Proceedings 44th Canadian Geotechnical Conference
Calgary, Alberta September 29 to October 2, 1991

GEOSYNTHETICS - ENVIRONMENTAL APPLICATIONS IN WASTE CONTAINMENT

R.K. Rowe, J.D. Smith
University of Western Ontario, London, Ontario

ABSTRACT

This paper reviews the applications for geosynthetics in waste containment. Consideration is given to geotextiles as filters and separators in otherwise conventional landfill design, the use of drainage mats as a replacement for conventional granular drainage layers, the use of geomembrane liners as a supplement to natural or compacted clay barriers, and finally to a fully "geosynthetic design" which incorporates geotextiles, geosynthetic drainage mats, geomembranes and geogrids (for reinforcement).

INTRODUCTION

Geosynthetics have gained widespread acceptance for use in waste containment facilities in many regulatory jurisdictions and yet are being viewed with considerable suspicion in other jurisdictions. The object of this paper is to review applications for geosynthetics in waste containment and to comment on the regulatory and engineering implications of using geosynthetics.

GEOTEXTILES AS FILTERS AND SEPARATORS

The primary leachate collection system (installed below the waste) provides a very important part in the design of modern landfills. This layer serves to minimize the hydraulic head acting on the primary liner and hence minimizes potential contaminant migration. The potential clogging of this granular layer is well recognized and instances of granular layers above a liner which are not acting as a drainage layer can be found in the literature (eg. see Reades et al., 1990). The potential for clogging of the drain is related to the pore size, the surface area of granular particles and the residency time for leachate in the drainage layer. Generally, the larger the pore size of the drainage layer, the smaller the surface area on which biological growth can occur. The faster the leachate flows (i.e. the smaller the residency time) the smaller will be the potential for clogging. Based on these considerations, it is evident that sand is far more likely to clog than clear stone. However, a coarse granular filter is likely to be susceptible to blockage by downward movement of waste and intrusion of the underlying compacted clay (if present) unless protected. Geotextile may be used (as shown in Figure 1) to minimize contamination/clogging of these granular layers. The upper "filter geotextile" is intended to minimize the migration of solids from the waste (including a portion of suspended solids in the leachate) while permitting liquid to pass. The lower "separator geotextile" shown in Figure 1 is intended to minimize intermixing of the fine-grained liner material and the coarse-grained drainage stone.

Filter Design

In filter design, candidate geotextiles must satisfy three requirements: they must have adequate soil retention capability, be sufficiently permeable, and have sufficient resistance to clogging. With regard to retention capability, the objective of the geotextile is to filter out particle sizes which would settle out if permitted to migrate into the drain. Thus the design of the protection geotextile is related to the hydraulic design of the drainage layer - the slower the flow in the granular layer (i.e. the lower the hydraulic conductivity and/or slope of the drainage layer) the slower will be flow and hence the smaller the particle size which can be permitted to pass through the geotextile. The candidate geotextile must be sufficiently permeable to allow leachate to pass through the waste into the drainage layer; this criterion will be readily satisfied provided that the hydraulic conductivity of the geotextile exceeds that of the waste. The high potential for clogging of leachate collection systems is evident from observed clogging of sand layers above liners. An indication of the degree of clogging of geotextile filters that can occur due to

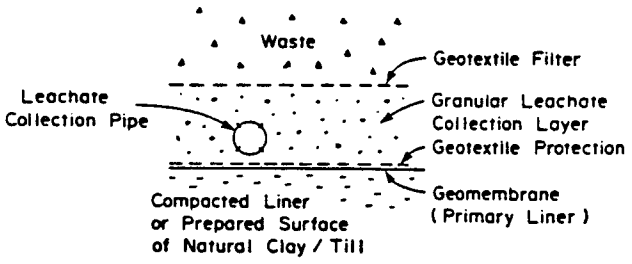

Figure 1 Schematic of a conventional leachate collection system incorporating geotextiles

accumulations of leachate fines and microbial growth may be obtained from recent studies (Cancelli & Cazzuffi, 1987; Koerner & Koerner, 1989, 1990). These studies suggest decreases in geotextile permittivity (cross-plane permeability) of several orders of magnitude can be expected after a relatively short period of exposure to leachate flow. One study (Koerner & Koerner, 1989) indicates a rough correlation between the TS/BOD levels of the leachate and the degree of geotextile clogging.

Clogging

While some filter clogging must be expected, there are several strategies which may be employed to decrease the degree of clogging and the rate of fines accumulation and bioslime growth. Two such strategies are suggested by recent test results (Koerner & Koerner, 1990). These tests indicate that inclusion of a granular layer over the geotextile has a "buffering" effect which acts to decrease the rate of permeability decrease, and also show that a large increase in system permeability occurs following backflushing with biocides. The use of a granular buffer layer will also protect the geotextile from damage during placement of the first few layers of waste. Further decreases in the degree and rate of filter clogging may occur by the addition of antimicrobial agents to the geotextile material (Hamilton & Dylingowski, 1989) and by selection of a high percent open area geotextile (Giroud, 1987; Koerner & Koerner, 1989), although this latter criterion must be balanced by the need to provide adequate retention (as discussed above).

The use of one or more of the above strategies may result in a decreased degree and rate of clogging and a more efficient collection of leachate, but in any case, clogging of a filter does not mean that the filter becomes impermeable - it simply means that its permeability has dropped. Typically the geotextile will have had an initial permeability (hydraulic conductivity) several orders of magnitude larger than typical values for compacted waste (viz. 10^{-3}-10^{-5} cm/s). The "clogging" of the geotextile would not be expected to have any significant effect so long as the permeability of the clogged geotextile is above that of the waste. Even if the clogging decreases the permeability below that of the waste, this may not be a major concern provided the filter is continuous across the site and is underlain by a continuous drainage blanket. A "clogged" filter will result in some perching of leachate above it. This is not problematic with respect to contaminant impact on underlying groundwater/aquifers since the leachate is separated from the liner by the drainage layer and hence the perched mounding does not represent mounding on the liner. Clearly, as the perched mounding increases so too does the gradient across the "clogged" geotextile until the gradient is sufficient to provide transmission of infiltration to the drainage layer. For example, if the clogging of a 3 mm thick geotextile causes a decrease in permeability from say $1x10^{-1}$ cm/s to $1x10^{-7}$ cm/s (i.e. by six orders of magnitude) the "perching" required to maintain continuity of flow for an infiltration rate of 0.15 m/a is less than 11 mm! Even assuming that the clogged (10^{-7} cm/s) zone extends 150 mm above the geotextile, the mounding required above the "clogged zone" to transmit an infiltration of 150 mm/a is only about 560 mm.

Construction Damage

Defects arising from construction damage, poor seaming technique, and rupture from excessive subgrade settlement may cause an intact geotextile to become discontinuous. The survivability of geotextiles during installation has been the subject of some study (eg. Koerner & Koerner, 1990; Bonaparte et al., 1988). Damage arising from construction is possible from the puncture of coarse granular materials above and below the geotextile and from tearing due to the action of heavy machinery. The geotextile should have sufficient strength and puncture resistance to survive normal construction. The construction specification should clearly emphasize the importance of maintaining the integrity of the geotextile. Rupture from subgrade settlements can be minimized by the use of low modulus geotextiles or by appropriate subgrade preparation.

Separator Design

The design of the separator layer between the drainage layer and the underlying fine-grained natural or compacted soil is more straight forward than the design of the filter layer discussed above, and follows conventional practice (eg. see Koerner, 1990b). Selection of the geotextile for this layer also requires consideration of ways of minimizing the potential defects as discussed above.

DRAINAGE MATS AS A REPLACEMENT FOR CONVENTIONAL GRANULAR DRAINAGE LAYERS

Synthetic drainage mats are waffled, net (geonets), or mesh materials which are structured to include open channels for the in-plane conveyance of relatively large quantities of fluids. The use of these mats for leachate collection and detection at waste disposal facilities is becoming increasingly common (Koerner & Hwu, 1989). For this application, the mats are often used in conjunction with an upstream geotextile filter and downstream geomembrane barrier, to form a composite system. The geotextile and the geomembrane restrict the movement of soil particles into the open channels. Figure 2 shows a typical leachate collection and leak detection system using drainage mats, with geotextiles to minimize soil intrusion into the drainage mats. In this situation, the primary design considerations of the mats are flow capacity and conductivity, for the leachate collection and leak detection layers, respectively.

Flow Capacity and Compressibility

The flow regime within the drainage mats is usually turbulent, so the flow capacity is dependent on the hydraulic gradient, and design must be based on comparisons of the required and actual material flow rates (i.e. flow calculations based on the assumption of an intrinsic

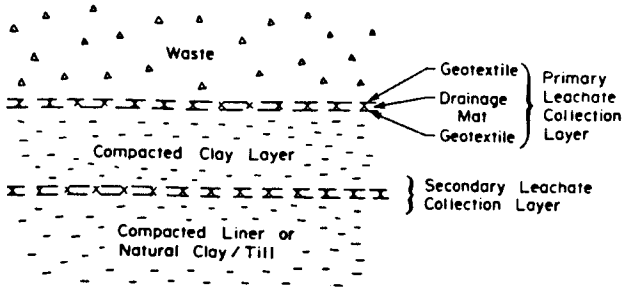

Figure 2 Schematic of geosynthetic primary and secondary leachate collection systems involving geotextiles and drainage mats

material permeability or transmissivity are not possible). In addition to the hydraulic gradient, several other factors have been identified which will influence the flow behaviour and capacity of the drainage mat (Williams et al., 1984; Koerner et al., 1986; Lundell & Menoff, 1989). These include mat compression due to overburden loads, compression-induced creep, mat material (affects compressive behaviour) and thickness (or number of layers), boundary conditions, the temperature and viscosity of the flowing fluids, and the directional drainage characteristics.

In the design for drainage, it is necessary to conduct laboratory simulation tests on candidate materials, using the actual loads and boundary conditions of the field situation. The ASTM D-4716 test protocol provides guidance for these simulation tests. The test program should be conducted to provide relations between the flow rate, hydraulic gradient, and the applied pressure. The compressive strength of the mat must be determined to be adequate under expected overburden loads. Consideration must also be given to compressive creep behaviour. Koerner et al. (1986) and Cancelli et al. (1987) have used a three element model to estimate creep behaviour. This approach shows promise however caution is required in extrapolating long term behaviour. Three time-dependent material behaviours are involved - the waste, the geosynthetic and the soil. It is difficult enough to predict the longer term deformation of any one of these components; it is even more difficult to predict the long term interaction of the three.

The level of confidence in the long term behaviour of these systems decreases with the length of time that the system is required to be operative. In this respect, careful consideration should be given to the contaminating lifespan of the landfill. Generally (eg. see Rowe, 1991a,b,c), the larger the landfill thickness and the lower the infiltration, the greater will be the concern regarding long term performance. The longer the contaminating lifespan, the greater is the need for backup systems in the event that the leachate collection system fails.

Leak Detection

For drainage mats used for leak detection, the leak detection rates are governed by the conductivity of the mat and dimensions of the flow path. Mat conductivity may be evaluated for a range of hydraulic gradients and compressive loads as detailed by Williams et al. (1984).

Reinforcement Function of Adjacent Geosynthetics

The use of drainage mats for leachate collection and detection imposes a reinforcement function on the adjacent materials (usually geotextiles or geomembranes), which must span openings on the surface of the mat. Recent tests (Hwu et al., 1990) indicate that a flow rate reduction of one order of magnitude is possible due to geotextile intrusion into the apertures of geonets. Modest decreases in intrusion (and increase in flow) were observed for geotextiles stiffened by resin treating, burnishing, and scrim reinforcing, and a large decrease in intrusion results with the use of a composite fabric (needle-punched nonwoven over woven slit-film). A further consideration in the design of geotextiles and geomembranes over mat openings is long-term tensile creep. Limited studies of this design aspect have been performed (Hwu et al., 1990). The earlier comments regarding long term behaviour also apply to this aspect of drain performance.

Selection and Acceptability

Published data (eg. Koerner et al., 1986) shows wide variations in flow rate of various geosynthetic drainage products; some have flow capacities of the same order as 0.3 m of clear stone while others are similar to (or exceed) the flow capacity of 0.3 m of sand. The wide variations in flow rate illustrate the importance of laboratory simulation of the actual field situation for selection purposes. It should be noted that some products may be placed in multiple layers to increase the flow capacity. Test results (Koerner & Hwu, 1989) show that the flow rate increases from the use of additional layers cannot be reliably estimated from tests with a single layer but must also be determined from simulation testing.

With respect to the seaming of synthetic drainage mats, only limited research (notably, Zagorski & Wayne, 1990) has been performed, and this research has concerned geonet seams only. Of particular interest is the considerable reduction in geonet transmissivity when overlapping is used, due to intrusion of one geonet into the other.

The acceptability of drainage mats for leachate collection will depend on the regulatory environment and the length of time that the drainage mat must operate to protect the environment (i.e. the contaminating lifespan). It is a relatively simple matter to design a mat that is only required to function for a 30 year post closure period. However, many modern landfills have contaminating lifespans of several hundred years. The long term performance of any leachate collection system is a major consideration in these cases, particularly when regulations require negligible impact on groundwater in perpetuity. One means of increasing the probability of the long term operation is to design a redundant system. This may, for example, include (from bottom up) a geomembrane, a drainage mat, a geotextile filter, a sand protective layer, a coarse stone drainage layer, a geotextile filter, a sand protective layer and waste.

GEOMEMBRANES AS A SUPPLEMENT TO NATURAL OR COMPACTED CLAY BARRIERS

Under certain hydrogeological and geotechnical conditions, natural or compacted clay barriers are unable to provide the required level of environmental protection from landfill contaminants. The use of geomembranes as a complementary barrier material may provide an economical means of obtaining the additional protection necessary to meet regulatory standards. This use of geomembranes requires an assessment of the environmental protection provided. This assessment should take the form of an evaluation of the leachate flow rates through geomembranes, and this will be discussed below with reference to the schematic shown in Figure 3.

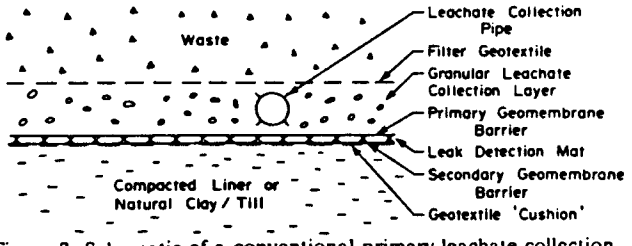

Figure 3 Schematic of a conventional primary leachate collection, primary (geomembrane) liner, geosynthetic leak detection system and secondary (clay) liner

Contaminant Transport Through Geomembranes

There are two mechanisms of contaminant transport through geomembranes; these are the processes of molecular diffusion under a chemical potential gradient (Park, 1986) and leakage through holes under a hydraulic gradient. The rate of molecular diffusion of contaminants is dependent upon the contaminant species, the magnitude of the chemical potential gradient, and the geomembrane material and thickness.

An assessment of leakage through holes in the geomembrane requires an estimate of the size and frequency of such holes. Such an assessment based on a combination of theory and an analysis of geomembrane case histories has been provided by Giroud and Bonaparte (1989a,b). Equations relating the leakage rate through these holes to the hydraulic head acting for the case where the geomembrane is underlain by a pervious material (eg. sand, gravel or drainage mat as shown in Figure 3) and for the case where the geomembrane is underlain by a clay layer (Figure 4) have been presented by Giroud and Bonaparte (1989a,b).

The occurrence of defects in the geomembrane liner can be reduced by the use of a geotextile "cushion" between the geomembrane and adjacent soil layers. When the geotextile is used between the geomembrane and a clay barrier, the geotextile may increase leakage rates by providing a lateral flow plane, increasing the area over which the hydraulic head acts, as discussed in the reference cited above.

When a composite lining system is used (Figure 4), practical difficulties may be encountered in construction since compaction of the clay layer of the primary composite liner may be restricted by concerns over damage to the underlying geosynthetic components of the leak detection system.

Migration of contaminant through liner systems has been discussed by Rowe (1991d).

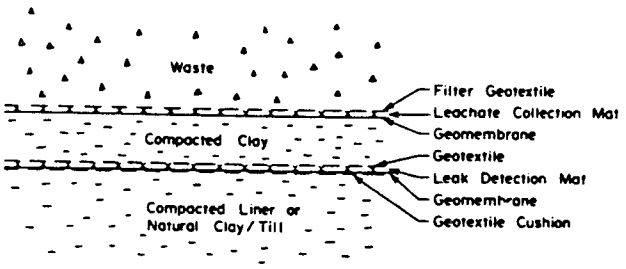

Figure 4 Schematic of a geosynthetic primary leachate collection system, composite (geomembrane and clay) primary liner, geosynthetic leak detection and secondary (clay) liner

FULLY GEOSYNTHETIC DESIGN

In the previous sections, the functions and some design considerations for the individual geosynthetic components of a landfill lining system have been discussed. This section will discuss design considerations applicable to other geosynthetic components of a waste containment facility and other factors including stress and durability aspects.

Landfill Capping

A schematic of a design which uses geosynthetics as part of the leachate collection, leak detection and leachate containment systems as shown in Figure 5. This schematic also shows the geosynthetic components of the landfill capping system used to control the amounts of leachate generation by rainfall infiltration. The geosynthetic capping system will typically comprise a geomembrane barrier, a synthetic drainage mat for rainfall collection, a geotextile filter between the drainage mat and the final soil cover, and a geotextile drainage layer below the geomembrane for the transmission of landfill gases to a higher vent or collection location. The use of geotextiles for gas transmission has been discussed elsewhere (Koerner et al., 1984). A tight capping system should not necessarily be placed immediately following attainment of landfill capacity. Some infiltration of rainfall will occur through the geomembrane (due to holes, permeation, and eventual degradation) and, if the capping system is placed immediately, the field capacity of the landfill may not be reached for decades, at which time maximum leachate generation will occur. At this time, the efficiency of the leachate collection and containment system may be compromised due to degradation, creep, etc. and environmental damage may ensue. In some instances, it may be preferable to allow infiltration to occur under controlled conditions until degradation of the collection system is detected and then construct the tight capping system. This strategy will remove a substantial portion of landfill contaminants early while the leachate collection system is most efficient. For further details on this aspect of landfill design see Rowe (1991a,b,c).

Reinforcement

Tensile forces will be mobilized in the geosynthetic components lining the side slopes of the waste containment facility due to the waste overburden loads, waste settlement and consolidation (downdrag forces), and from the self weight of the geosynthetic components themselves. The geosynthetics in the landfill capping system will also develop tensile forces due to the sliding potential of the final soil cover. The current method for the evaluation of these tensile forces is by static equilibrium methods (Richardson & Koerner, 1988). This evaluation requires knowledge of the friction characteristics between the various components of the lining system. These characteristics may be determined by direct shear friction testing (Bove, 1990). The geosynthetics in tension must be anchored at the top of the slope and descriptions of anchoring methods and determination of the anchorage capacity are available (Richardson & Koerner, 1988).

Figure 5 shows the inclusion of geogrids to steepen the side slopes, which will increase the available landfill airspace. Jewell (1991) has published design charts for geogrid reinforced slopes. Note that an increase in slope angle will be accompanied by an increase in the tensile forces mobilized in the geosynthetics lining the slope.

Differential settlements must be expected to occur at various locations under the landfill capping system owing to non-uniform waste movements. Localized settlements may also occur at other locations where soft zones exist, such as backfilled trenches and improperly compacted areas. Open voids may develop due to tension cracking, karstic collapse, or soil dissolution. Geosynthetics which overlie these settlements and/or voids must have sufficient strength to conform to the settlements or bridge the void. Giroud et al. (1990) have developed design charts for the case of geosynthetic systems overlying settlements or voids.

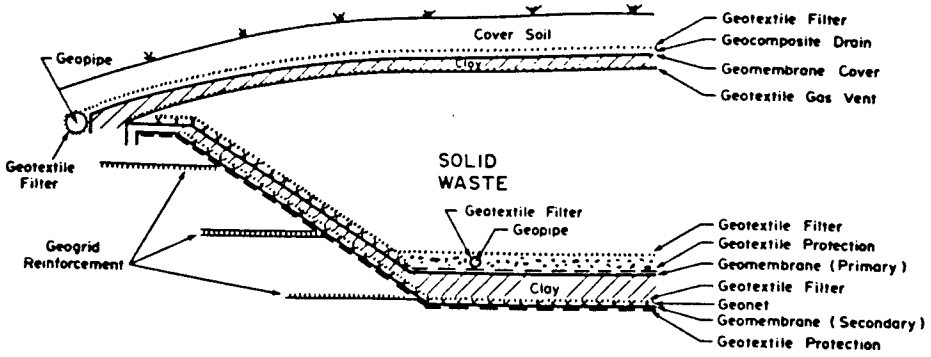

Figure 5 Schematic of a complete landfill system showing geosynthetic components (After Koerner, 1990a)

The geosynthetics in tension must have sufficient strength to withstand the tensile forces they are subjected to, and high safety factors should be used since strength losses due to installation damage, long term creep, and degradation mechanisms must be expected. Possible degradation mechanisms include UV exposure (during construction and on unprotected slopes), chemical reactions with leachate, swelling due to chemical adsorption, extraction, oxidation, and biological attack (Koerner et al., 1990). The possibility of chemical and swelling degradation can be minimized by the selection of geosynthetics chemically resistant to the leachate. The U.S. EPA has developed Method 9090 (EPA, 1985) in which geomembrane specimens are exposed to leachate in a controlled environment followed by physical and mechanical testing. Changes in mechanical behaviour after exposure are evaluated and the compatibility of the geomembrane with the leachate is assessed. This method may be readily extended to include all geosynthetic components which may be exposed to the landfill leachate (Koerner, 1990a). Similarly, compatibility of the geosynthetics above the waste with landfill gases (primarily methane) should be assured.

Service Life

The severity of the degradation mechanisms listed above will govern the service life of the various geosynthetic components of the facility. Installation damage, the magnitude of the imposed mechanical stresses, and synergism between the various mechanisms may increase the rate of degradation (Koerner et al., 1990). Accelerated tests have been developed which may be used to predict service lifetimes, however, these tests are not particularly realistic. With respect to geomembranes, Koerner (1990) has noted that "the service lifetimes of the various geomembranes are rarely in excess of 30 years". It would seem prudent to consider the limited experience and design waste containment systems such that in the event of a worst case failure after 30-40 years, the environment will not be compromised.

SOME OTHER DESIGN CONSIDERATIONS

The potential impact of landfill leachates on underlying groundwater resources is minimized by the use of a well designed and constructed leachate collection system. An effective collection system will remove a large portion of contaminants from the landfill (minimizing the contaminant available to migrate into the hydrogeological system) and will reduce the head acting on barrier materials, thereby decreasing the volume and rate of contaminant escape through the barrier. The assessment of the impact on underlying groundwater resources requires an estimate of leachate head (i.e. the leachate mound) acting over the base of the landfill. Various methods of estimating the leachate mound have been proposed, and a summary of these methods has been published by Rowe (1988). Consideration of the inherent assumptions of each method must be made for each case. The various methods typically assume that the leachate collection system is functioning (i.e. is not clogged). However, as discussed previously, the potential for clogging is high. While design may still proceed assuming no clogging will occur, the potential for clogging must be acknowledged and designs should be such that, in the event that the primary collection system does clog, environmental impacts will be minimal.

The assessment of potential environmental impact of any proposed landfill facility is a difficult task and the magnitude of the impact is sensitive to many parameters. In many cases, an assessment will only be possible using analysis techniques such as the finite layer and finite element methods. For example, Rowe (1991d) has analyzed typical lining systems consisting of a composite primary liner system and a secondary leak detection layer and has included consideration of factors such as diffusion through the geomembrane/clay composite system. It was shown that for the parameters examined, the impact on an underlying aquifer would be unacceptable based on Ontario's Reasonable Use Policy (MoE, 1986). Clearly, environmental impact assessments must be performed for each proposed design on a site specific basis, and it should be recognized that there is always the potential for unacceptable contamination, even with the use of low permeability geomembrane and clay barriers. The recognition of this potential also underscores the need for the monitoring of flows from leachate collection and detection layers, and the preparation of contingency plans in case of failure.

The implementation of contingency plans in case of failure of all or part of the waste containment system will occur when unacceptable levels of leachate are collected from the leak detection layer. There are other sources of flow from leak detection layers, however, and these potential sources have been identified by Gross et al. (1990). If leakage through the primary liner into the leak detection layer occurs simultaneously with flow from these other sources, the presence of the leachate may be masked. Chemical analysis of the flows may identify the presence of leachate, but there may be considerable dilution. The leak detection system should be designed

such that in case of a failure (i.e. a large rate of leakage), the time between detection and implementation of contingency measures will not be so long that environmental damage will occur.

Differential settlements of materials underlying geomembrane liners may increase the impact of contaminants on the hydrogeological system. Leachate will pond over the area where settlement occurs, and the straining of the geomembrane over the settlement may initiate holes or ruptures. The formation of tension cracks in the underlying compacted or natural clay barrier is also a possibility. An expected increase in the use of vertical landfill expansions to satisfy demand for landfill space may be expected to increase the occurrence of problems related to differential settlements. The use of geogrids over areas of potential differential settlements may reduce such impacts.

CONCLUDING COMMENTS

This paper has highlighted applications of a geosynthetic in the design of waste containment facilities. If designed appropriately, giving due consideration to the function and service life of the various components in the context of the contaminating lifespan of the landfill, geosynthetics can provide a means of considerably enhancing the performance of these facilities. However, appropriate design is only the first step. It remains to construct the facility. Although it is beyond the scope of this paper, it should be emphasized that construction quality control and assurance (CQC/CQA) are critical. If the geosynthetic is a serious component of a system then it must be designed seriously and the CQC/CQA procedure should be such as to ensure that the designer's intentions are met.

ACKNOWLEDGEMENT

The preparation of this paper was funded by the award of a Steacie Fellowship and Grant A1007 of the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

BONAPARTE, R., AH-LINE, A.M., CHARRON, R., and TISINGER, L., 1988.
Survivability and durability of a nonwoven geotextile. Proc. Geosynthetics for Soil Improvement, Nashville, pp. 68-91.

BOVE, J.A., 1990.
Direct shear friction testing for geosynthetics in waste containment. In Geosynthetic testing for waste containment applications. ASTM 1081, R.M. Koerner, Ed., Philadelphia, PA.

CANCELLI, A. and CAZZUFFI, D., 1987.
Permittivity of geotextiles in presence of water and pollutant fluids. Proceedings Geosynthetics '87, pp. 471-481.

CANCELLI, A., CAZZUFFI, D. and RIMOLDI, P., 1987.
Geocomposite drainage systems: mechanical properties and discharge capacity evaluation. Proceedings Geosynthetics '87, New Orleans, pp. 393-404.

GIROUD, J.P., 1987.
Tomorrow's designs for geotextile applications. Geotextile Testing and the Design Engineer, J.E. Fluet, Jr., Ed., ASTM STP 952, pp. 145-158.

GIROUD, J.P. and BONAPARTE, R., 1989.
Leakage through liners constructed with geomembranes - Part I. Geomembrane liners. Geotextiles and Geomembranes, Vol. 8, pp. 27-67.

GIROUD, J.P. and BONAPARTE, R., 1989.
Leakage through liners constructed with geomembranes - Part II. Composite liners. Geotextiles and Geomembranes, Vol. 8, pp. 71-111.

GIROUD, J.P., BONAPARTE, R., BEECH, J.F. and GROSS, B.A., 1990.
Design of soil layer - geosynthetic systems overlying voids. Geotextiles and Geomembranes, Vol. 9, pp. 11-50.

GROSS, B.A., BONAPARTE, R., and GIROUD, J.P., 1990.
Evaluation of flow from landfill leachate detection layers. Fourth Intl. Conf. on Geotextiles and Geomembranes, The Hague, pp. 481-486.

HAMILTON, N.F. and DYLINGOWSKI, P.J., 1989.
Bioslime control on geosynthetics. Proc. Durability and Aging of Geosynthetics, R.M. Koerner, Ed., Elsevier Appl. Sci. Publ. Ltd., London, pp. 278-292.

HWU, B., KOERNER, R.M. and SPRAGUE, C.J., 1990.
Geotextile intrusion into geonets. Fourth Intl. Conf. on Geotextiles, The Hague, pp. 351-356.

JEWELL, R.A., 1991.
Application of revised design charts for steep reinforced slopes. Geotextiles and Geomembranes, Vol. 10, pp. 203-233.

KOERNER, R.M., 1990a.
Preservation of the environment via geosynthetic containment systems. Fourth Intl. Conf. on Geotextiles and Geomembranes, The Hague, pp.

KOERNER, R.M., 1990b.
Designing with geosynthetics. Englewood Cliffs, NJ, Prentice-Hall Inc.

KOERNER, R.M. and HWU, B., 1989.
Behaviour of double geonet drainage systems. Geotechnical Fabrics Report, IFAI Publ., pp. 39-44.

KOERNER, G.R. and KOERNER, R.M., 1989.
Biological clogging in leachate collection systems. Proc. Durability and Aging of Geosynthetics, R.M. Koerner, Ed., Elsevier Appl. Sci. Publ. Ltd., London, pp. 260-277.

KOERNER, G.R. and KOERNER, R.M., 1990.
Biological activity and remediation involving geotextile landfill leachate filters. Symp. on Geosynthetic Testing for Waste Containment Applications, ASTM STP 1081.

KOERNER, G.R. and KOERNER, R.M., 1990.
The installation survivability of geotextiles and geogrids. Fourth Intl. Conf. on Geotextiles, The Hague, pp. 597-602.

KOERNER, R.M., BOVE, J.A. and MARTIN, J.P., 1984.
Water and air transmissivity of geotextiles. Geotextiles and Geomembranes, Vol. 1, pp. 57-73.

KOERNER, R.M., HALSE, Y.H. and LORD JR., A.E. 1990.
Long-term durability and aging of geomembranes. In Waste containment systems: Construction, regulation, and performance. ASCE Spec. Tech. Publ. No. 26, Bonaparte, R., Ed., New York, NY, pp. 106-134.

KOERNER, R.M., LUCIANI, V.A., FREESE, J.S. and CARROLL, R.G., JR., 1986.
Prefabricated drainage composites: evaluation and design guidelines. Third Intl. Conf. on Geotextiles, Vienna, pp. 551-556.

LUNDELL, C.M. and MENOFF, S.D., 1989.
The use of geosynthetics as drainage media at solid waste landfills. Proceedings Geosynthetics '89, San Diego, pp. 10-17.

ONTARIO MINISTRY OF THE ENVIRONMENT, 1986.
Ontario policy - Incorporation of the reasonable use concept in MoE groundwater management facilities. Policy 15-08-01.

PARK, G.S., 1986.
Transport principles - solution. Diffusion and permeation in polymer membranes. In Synthetic membranes: science, engineering, and applications. Bangay, P.M. and Al. Ed. Reidel Publ. Co.

READES, D.W., LAHTI, L.R., QUIGLEY, R.M. and BACOPOULOS, A., 1990.
Detailed case history of clay liner performance. In Waste Containment systems: Construction, regulation, and performance. ASCE Spec. Tech. Publ. No. 26, Bonaparte, R., Ed., New York, NY, pp. 156-174.

RICHARDSON, G.N. and KOERNER, R.M., 1988.
Geosynthetic design guidance for hazardous waste landfill cells and surface impoundments. EPA/600/52-87/097, Cincinnati, OH.

ROLLIN, A.L. and DENIS, R., 1987.
Geosynthetic filtration in landfill design. Proceedings Geosynthetics '87, pp. 456-470.

ROLLIN, A.L. and LOMBARD, G., 1988.
Mechanisms affecting long-term filtration behaviour of geotextiles. Geotextiles and Geomembranes, Vol. 7, pp. 119-145.

ROWE, R.K., 1988.
Eleventh Canadian Geotechnical Colloquium: Contaminant migration through groundwater - the role of modelling in the design of barriers. Canadian Geotechnical Journal, Vol. 25, pp. 778-798.

ROWE, R.K., 1991a.
Contaminant impact assessment and the contaminant lifespan of landfills. Canadian Journal of Civil Engineering, Vol. 18, No. 2, pp. 244-253.

ROWE, R.K., 1991b.
Environmental geotechnology: Some pertinent considerations, Keynote paper - 7th International Conference of the International Association for Computer Methods and Advances in Geomechanics, Cairns, Vol. 1, pp. 35-48.

ROWE, R.K., 1991c.
Some considerations in the design of barrier systems Keynote paper - Proceedings 1st Canadian Conference on Environmental Geotechniques, Montreal, pp. 157-164.

ROWE, R.K., 1991d.
Leachate detection or hydraulic control: Two design options. Proceedings of 3rd International Landfill Symposium, Sardinia, Italy.

U.S. ENVIRONMENTAL PROTECTION AGENCY, 1985.
Compatibility test for wastes and geomembrane liners, Method 9090.

WILLIAMS, N., GIROUD, J.P., and BONAPARTE, R., 1984.
Properties of plastic nets for liquid and gas drainage associated with geomembranes. Intl. Conf. on Geomembranes, Denver, pp. 399-404.

ZAGORSKI, G.A., and WAYNE, M.H., 1990.
Geonet seams. Geotextiles and Geomembranes, Vol. 9, pp. 487-499.