMMARY: A methodology for the design of landfill liner systems constructed over existing municipal waste is presented within. Long-term strain of the liner system, due to settlement of underlying waste, is addressed. Polyethylene geomembranes, low strain conditions, and axi-symmetric deflections are specifically examined. The paper is directed toward practitioners and regulatory authorities.

1. INTRODUCTION

One option in siting municipal landfills is to construct new cells on top of existing landfills. Such expansions may be vertical, lateral, or a combination of both as illustrated in Figure 1. A design concern with this type of construction is the long-term integrity of the bottom liner of the new landfill cell and maintaining separation between new and old cells. Landfills are normally designed with the goal of eliminating, or minimizing, mobilization of tensile stresses in the liner components. However, tensile loads may not be eliminated for landfill liners that are subject to settlement over time, such as those placed over existing waste. Much of the work to date on the development of design methodologies for landfill liners on yielding foundations has focused on definition of geometric configuration and boundary loading conditions. Viscoelastic material response of the geosynthetic liner system components under long-term loading is examined within this paper.

2. DEFLECTION MODEL

Depressions in landfill liner systems can occur over time due to differential settlement of the underlying waste. The geosynthetic components may deflect into the depressions until their rupture limits are reached. The liner may be supported by the subgrade, though a worse case scenario is one where the depression is modelled as a void and the liner is unsupported except around the edges of the void.

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The analysis presented within is based upon an assumed circular void, and an axisymmetric deflection of the liner. This model may or may not be appropriate for specific landfill liner designs. However, the analysis procedure can be used to provide relative long-term performance comparisons of various liner systems.

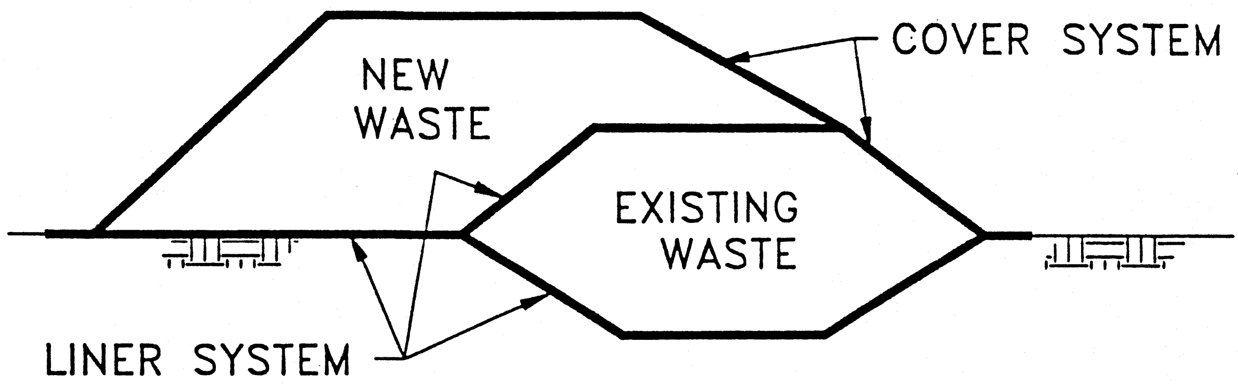

Figure 1. Lateral/vertical landfill expansion.

3. MATERIAL PROPERTIES

A typical cross section of a landfill liner system for a vertical expansion is shown in Figure 2. The primary function and performance of the geosynthetics, relative to a deformed foundation, are discussed below.

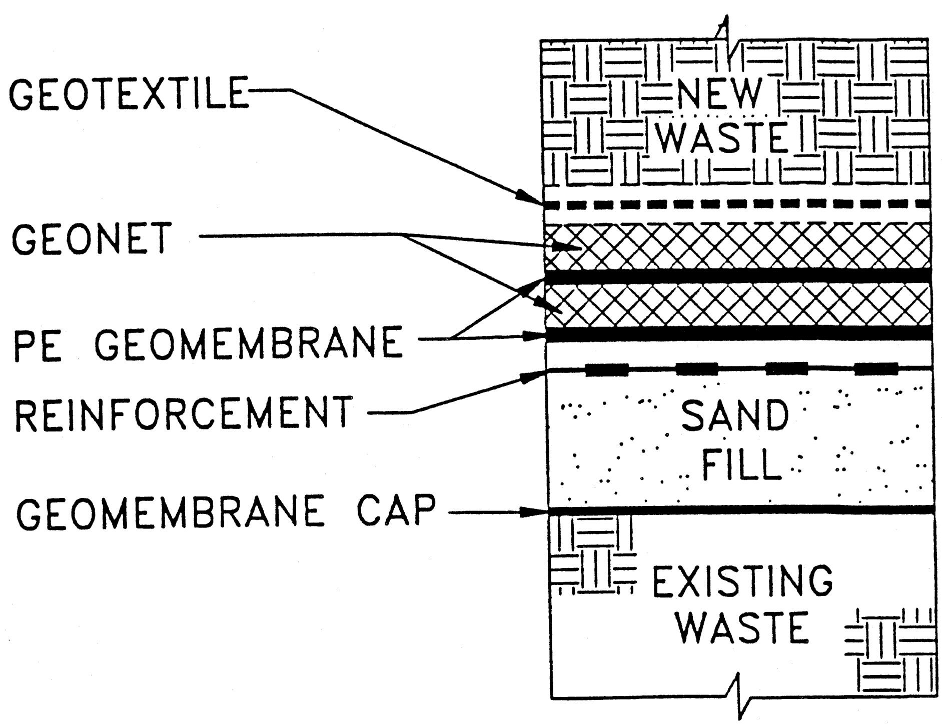

Figure 2. Typical landfill liner for a vertical expansion.

The geotextile used for filtration is typically a light-weight (eg., 200 g/m^2), nonwoven material. The geotextile is installed with adjacent rolls overlapped. It should be capable of conforming to deformations created by foundation settlements without impairing its function. Geonets used in landfills are typically 5 to 6 mm thick and manufactured of polyethylene. Geonets are usually installed with sides of adjacent rolls butted together and held in-place during construction with plastic ties. The geonets also should be capable of conforming to deformations without impairing their overall function of drainage, though localized drainage could be impaired if deformations occur directly beneath a butted seam and edges of adjacent rolls are separated. It is assumed that any tensile load in the filtration textile and drainage net is negligible in addressing liner settlements. This assumption implies that the geotextile and geonet strain, to the degree set by the membrane and/or reinforcement limitation, without substantial stress.

Two polyethylene (PE) geomembranes are typically used in the bottom liner of municipal landfills. Adjacent panels of geomembranes are overlapped and seamed by heat welding. The primary function of the geomembrane is to provide a barrier that prevents loss of leachate. Long-term tensile properties of the geomembranes should be defined, with laboratory testing, for applications where differential settlements may occur. Long-term allowable stress in the geomembrane may be quantified with the method presented by Berg and Bonaparte (1993), for PE geomembranes under load-controlled boundary conditions. This method should be modified for deformation-controlled boundary conditions and other types of geomembranes.

Geosynthetic reinforcement (eg., geogrids) may be added to landfill liner systems to enhance the performance of a liner system over a yielding foundation. The primary function of the geosynthetic reinforcement is to provide structural support over a deforming foundation. The long-term tensile strength of the reinforcement should be quantified with one of several similar methods presented in the literature (e.g., Bonaparte and Berg, 1987a; Jewell and Greenwood, 1988; GRI, 1990; Koerner, 1990; Berg, 1993). Alternatively, the geosynthetic composite liner system, or those components significantly contributing to structural support, could be tested under assumed geometric and boundary loading conditions, and the long-term stress-strain relationship defined.

4. DESIGN PROCEDURE

The design procedure presented herein is based upon tension membrane theory (Giroud, 1981), soil arching theory (Bonaparte and Berg, 1987b; Giroud et al. 1990), definition of a safe allowable tension and strain in a PE geomembrane (Berg and Bonaparte, 1993), and definition of a safety factor against rupture of a liner system (Berg and Collin, 1993). A void is used to model a depression or settlement.

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4.1 Tension Membrane

With tension membrane theory, the liner system acts as a membrane to span a void The membrane deflects axi-symmetrically into the void. It is assumed that the soil-membrane interface above the void is frictionless and that overlying loads are applied normal to the deflected membrane. Thus, the liner components are subject to tensile stress only, and not shear stress. Giroud (1981) has shown that the tension in a membrane over a circular void is approximately equal to:

$$T = p \, \Omega \, r \qquad \text{EQ. 1}$$

where,

p = normal pressure;
Ω = f (deflection depth); and
r = radius.

The dimensionless factor, Ω, is a function of the allowable membrane design strain, E_d, and can be calculated as:

$$1 + E_d = 2 \, \Omega \, \sin^{-1}(\Omega/2) \qquad \text{EQ. 2}$$

4.2 Arching

The normal pressure, p, on the membrane, computed with arching theory (Giroud et al., 1990), is:

$$p = 2 \, \gamma \, r \, (1 - e^{-0.5H/r}) \qquad \text{EQ. 3}$$

where,

γ = unit weight of overlying waste;
r = radius of circular void (m);
H = height of waste above liner (m).

4.3 Liner System Safety Factor

The design goal is to prevent rupture of the geomembrane component of the landfill liner system, and maintain integrity of the separation barrier. Hence, the analyses target a safety factor against rupture of the geosynthetic liner components. The methodology for computing safety factors against liner rupture presented by Berg and Collin (1993) is used within. This methodology incorporates the mobilized tensile strength of the geomembrane and addresses both systems with and without geosynthetic reinforcing elements. A factor of safety against rupture of the liner system must be selected by the designer. This factor should reflect judgement used in other assumptions, reliability of material properties, and consequences of rupture of the liner system.

Liner systems with geosynthetic reinforcement differ from systems without reinforcement in how the factor of safety against rupture is defined. The factor of safety against rupture for a system with only geomembranes carrying loads is solely dependent upon the rupture stress and safety factor against rupture of the geomembrane. The factor of safety against rupture of a liner system with reinforcement is dependent upon rupture stress of the geomembrane and the mobilized stress in the reinforcement at the rupture strain of the geomembrane.

The overall factor of safety against rupture of a PE geomembrane, subject to load-controlled boundary conditions, from Berg and Bonaparte (1993), is equal to:

$$FS = \frac{\sigma_r \, x \, FC \, x \, FW \, x \, FI}{\sigma_a} \qquad \text{EQ. 4}$$

where

FS	=	overall factor of safety against rupture of the geomembrane (dimensionless);
σ_r	=	geomembrane rupture stress at the design life/temperature as illustrated in Figure 3 (N/mm^2);
FC	=	reduction factor to account for chemical (or radiation) degradation over the design life (dimensionless);
FW	=	reduction factor (i.e., weld factor) to account for long-term seam strength (dimensionless);
FI	=	reduction factor to account for installation damage (dimensionless); and
σ_a	=	geomembrane allowable long-term tensile stress at the design life/temperature as illustrated in Figure 3 (N/mm^2).

An overall factor of safety of 2 to 3 for PE geomembranes appears reasonable, as discussed by Berg and Bonaparte (1993). Again, the factor of safety against liner system rupture is equal to the factor of safety against rupture of the geomembrane(s) when a geosynthetic reinforcement component is not included.

The overall factor of safety against rupture of a liner system that incorporates reinforcement elements may be defined (Berg and Collin, 1993) as:

$$FS_{ls} = \frac{(\sigma_f \, x \, t_m \, x \, N) + T_{reinf}}{(\sigma_a \, x \, t_m \, x \, N)} \qquad \text{EQ. 5}$$

where

N	=	number of geomembranes of equal thickness t_m (dimensionless);
FS_{ls}	=	factor of safety against rupture of the liner system (dimensionless);
σ_f	=	failure stress of the geomembrane at the design life and temperature (i.e., $\sigma_f = \sigma_r$ x FC x FW x FI, as illustrated in Figure 3) (N/mm^2);
t_m	=	minimum thickness of geomembrane(s) (mm); and
T_{reinf}	=	mobilized tension (σ_R x t_R x N_R) in the reinforcement element(s) at a strain compatible with σ_f (σ_R illustrated in Figure 4) (kN/m).

Assuming equal strain in geomembrane and reinforcement elements, the allowable tensile load, T_{ls}, in liner systems with and without reinforcement is:

(a) without reinforcement

$$T_{ls} = \sigma_a \times t_m \times N \qquad \text{EQ. 6}$$

and

(b) with reinforcement

$$T_{ls} = (\sigma_a \times t_m \times N) + T_a \qquad \text{EQ. 7}$$

where T_a equals mobilized tension in the reinforcement element(s) at a strain compatible with the mobilized tension in the geomembrane(s) (σ_{a2} or σ_{a3}), illustrated as ϵ_{a2} and ϵ_{a3} in Figure 4. In incorporating reinforcement and assuming strain compatibility at a time equal to the design life, it is inherently assumed that both the geomembrane(s) and reinforcement(s) remain within their linear viscoelastic limits. This assumption is appropriate if low levels of initial and final strains are anticipated.

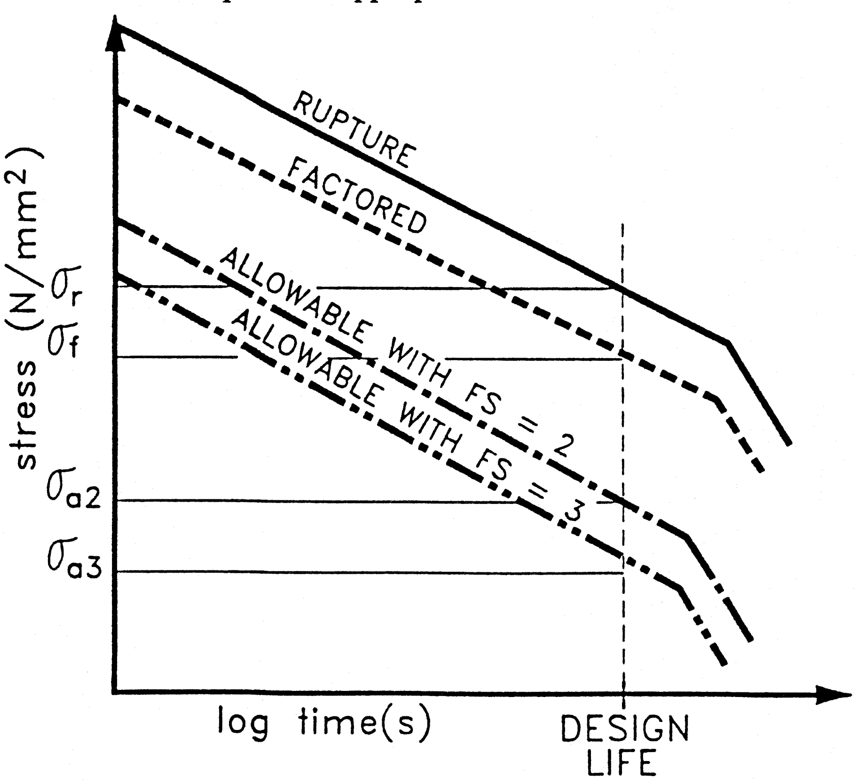

Figure 3. Geomembrane Rupture Lines

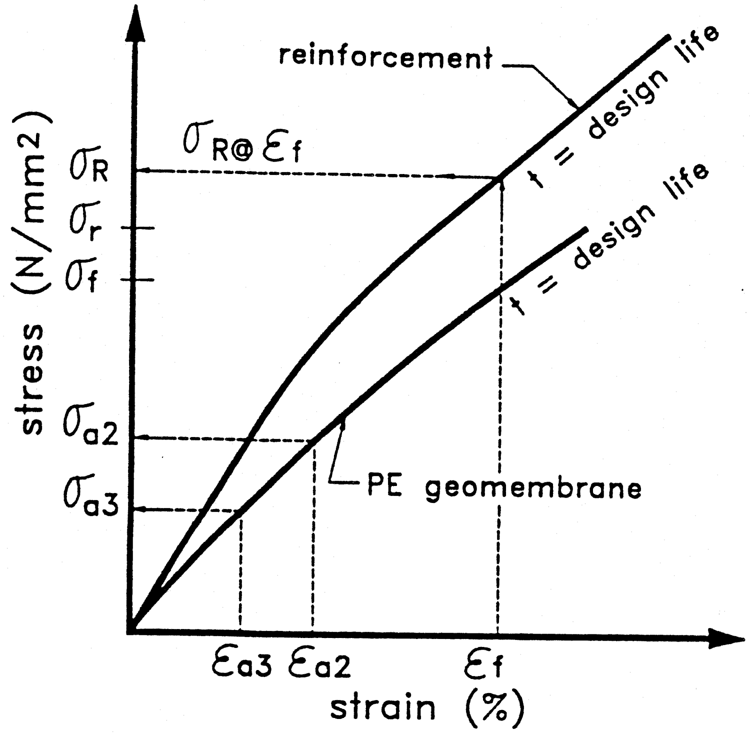

Figure 4. Isochronous Curves

5. EXAMPLE CALCULATIONS

Three example calculations are presented for landfill expansion liner systems. The first example incorporates two 1.5 mm PE geomembranes, which are susceptible to brittle fracture within the design life. The second calculation is comprised of the same geomembranes used in Example Calculation # 1 and a structural geogrid reinforcement element. The third example incorporates two 2.5 mm PE geomembranes, which are resistant to brittle fracture over the design life, and a structural geogrid reinforcement element.

<u>Example Calculation # 1</u>. The liner system consists of two 1.5 mm PE geomembranes, two geonets, and one filtration geotextile. Determine the diameter of void this liner system can safely span.

Assumptions:

- a circular depression, or void, models possible foundation deformations
- the liner system does not touch bottom of the depression
- geomembranes are subject to a load-controlled boundary condition
- 30 m of waste will be placed above the lining system
- the stress rupture-time relationship of the geomembrane is defined by Figure 5
- the strain-time relationship of the geomembrane is defined by Figure 6
- waste unit weight equals 10 kN/m^3
- long-term tensile load in the geonets $\approx$ 0
- long-term tensile load in the filtration geotextile $\approx$ 0

Computation of the allowable stress on the PE geomembrane (from Berg and Bonaparte, 1993) is

STEP 1: Establish in-service environment and design life
Assumption - service temperature is 23°C
Assumption - design life equals 50 years

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Example Calculation # 1. (*continued*)

STEP 2: Establish stress-strain and rupture characteristics
From Figure 5, $\sigma_r = 7.2$ N/mm^2

STEP 3: Quantify a chemical degradation factor
Assumption - degradation factor, FC = 1.0

STEP 4: Quantify a seam factor
No data available, assume that the long-term seam factor, FW = 0.8

STEP 5: Quantify an installation damage factor
Assumption - installation damage factor, FI = 1.0

STEP 6: Select an overall factor of safety for the PE geomembranes
Select an overall factor of safety against rupture of 3.0

STEP 7: Compute long-term allowable tensile stress

$$\sigma_a = \frac{\sigma_r \ x \ FC \ x \ FW \ x \ FI}{FS}$$

$$\sigma_a = \frac{7.2 \ N/mm^2 \ x \ 1.0 \ x \ 0.8 \ x \ 1.0}{3.0} = 1.9 \ N/mm^2$$

Thus, allowable long-term tensile stress in this (Figure 5) polyethylene geomembrane is $\sigma_a = 1.9$ N/mm^2. The strain at this long-term stress level, from extrapolated 50-year isochronous line on Figure 6, is approximately 1.0%.

The tensile load capacity of the liner system, at the allowable stress level of the geomembranes is

$$T_a = \sigma_a \ x \ 2 \ x \ t_m$$

$$T_a = 1.9 \ N/mm^2 \ x \ 2 \ x \ 1.5 \ mm = 5.7 \ kN/m$$

Membrane tension, α, on the liner system (equations from Giroud et al., 1990) is

$$\alpha = p \ r \ \Omega$$

The design strain limit is $\epsilon_d \approx 1.0$ %, therefore $\Omega = 2.07$ (from Giroud et al., 1990)
Pressure, p, on the liner system computed with arching theory (equation from Giroud et al., 1990) is

$$p = 2 \gamma r (1 - e^{-0.5 H/r})$$

$$\alpha \approx 5.7 \ kN/m \approx 2 \gamma r (1 - e^{-0.5H/r}) \ x \ r \ x \ 2.07$$

$$r \approx 0.37 \ m$$

Therefore, this liner system is capable of carrying an allowable isotropic tensile load, under load-controlled boundary conditions, of 5.7 kN/m and can span a circular deflection or void of 0.74 m in diameter.

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Example Calculation # 2. This liner system consists of two 1.5 mm PE geomembranes, two geonets, one filtration geotextile, and a geosynthetic reinforcement element.

Assumptions:

- a circular depression, or void, models possible foundation deformations
- liner system does not touch bottom of depression
- geomembranes are subject to a load-controlled boundary condition
- 30 m of waste will be placed above the lining system
- the stress rupture-time relationship of the geomembrane is defined by Figure 5
- the strain-time relationship of the geomembrane is defined by Figure 6
- waste unit weight equals 10 kN/m^3
- long-term tensile load in the geonets ≈ 0
- long-term tensile load in the filtration geotextile ≈ 0

Computation of the allowable stress on the PE geomembrane (from Berg and Bonaparte, 1993) is

STEPs 1 through 5: same as example calculation # 2

STEP 6: Select an overall factor of safety for the PE geomembranes
Select an overall factor of safety against rupture of the geomembranes of 2.0, provided the inclusion of the geosynthetic reinforcement raises the overall factor of safety against rupture of the liner system to 3.0 or larger.

STEP 7: Compute long-term allowable tensile stress

$$\sigma_a = \frac{\sigma_r \ x \ FC \ x \ FW \ x \ FI}{FS}$$

$$\sigma_a = \frac{7.2 \ N/mm^2 \ x \ 1.0 \ x \ 0.8 \ x \ 1.0}{2.0} = 2.9 \quad N/mm^2$$

Thus, allowable long-term tensile stress in this (Figure 5) PE geomembrane is $\sigma_a = 2.9$ N/mm^2.

The strain at this stress level, from extrapolated 50-year isochronous line on Figure 6, is $\approx 1.8\%$. Check factor of safety against liner rupture and determine minimum requirements of geosynthetic reinforcement. Factor of safety against rupture of the geomembranes is applied to the rupture stress, σ_r. The factor of safety against rupture of the liner system may be computed as the ratio of tensile stress, or load, at rupture to the allowable stress, or load, in the geomembrane(s). The factor of safety is equal to

$$FS_{ls} = \frac{\sigma_f \, (\, t_m \ x \ N \,) \ + \ T_{reinf}}{\sigma_a \, (\, t_m \ x \ N \,)} \geq 3.0$$

where T_{reinf} is at ϵ_f of the geomembrane

$$\sigma_f = \sigma_r \ x \ FC \ x \ FW \ x \ FI$$

Example Calculation #2. (*continued*)

$$\sigma_f \;=\; 7.2\ N/mm^2\ x\ 1.0\ x\ 0.8\ x\ 1.0 \;=\; 5.76\ N/mm^2$$

From Figure 6, the geomembrane failure strain is 5%.

$$\frac{5.76\ N/mm^2\ x\ (\ 1.5\ mm\ x\ 2\ )\ +\ T_{reinf}}{2.9\ N/mm^2\ x\ (\ 1.5\ mm\ x\ 2\ )} \;\geq\; 3.0$$

$$T_{reinf} \;=\; 8.8\ kN/m$$

where

T_{reinf} = minimum isotropic tensile strength of the reinforcement at the geomembrane failure strain of (5% as determined from Figure 6) at the design temperature and life (kN/m).

Select the UX1400HT geogrid, Figure 7, with an isotropic tensile strength greater than 8.8 kN/m at a 5% strain. Its isotropic tensile strength at a strain of 1.8% is equal to 4.0 kN/m. Therefore tensile strength, T_a, equals 4.0 kN/m.

The tensile load capacity of the liner system, at the allowable stress level of the geomembranes is

$$T_{system} \;=\; (\ \sigma_a\ x\ t_m\ x\ N\ )\ +\ T_a$$

$$T_{system} \;=\; (\ 2.9\ N/mm^2\ x\ 1.5\ mm\ x\ 2\ )\ +\ 4.0\ kN/m$$

$$T_{system} \;=\; 8.7\ +\ 4.0 \;=\; 12.7\ kN/m$$

Membrane tension, α, on the liner system (equations from Giroud et al., 1990) is

$$\alpha \;\approx\; p\ r\ \Omega$$

The design strain limit is ϵ_d = 1.8 %, therefore Ω = 1.52 (from Giroud et al., 1990)

$$\alpha \;=\; 12.7\ kN/m \;\approx\; 2\ \gamma\ r\ (\ 1\ -\ e^{-0.5H/r}\ )\ x\ r\ x\ 1.52$$

$$r \;\approx\; 0.65\ m$$

Therefore, this liner system is capable of carrying an allowable axisymmetric tensile load of 12 kN/m and can span a circular deflection or void of 1.3 m in diameter.

STEP 8: Check that both the geomembrane and reinforcement remain in their linear viscoelastic limits under initial and final strains.

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Example Calculation # 3. This liner system consists of two 2.5 mm PE geomembranes that do not show a transition from ductile to brittle failure during the design life, two geonets, one filtration geotextile, and a geosynthetic reinforcement element.

Assumptions:

- a circular depression, or void, models possible foundation deformations
- liner system does not touch bottom of depression
- geomembranes are subject to a load-controlled boundary condition
- 30 m of waste will be placed above the lining system
- the stress rupture-time relationship of the geomembrane is defined by Figure 5
- the strain-time relationship of the geomembrane is defined by Figure 6
- waste unit weight equals 10 kN/m^3
- long-term tensile load in the geonets ≈ 0
- long-term tensile load in the filtration geotextile ≈ 0

Computation of the allowable stress on the PE geomembrane (from Berg and Bonaparte, 1993) is

STEPs 1, 3, 4, and 5: same as example calculation # 2

STEP 2: From Figure 5, $\sigma_r = 13.6\ N/mm^2$

STEP 6: Select an overall factor of safety for the PE geomembranes
Select an overall factor of safety against rupture of the geomembranes of 2.0, provided the inclusion of the geosynthetic reinforcement raises the overall factor of safety against rupture of the liner system to 3.0 or larger.

STEP 7: Compute long-term allowable tensile stress

$$\sigma_a = \frac{\sigma_r \ x \ FC \ x \ FW \ x \ FI}{FS}$$

$$\sigma_a = \frac{13.6 \ N/mm^2 \ x \ 1.0 \ x \ 0.8 \ x \ 1.0}{2.0} = 5.4 \ N/mm^2$$

Thus, allowable long-term tensile stress in this (Figure 5) PE geomembrane is $\sigma_a = 5.4\ N/mm^2$.

The strain at this stress level, from extrapolated 50-year isochronous line on Figure 6, is $\approx$ 4.8%. Check factor of safety against liner rupture and determine minimum requirements of geosynthetic reinforcement. Factor of safety against rupture of the geomembranes is applied to the rupture stress, σ_r. The factor of safety against rupture of the liner system may be computed as the ratio of tensile stress, or load, at rupture to the allowable stress, or load, in the geomembrane(s). The factor of safety is equal to

$$FS_{ls} = \frac{\sigma_f \ (t_m \ x \ N) \ + \ T_{reinf}}{\sigma_a \ (t_m \ x \ N)} \geq 3.0$$

where T_{reinf} is at ϵ_f of the geomembrane

$$\sigma_f = \sigma_r \ x \ FC \ x \ FW \ x \ FI$$

Example Calculation #3. (*continued*)

$$\sigma_f = 13.6\ N/mm^2 \times 1.0 \times 0.8 \times 1.0 = 10.9\ N/mm^2$$

From Figure 6, the geomembrane failure strain is 13.7%.

$$\frac{10.9\ N/mm^2 \times (\ 2.5\ mm \times 2\ ) + T_{reinf}}{5.4\ N/mm^2 \times (\ 2.5\ mm \times 2\ )} \geq 3.0$$

$$T_{reinf} = 26.5\ kN/m$$

where

T_{reinf} = minimum isotropic tensile strength of the reinforcement at the geomembrane failure strain (13.7% as determined from Figure 6) at the design temperature and life (kN/m).

Select the UX1500HT geogrid, Figure 7, with an isotropic tensile strength greater than 26.5 kN/m at a strain of 13.7%. Its isotropic tensile strength at a strain of 4.8% is equal to 16 kN/m. Therefore tensile strength, T_a, equals 16 kN/m.

The tensile load capacity of the liner system, at the allowable stress level of the geomembranes is

$$T_{system} = (\ \sigma_a \times t_m \times N\ ) + T_a$$

$$T_{system} = (\ 5.4\ N/mm^2 \times 2.5\ mm \times 2\ ) + 16\ kN/m$$

$$T_{system} = 27 + 16 = 43\ kN/m$$

Membrane tension, α, on the liner system (equations from Giroud et al., 1990) is

$$\alpha \approx p\ r\ \Omega$$

The design strain limit is ϵ_d = 4.8 %, therefore Ω = 0.98 (from Giroud et al., 1990)

$$\alpha = 43\ kN/m \approx 2\ \gamma\ r\ (\ 1 - e^{-0.5H/r}\ ) \times r \times 0.98$$

$$r \approx 1.5\ m$$

Therefore, this liner system is capable of carrying an allowable axisymmetric tensile load of 43 kN/m and can span a circular deflection or void of 3.0 m in diameter.

STEP 8: Check that both the geomembrane and reinforcement remain in their linear viscoelastic limits under initial and final strains.

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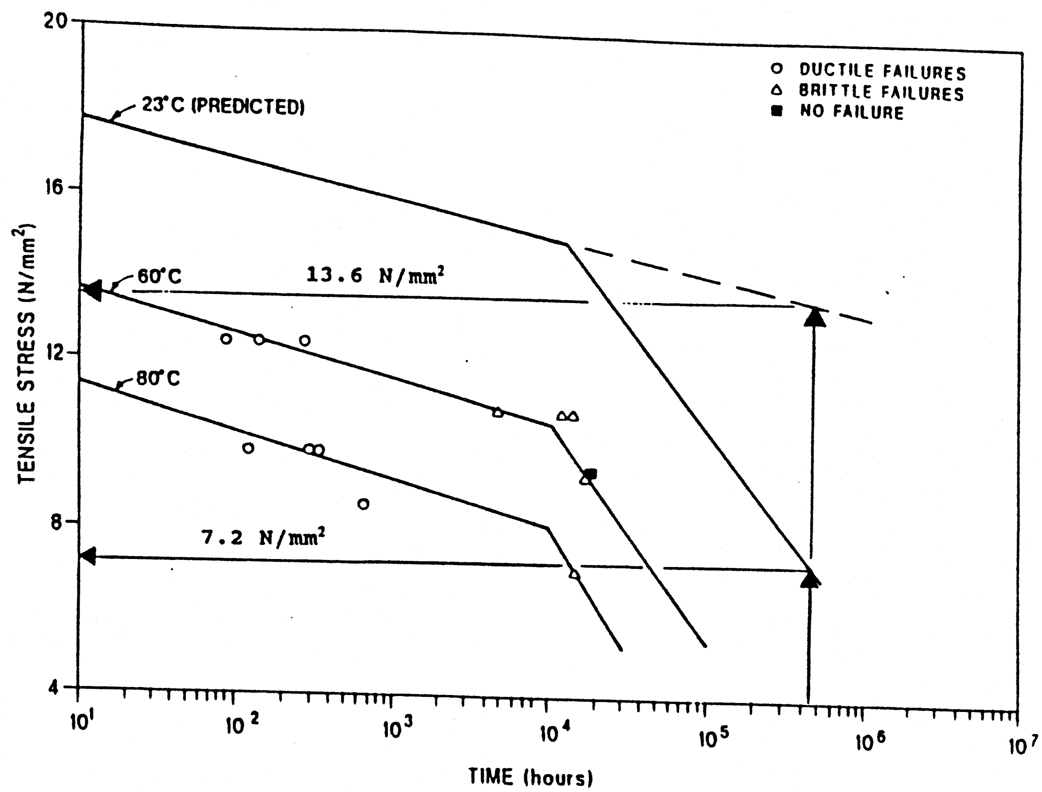

Figure 5. Stress rupture line for axi-symmetric loading of a PE geomembrane, at 23° C, derived with elevated temperature testing (after Berg and Bonaparte, 1993).

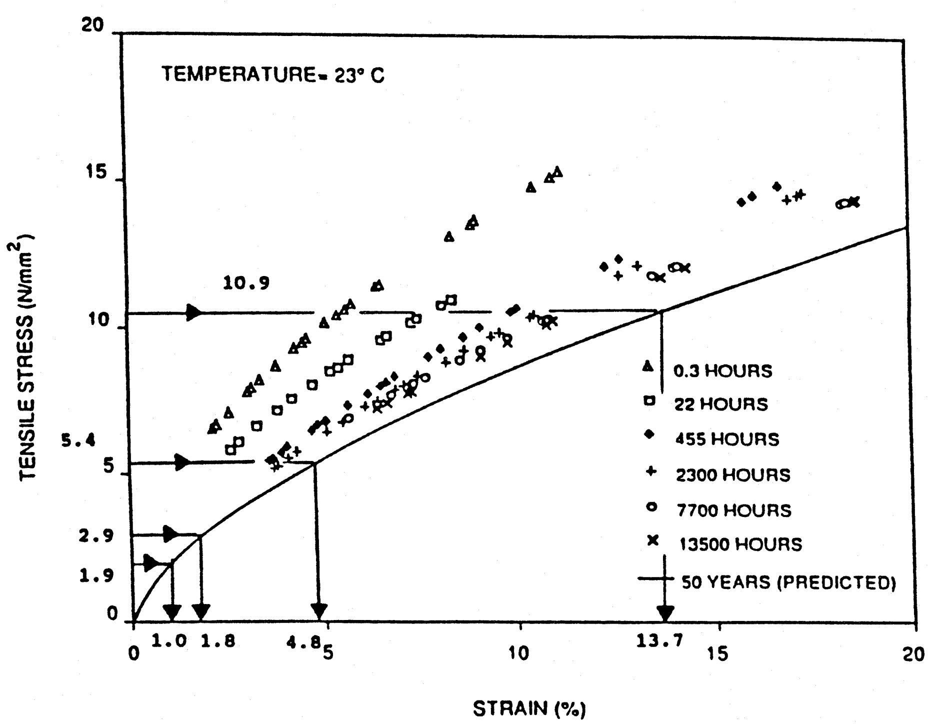

Figure 6. 50-year isochronous curve for axi-symmetric loading of a PE geomembrane, derived with elevated temperature testing (after Berg and Bonaparte, 1993).

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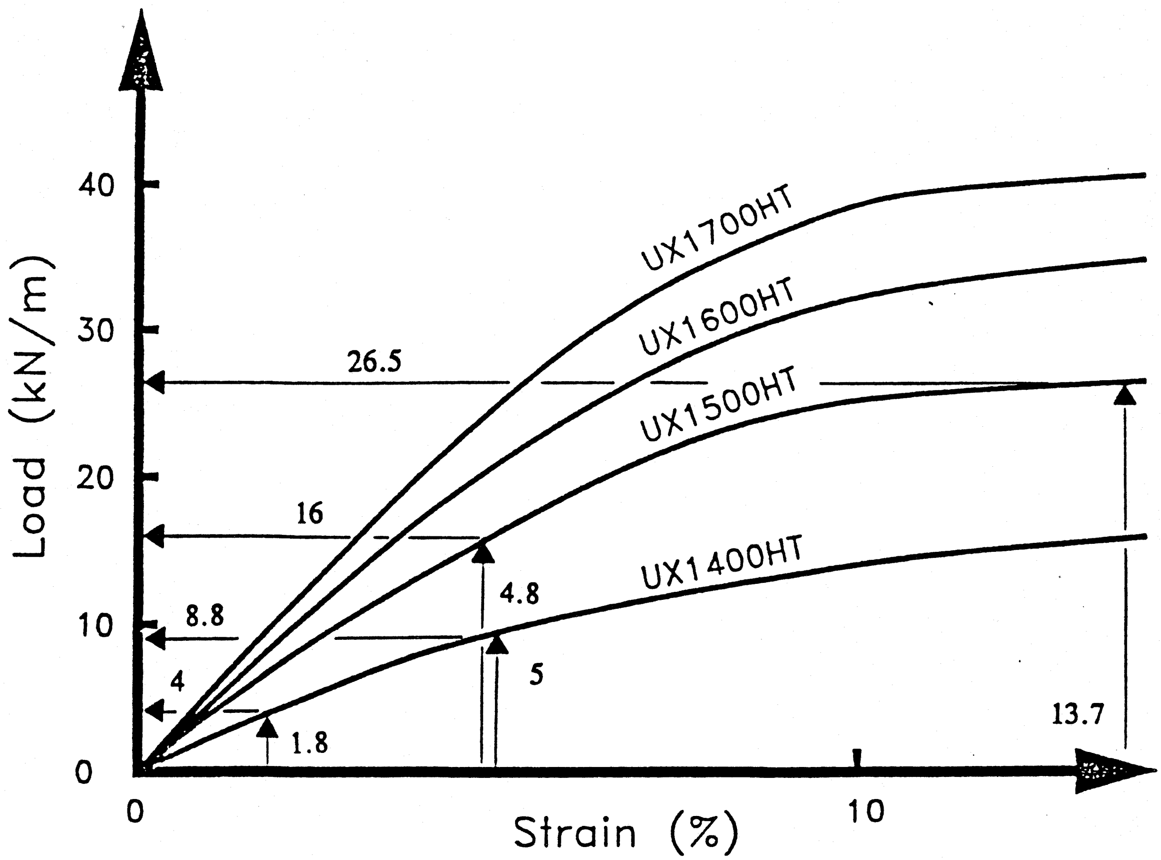

Figure 7. Isochronous curves of axi-symmetrically loaded structural geogrids.

6. CONCLUSIONS

The state-of-practice of landfill liner design for lateral and vertical expansions has advanced rapidly over the last several years. Procedures as demonstrated in this paper are now available to design these liner systems based upon long-term performance tests of both the geomembrane and geogrid reinforcement. Liner systems may be designed with geomembranes providing the entire tensile force, or with inclusion of geosynthetic reinforcing elements. A designer or regulatory agency may use a lower factor of safety against rupture of the geomembranes if a reinforcement geosynthetic is used, provided that the overall factor of safety against rupture of the liner system meets designer and regulatory agency requirements.

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