The Mercer Lecture

2005-2006

Sponsored by Tensar International
with the endorsement of
the International Society for Soil Mechanics and Geotechnical Engineering
and the International Geosynthetics Society
(ISSMGE & IGS)

Contribution of Geosynthetics to the Geotechnical Aspects of Waste Containment

by

J.P. Giroud

Consulting Engineer

JP GIROUD, INC.

Chairman Emeritus of GeoSyntec Consultants

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Introduction to the Mercer Lecture Series on the next page,
followed by biographical note, abstract of the lecture,
lecture notes, and copies of all slides

Introduction to the Mercer Lecture Series

The Mercer Lecture is a biennial lecture which is sponsored by Tensar International with the endorsement of the International Society for Soil Mechanics and Geotechnical Engineering and the International Geosynthetics Society.

The aim of the lecture is to help promote co-operation of information exchange between the geotechnical engineering profession and the geosynthetics industry.

Tensar International believe that this is achieved by sponsoring an eminent practitioner to undertake a lecture tour on the subject of Geosynthetics in Geotechnical Engineering.

The lecture is given in three continents, typically Europe, North America and the Far East, with, in each case, the venue and date being agreed by the selection committee comprising representatives of Tensar International, ISSMGE and IGS.

The lectures were presented in 1992 by Professor Bob Koerner, in 1994 by Professor Jean-Pierre Gourc, in 1996 by Professor Fumio Tatsuoka, by Professor Alan McGown in 1999/2000 and Professor Richard Bathurst in 2003/2004. The current lecture series is delivered by Dr Jean-Pierre Giroud during 2005/2006, in Sardinia (Italy) and South Africa (Durban), in 2005, and Kyoto (Japan), in 2006. It is the first time the Mercer Lecture is presented in Africa.

James Paul
Tensar International

Articles on the Mercer Lecture can be found in IGS News:
Vol. 21, No. 2, July 2005, p. 7, and Vol. 21, No. 3, November 2005, pp. 6-8.

IGS News can be obtained on www.geosyntheticssociety.org

The 2005-2006 Mercer Lecturer

Dr. Giroud, a pioneer in the field of geosynthetics since 1970, is recognized throughout the world as a geosynthetics leading expert. A former professor of geotechnical engineering, he is a consulting engineer under JP GIROUD, INC., and chairman emeritus and founder of GeoSyntec Consultants. Dr. Giroud is past president of the International Geosynthetics Society (the IGS), chairman of the editorial board of *Geosynthetics International*, and was Chairman of the Editorial Board of *Geotextiles and Geomembranes* (1984-1994). Dr. Giroud was chairman of the 2nd International Conference on Geotextiles (1982) and the International Conference on Geomembranes (1984). He served two terms as chairman of the Technical Committee on Geosynthetics of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE).

Dr. Giroud coined the terms "geotextile" and "geomembrane" in 1977, thus starting the geo-terminology used in geosynthetics engineering. He has authored over 350 publications, including a monumental Geosynthetics Bibliography (1721 pages, more than 10,000 references). He recently wrote the chapter on filter criteria in the prestigious book commemorating the 75th anniversary of Karl Terzaghi's book "*Erdbaumechanik*".

Dr. Giroud has developed many of the design methods used in geosynthetics engineering, in particular for landfills. For example, he developed methods for the evaluation of leakage through liners, for the design of leachate collection layers and leakage detection layers, for soil cover stability, for the reinforcement of liners and soil layers overlying voids, and for the resistance of geomembranes exposed to wind uplift. Also, he played a key role in the development of construction quality assurance (1983-1984). Dr. Giroud has taught numerous training courses on geosynthetics in landfills for the U.S. Environmental Protection Agency (which he advised for the development of landfill regulations). As a result, he is often referred to as "the father of geosynthetic liner systems". Dr. Giroud has also developed design methods used in other branches of geosynthetics engineering, most notably for filters and unpaved roads.

Dr. Giroud has extensive field experience and has originated a number of geosynthetics applications such as: first nonwoven geotextile filter (1970), first geotextile filter in a dam (1970), first geotextile cushion for geomembrane (1971), first double liner with two geomembranes (1974), first entirely geosynthetic double liner system with two geomembranes and a geonet leakage detection system (1981). He has been instrumental in the development of the technique of exposed geomembrane landfill covers (1995-1998).

Dr. Giroud has received awards from the French Society of Engineers and Scientists, the Industrial Fabrics Association International, and the IGS (in 1994 for liner leakage prediction and in 2004 for filter design). In 1994, the IGS named its highest award "The Giroud Lecture", "in recognition of the invaluable contributions of Dr. J.P. Giroud to the technical advancement of the geosynthetics discipline". In 2002, Dr. Giroud became Honorary Member of the IGS with the citation "Dr. Giroud is truly the father of the International Geosynthetics Society and the geosynthetics industry". In 2005, Dr. Giroud has been awarded the status of "hero" of the Geo-Institute of the American Society of Civil Engineers (ASCE).

Dr. Giroud has delivered keynote lectures at numerous international conferences. In 2005, he presented the prestigious Vienna Terzaghi Lecture, and, in 2005-2006, the prestigious Mercer Lecture series.

Dr. Giroud can be contacted at jpg@jpgiroud.com

The Mercer Lecture

Contribution of geosynthetics
to the geotechnical aspects of waste containment

by J.P. Giroud

ABSTRACT

Geosynthetics are indispensable in modern waste containment and, more generally, in geotechnical and geoenvironmental engineering. They provide new solutions and, at the same time, pose new challenges to geotechnical engineers. The two main geotechnical goals in waste containment design are the control of liquids that transport contaminants and the short- and long-term integrity of landfills. The lecture shows how geosynthetics are used to achieve these geotechnical goals and identifies areas where research and development are needed.

The first part of the lecture addresses the contribution of geosynthetics to liquid control. Composite liners, which associate clay (and/or bentonite geocomposites) with geomembranes, are orders of magnitude more effective than clay alone. However, it is shown that geotechnical engineers are challenged by aspects of material behavior that are unusual in traditional geotechnical engineering, such as: desiccation of clay or bentonite even when these materials are covered with a geomembrane, and geomembrane wrinkling due to thermal expansion, two mechanisms that may impair the effectiveness of composite liners. Another aspect of liquid control is the use of drainage layers to collect and remove leachate. The benefits that result from the use of geosynthetic drainage materials are mentioned. At the same time, the challenges associated with these materials are discussed, such as: the equivalency between geosynthetic and granular leachate collection layers, and the design of geosynthetic leakage collection layers to accommodate the flow generated by concentrated leaks. The first part of the lecture ends with a comparison between single and double liners, in particular in the case of landfills in developing countries.

The second part of the lecture addresses the contribution of geosynthetics to short- and long-term integrity of landfills. The steep slopes needed to increase waste storage capacity lead to stability problems. Geosynthetics are extensively used in landfill slopes, but their use is associated with numerous challenges. On one hand, geotechnical engineers are well prepared to deal with stability problems. On the other hand, they have to face new challenges such as: the development of slip planes in slopes with multiple interfaces, the influence of pore pressure on the behavior of waste, and the influence of gas pressure on the stability of landfill covers. Also, it is shown that geosynthetic drainage materials, which appear to be equivalent to granular drainage materials from the viewpoint of the impact of drainage on slope stability based on traditional steady-state flow calculations, are in fact not equivalent as shown by transient flow calculations. Thus, a greater factor of safety regarding flow capacity is required from geosynthetic drainage materials to achieve the same safety regarding stability as granular drainage materials.

The examples mentioned above are only a few of the geosynthetics benefits and associated challenges that are presented in the lecture. Field situations, including failures, are shown using numerous photographs. The lecture provides useful information to practicing engineers and the challenges presented should inspire researchers.

* * * * *

The Mercer Lecture

Contribution of geosynthetics
to the geotechnical aspects of waste containment

by J.P. Giroud

NOTES

Most slides are self explanatory. A few notes follow.

SLIDE 50 (2nd slide of page 9)
This leads to the concept of equivalency factor between a geosynthetic drain and a granular drain.
This equation shows that the hydraulic transmissivity of a geosynthetic drain should be E, the equivalency factor, multiplied by the hydraulic transmissivity of the prescribed granular drainage layer.
The equivalency factor is expressed by this equation. We will not discuss this equation, but we will use it for a typical leachate collection layer described here.
In this typical case, the equivalency factor is 1.8, which is approximately 2. In other words, in this particular case, the hydraulic transmissivity of the geosynthetic drain should be approximately twice the hydraulic transmissivity of the prescribed granular drainage layer.

SLIDE 57 (3rd slide of page 10)
To monitor what is happening in a landfill, we need one-dimensional lines of communication through the two-dimensional envelope that separates the landfill from the rest of the world.
We already have one-dimensional lines of communication with the leachate removal pipes and the gas extraction pipes. These pipes make it possible to monitor some limited aspects of the behavior of a landfill.
Now, to monitor other aspects of the behavior of a landfill, we need many other one-dimensional lines of communication, such as monitoring wires, or even zero-dimensional lines of communication, such as wireless monitoring.

SLIDE 60 (6th slide of page 10)
Speaking of temperature, I would like to point out that we ignore the importance of temperature when we design landfills with the properties of geosynthetics measured at 20°C whereas the temperature of a landfill may be 40°C. For example, . . .
. . . and what about the influence of temperature on interface friction? I do not know anybody who knows anything on this subject. However, the influence of temperature on interface friction may well explain some of the unexplained slope failures.

SLIDE 69 (3rd slide of page 12)
We do not have intimate contact at locations where the geomembrane exhibits wrinkles.
This happens, in particular, with HDPE geomembranes.

SLIDE 70 (4th slide of page 12)
If there is intimate contact between the geomembrane and the underlying clay, the rate of leakage through a geomembrane defect is limited because the area available for leakage is small. In contrast, if there is a wrinkle, the area available for leakage is larger and the rate of leakage is larger.

SLIDE 73 (1st slide of page 13)
If the temperature increases, the geomembrane expands, which generates the wrinkles. The bending of the geomembrane in the wrinkles generates the bending forces shown in green. The bending forces are balanced by the friction forces between the soil and the portion of geomembrane located between two adjacent wrinkles.

SLIDE 74 (2nd slide of page 13)
This model demonstrates what happens in the case of stiff geomembranes such as HDPE geomembranes.
. . . Ironically, this is consistent with observations, but opposite to what is reported by observers. Indeed, people who have seen HDPE geomembranes in the field typically report that they have seen many wrinkles. The reality is that they have seen high wrinkles. And these wrinkles are high because there are not many. This is a good lesson on the validity of some observations.

SLIDE 77 (5th slide of page 13)
In conclusion, the lesson learned from the rational analysis I have presented is that the wrinkle problem can be minimized by using flexible geomembranes with a high interface friction angle. Unfortunately, the geomembranes currently available with a high interface friction angle are stiff. Here, we have a challenge for manufacturers.

SLIDE 80 (2nd slide of page 14)
We all know that clay can be cracked prior to being covered by a geomembrane.

SLIDE 87 (3rd slide of page 15)
Here we see a geomembrane that has been cut open for a reason that has nothing to do with the underlying GCL. The people present at the site when the geomembrane was cut open were surprised to see that there was a gap between adjacent panels of GCL, whereas the panels had been installed with an overlap.

SLIDE 88 (4th slide of page 15)
On this photo, taken after the geomembrane had been entirely removed, we see the gap between GCL panels at the location where there was an overlap.
It was suspected that the lateral shrinkage of the GCL was caused by temperature-humidity cycles, a mechanism similar to the mechanism that caused the desiccation of compacted clay discussed earlier.

SLIDE 89 (5th slide of page 15)
Therefore, specimens of GCL were subjected to temperature-humidity cycles.
We see here a rectangular specimen of GCL before the cycles. The rectangular specimen of GCL was clamped at both ends to simulate anchorage at crest and toe of slope in the field.
On the right, we see the specimen of GCL after 20 cycles. The lateral shrinkage is shown by the yellow arrows.

SLIDE 90 (6th slide of page 15)
Here we see the result of 40 cycles for a particular type of GCL.
The zigzag curve represents the successive hydration and drying of the GCL specimen.
The red curve represents shrinkage after drying. Part of this shrinkage is reversible as a result of hydration. However, there is residual shrinkage after hydration as shown by the blue curve.
After 40 cycles, the residual shrinkage is 12%.
And 12% of a 5 m wide panel is a shrinkage of 0.6 m, which explains the separation of overlaps.

SLIDE 95 (5th slide of page 16)
I did simple calculations of advective flow and diffusion through liners. I considered two types of composite liners: geomembrane on compacted clay and geomembrane on GCL. In both cases, I considered a typical number of defects in the geomembrane. I also considered compacted clay alone.

SLIDE 96 (6th slide of page 16)
Only orders of magnitude of contaminant transport are shown in the table.
The reference value, shown as 1 in the table, is the amount of inorganic contaminant transport through a composite liner. In fact, approximately the same amount of inorganic contaminant is transported with a geomembrane-on-clay composite liner and a geomembrane-on-GCL composite liner. However, the mechanism is different. In the case of a composite liner that consists of a geomembrane on GCL, inorganic contaminant transport is essentially by diffusion; whereas, in the case of a composite liner that consists of a geomembrane on compacted clay, both advective flow and diffusion contribute to inorganic contaminant transport.
Now, if we compare with compacted clay, we see 1000 times more inorganic contaminant transport due essentially to advective flow. This confirms the benefit of composite liners. As I mentioned earlier, composite liners are excellent barriers against advective flow. Also, geomembranes are excellent barriers against diffusion of inorganic contaminants.
Now, let’s consider the case of organic contaminants. With compacted clay, we still have 1000 units of contaminant transport. This is because, with compacted clay, contaminant transport is due to advective flow; therefore, there is no difference between organic and inorganic contaminant transport. In the case of a composite liner that consists of a geomembrane on compacted clay, we see an improvement by an order of magnitude. This is because the geomembrane has eliminated most of the advective flow and the dominant mechanism is then diffusion.
Finally, in the case of a composite liner that consists of a geomembrane on a GCL, we see a large amount of contaminant transport, essentially by diffusion. This is because both geomembrane and GCL are not good barriers against organic contaminant transport by diffusion.

SLIDE 99 (3rd slide of page 17)
Here, on the top drawing, we see the cross section of a leakage collection layer located between the primary liner and the secondary liner of a double liner.
If there is a concentrated leak through the primary liner, the liquid flow in the leakage collection layer has a conical shape with the apex, or peak, located below the leak. The blue arrows show the direction of flow.
The lower drawing is a plan view of the leakage collection layer. In the lower drawing, we see the parabola that is the boundary between the wetted area and the dry area of the leakage collection layer.
Calculations based on this model lead to an extremely simple equation where Q is the leakage rate, k is the hydraulic conductivity of the drainage material, and t_{peak} is the liquid depth at the peak.

SLIDE 104 (2nd slide of page 18)
To answer this question, let's compare a single and a double liner in an under-equipped area, I mean an area where the only existing landfill is not lined with a composite liner, but is lined with clay only.
A new landfill is to be constructed. Two liner systems are considered for the new landfill: a single composite liner and a double composite liner. Of course, the double composite liner is better than the single composite liner. However, the double composite liner requires more time for design and more time for construction. It is assumed that it will take four additional months to construct the landfill with a double composite liner compared to the landfill with the single composite liner.

SLIDE 105 (3rd slide of page 18)
To compare the two liner systems, we will use the graph of ground contamination on the vertical axis versus time on the horizontal axis.
First, we use the graph for the single composite liner. The single composite liner being a good liner system, the curve of contamination with time grows very gently. It is likely that this curve will stop growing at some point, when no more leachate is generated, but we will conservatively assume that the curve grows indefinitely.
Now, let's draw the same curve for the double composite liner. The double composite liner is orders of magnitude better than the single composite liner. Therefore, at the same scale, the curve for the contamination caused by the double composite liner runs along the horizontal axis. In other words, there is virtually zero contamination with the double composite liner.
But, we should not forget that the double composite liner will be completed 4 months after the single composite liner. During these 4 months, the existing landfill will be used. This landfill is lined with clay only; therefore, the curve that represents the rate of contamination for this existing landfill is very steep. The amount of ground contamination generated during these 4 months is represented by the red area under the curve.
Now, how much time would it take to generate the same amount of ground contamination with the single composite liner? This time is obtained by drawing the same red area under the curve for the single composite liner. I made (and published) the calculation for a typical case and obtained 1000 years.

SLIDE 111 (3rd slide of page 19)
Here we see a very large waste slide related to leachate recirculation.
The landfill area before the slide is limited by the green dashed line.
After the slide, the waste traveled about one kilometer and reached a river where it caused massive pollution of the water.
The slide had been caused by high pore pressure due to excessive leachate recirculation.

SLIDE 114 (6th slide of page 19)
Since water is detrimental to stability, drainage is important in landfill covers.
We see here a drainage geocomposite being installed in a landfill cover.

SLIDE 115 (1st slide of page 20)
I will show what we can learn from the analysis of a real case of landfill cover instability due to insufficient drainage.

SLIDE 116 (2nd slide of page 20)
If the drainage layer had been properly designed, it would have been able to convey all the water that percolates through the cover soil without being full. When the drainage layer is not full, all of the water that percolates through the cover soil flows vertically through the cover soil. Since the water flows vertically, the seepage forces are vertical. Therefore, they are equivalent to gravity and they have no additional impact on stability.
In this particular case, the calculated factor of safety against instability is 1.18. This is greater than one. In other words, the slope is stable.

SLIDE 117 (3rd slide of page 20)
In reality, the drainage layer was not sufficient. It was filled with water over most of its length. Therefore, water in the cover soil could not flow vertically and had to flow parallel to the slope. The resulting seepage forces, which are parallel to the slope, are very detrimental to stability. The calculated factor of safety is then 0.77.

SLIDE 118 (4th slide of page 20)
Geotechnical engineers in this room may wonder why I am telling this, because geotechnical engineers are familiar with these two factors of safety, which are obtained using steady-state flow calculations, where the basic equation is: “flow IN” equals “flow OUT”.
Now, I will show the scenario leading to instability, considering transient flow, where the basic equation is: “flow IN” equals the fraction of flow stored in the drainage layer plus the “flow OUT”.

SLIDE 119 (5th slide of page 20)
Here, I use the same example as before, to illustrate transient flow. Remember, the drainage layer is not sufficient. At the beginning, during a certain period of time after the rainfall starts, the drain is not full. Therefore, during this period of time the slope is stable.

SLIDE 120 (6th slide of page 20)
But, progressively, the drain becomes full starting at the toe of the slope. As a result, the factor of safety decreases progressively until it reaches the value of 1. At this point, the slope becomes unstable.

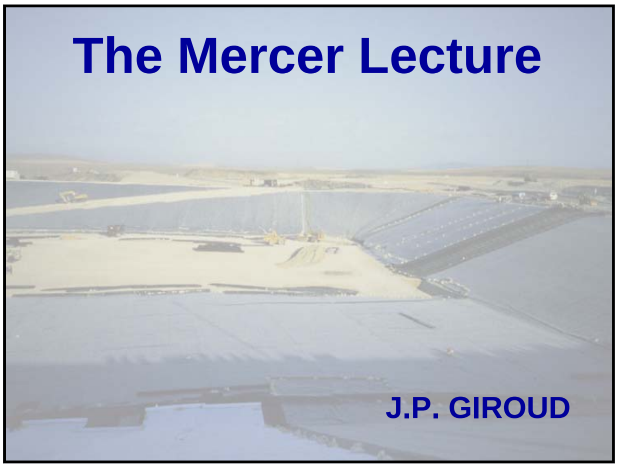
SLIDE 126 (6th slide of page 21)
I did the calculation and obtained this curve. The factor of safety is given on the vertical axis as a function of time on the horizontal axis. Time zero is the beginning of the rainfall. In this particular case, during 8 minutes, the drainage layer is not full and the factor of safety is 1.18. After 8 minutes, the drainage layer becomes progressively full and the factor of safety starts decreasing.
After 14 minutes, the factor of safety is equal to 1 and the slope is unstable. In fact, sloughing may start at the toe of the slope as soon as the factor of safety starts decreasing, that is 8 minutes after the beginning of the rainfall.

SLIDE 127 (1st slide of page 22)
The equation I used to generate the graph presented on the preceding slide contains a term shown in red, which is the storage capacity of the drainage layer.
This is not surprising. Remember the equation for transient flow. If the “flow OUT” is less than the “flow IN”, the difference is the storage.

SLIDE 134 (2nd slide of page 23)
Finally, it would be impossible to talk about landfill slope stability without mentioning that the stability of soil covers can be improved by geogrid reinforcement.

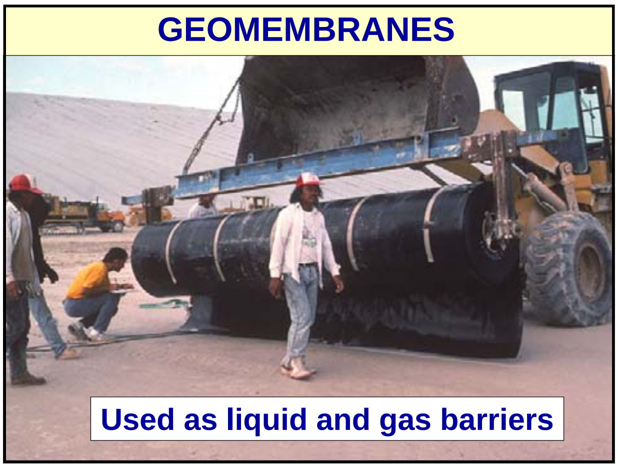
SLIDE 152 (2nd slide of page 26)
Regarding innovation, I want to pay a tribute to Brian Mercer, the namesake of this lecture. Without his innovative products, many of the applications I have shown would not have been possible.

* * * * *



A variety of geosynthetics are used in landfills:

- GEOMEMBRANES
- GEOTEXTILES
- GEONETS
- GEOCOMPOSITES
- GEOGRIDS
- GEOSYNTHETIC CLAY LINERS
- GEOMATS
- GEOCELLS

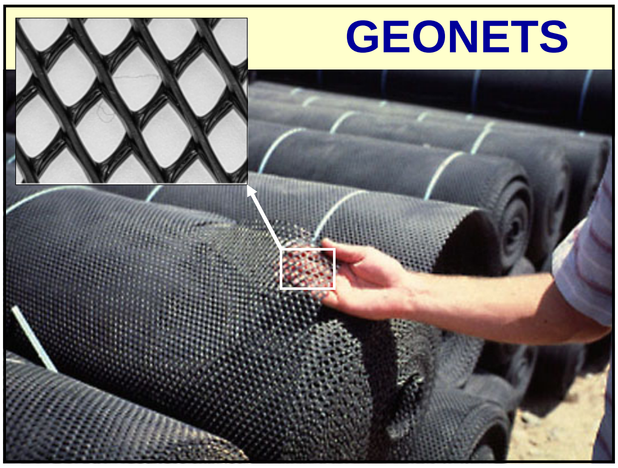


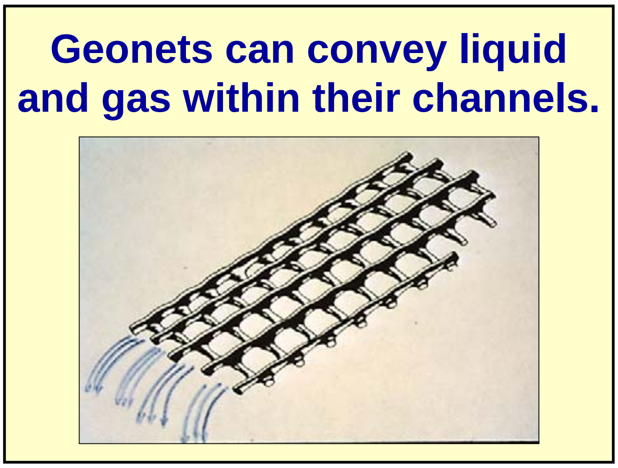

GEOTEXTILES
Used for a variety of functions

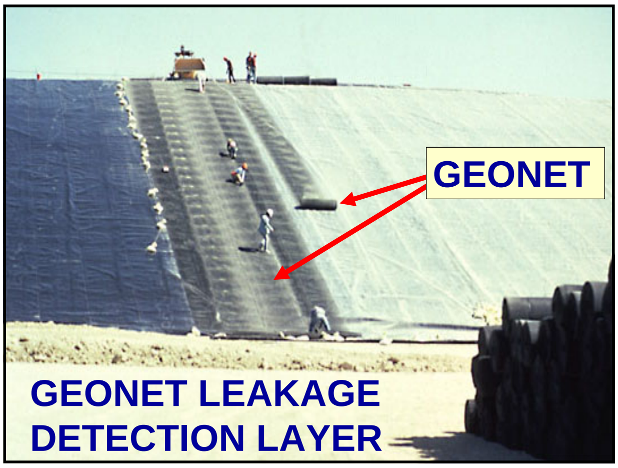

GEOTEXTILE REINFORCEMENT


GEOTEXTILE CUSHION

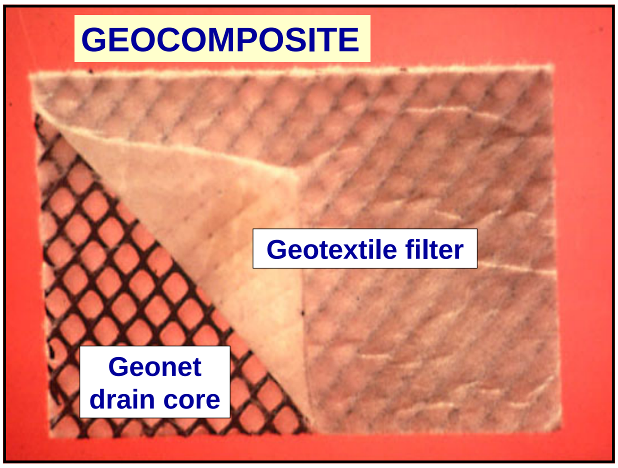

GEOTEXTILE
FILTER
ON TOP OF GEONET
LEACHATE COLLECTION LAYER


GEONETS


Geonets can convey liquid
and gas within their channels.



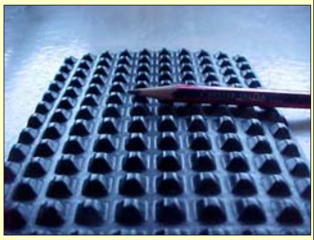
Geonets and geotextiles can be installed separately or can be combined to form a drainage geocomposite.

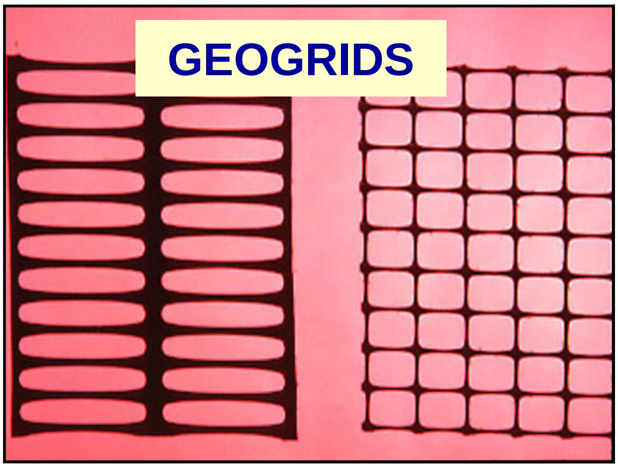


The drain core of a geocomposite can also be:

GEOMAT

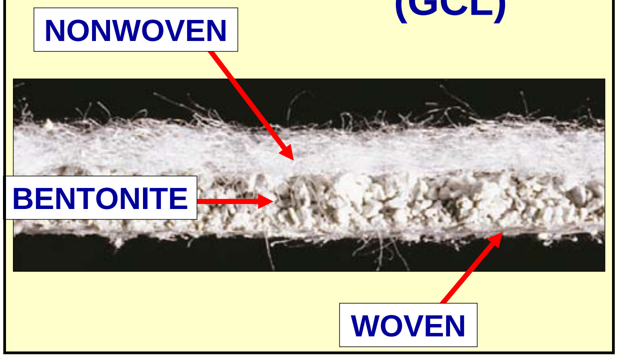
CUSPATED SHEET





ROLLS OF GEOGRID

GEOSYNTHETIC CLAY LINER (GCL)



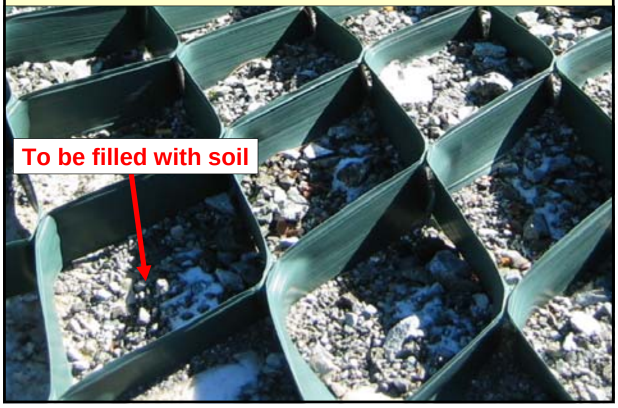
GEOSYNTHETIC CLAY LINERS used as liquid barriers

GCL IN LANDFILL CAP

GEOMATS

**GEOMAT ROLLS
USED FOR EROSION CONTROL
ON LANDFILL COVER**

GEOCELLS



**This extensive use of
geosynthetics in landfills
is not surprising,
because geosynthetics
have been
the most important development
in geotechnical engineering
in the second half
of the 20th century.**

However, there is more.

**The reason for the
extraordinary success of
geosynthetics in landfills
is
absolutely fundamental.**

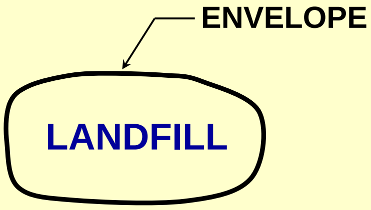
The rest of the world

The rest of the world

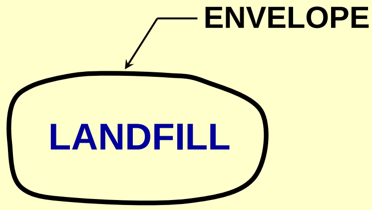
LANDFILL

The rest of the world

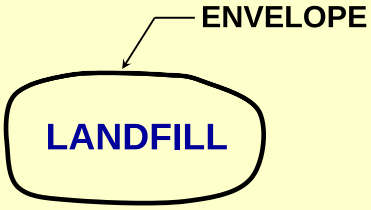
The rest of the world



The dimension of any envelope, in particular the envelope around a landfill, is the dimension of space minus one.



In a two-dimensional space (such as this drawing) the envelope is one-dimensional.



In the three-dimensional space (the real world) the envelope is two-dimensional.

But, nature does not provide two-dimensional materials.

Natural materials are essentially three-dimensional.

or three-directional.

**Since nature
does not provide two-dimensional materials,
synthetic materials
must be used.**

the geosynthetics

**For this fundamental reason,
because they are
the only two-dimensional
construction materials,
geosynthetics are
the obvious solution
for waste containment.**

**As a result,
acceptance of
geosynthetics in landfills
has been relatively
easy and rapid.**

**Also, regulators have found
landfill liner systems
easy to prescribe.**

**And, for landfill designers,
it is easy to design with
prescribed liner systems.**

**For some engineers,
designing a landfill consists
in drawing a sequence of
bold lines and dashed lines
directly copied from
regulations or geomembrane
manufacturers' brochures.**

DESIGNING BY CARTOONS

**"Designing by cartoons"
is 20% to 50% less expensive
than doing good design,
which has bad consequences:**

- **Bad designers may be selected
when selection is based on price.**
- **Some necessary analyses
are not performed
and the risk of failure is increased.**
- **Construction costs are higher
because design details
are not adapted to site conditions.**

The importance of regulations is such that it leads to equivalency-design, which consists in demonstrating that an alternative solution (often a geosynthetic solution) is equivalent to the prescribed solution.

Equivalency-design is not better than prescriptive design.

If the prescribed solution is inadequate, the equivalent solution is inadequate.

And, if the prescribed solution is adequate, the so-called "equivalent" solution may be inadequate.

"EQUIVALENCY" BETWEEN GRANULAR AND GEOSYNTHETIC DRAINAGE LAYERS

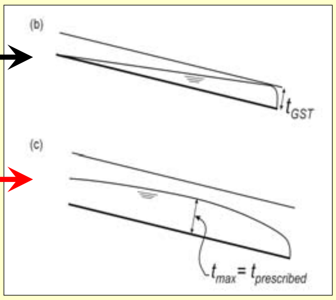
Use of geosynthetic drainage layers is allowed by some regulations, provided the geosynthetic drain is equivalent to the prescribed granular drainage layer.

It is generally believed (and often mentioned in regulations) that two drainage layers are equivalent if they have the same hydraulic transmissivity.

In reality, a granular drainage layer and a geosynthetic drain having the same hydraulic transmissivity are not equivalent.

The flow profile is linear in a geosynthetic drainage layer.

The flow profile is **different** (and more efficient) in a granular layer due to much greater thickness.



A GEOSYNTHETIC DRAIN SHOULD HAVE A HIGHER HYDRAULIC TRANSMISSIVITY

EQUIVALENCY FACTOR

Geosynthetic Drain / Granular Layer

$$\theta_{GST} = E \times \theta_{GRA\ PRESCRIBED}$$

$$E = \frac{1}{0.88}\left[1 + \left(\frac{t_{PRESCRIBED}}{0.88\,L}\right)\left(\frac{\cos\beta}{\tan\beta}\right)\right]$$

L = 30 m $\tan\beta$ = 2%
$t_{PRESCRIBED}$ = 0.3 m

→ **E = 1.8**

Regulations that approve alternative designs using a geocomposite drain having the same hydraulic transmissivity as the prescribed granular drainage layer should be revised because they are unconservative.

The alternative to prescriptive design is performance-based design.

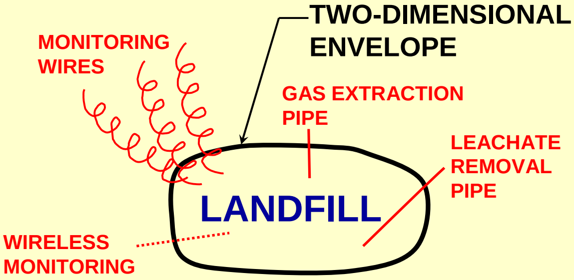
Performance-based design consists in evaluating if the expected performance of the waste containment system is acceptable for the environment.

The problem with performance-based design is that the performance criteria are often satisfied only by calculations, not by actual performance monitoring.

**For example,
the criterion for
maximum leachate depth
in a leachate collection layer
(in the USA, 0.3 m)
is typically satisfied by
conducting a calculation.**

**We know that the method
for leachate depth calculation
is accurate for an
ideal leachate collection layer;
but, is it accurate for
an actual leachate collection layer
in an actual landfill?**

**To answer this question,
the performance of landfills
must be monitored.**



**ONE-DIMENSIONAL
LINES OF COMMUNICATION**

**Landfill engineers
should learn from the
state of practice in dams
where monitoring
is done extensively.**

Here are some examples of what we need to monitor:

- **integrity of geomembrane liners**
- **stresses in geomembranes**
- **depth of leachate**
- **permeability/clogging of leachate collection layers**
- **pressure of fluids in waste**
- **temperature**

IMPORTANCE OF TEMPERATURE

Hydraulic conductivity increases
by 50% from 20°C to 40°C

Tensile strength (HDPE) decreases
by 15% from 20°C to 40°C

Durability (HDPE) decreases
by a factor of 5 from 20°C to 40°C

and what about the influence of
temperature on **interface friction** ?

Geotechnical engineers have been too slow at incorporating temperature in their design calculations.

If geotechnical engineers do not incorporate in design the actual conditions that prevail in a landfill,

landfill design will be dominated by prescriptive design.

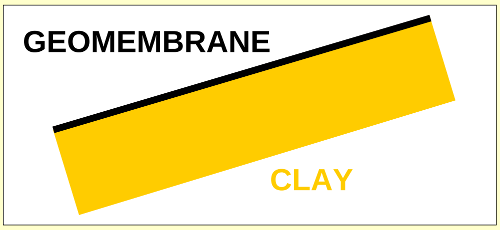
To avoid this situation, we need to identify and address technical challenges.

For example, in the early 1980s, I proclaimed that all liners leak.

The engineering community reacted positively, and recognized that, regardless of the quality of construction, there will always be a risk of defects in geomembranes, which led to:

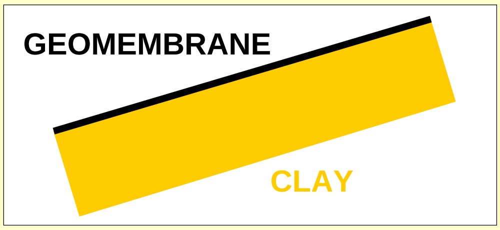
- **The development of methods to evaluate leakage**
- **The concept of composite liner**

COMPOSITE LINER



A composite liner associates two complementary materials, a geomembrane and a layer of clay, which can be compacted clay or a GCL.

COMPOSITE LINER



Associating two complementary materials addresses very well the "all liners leak" challenge.

Leakage through a composite liner is typically 2 to 4 orders magnitude less than leakage through a geomembrane alone (for the same hole size) or through a clay liner alone.

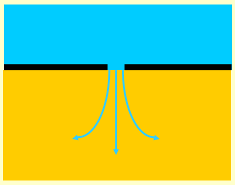
For prescribed composite liner with compacted clay

A composite liner is fully effective (i.e. leakage is significantly reduced) only if there is intimate contact between geomembrane and clay.

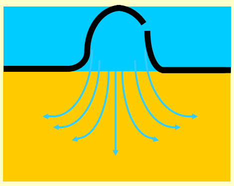
This concept is the cornerstone of the effectiveness of composite liners.

and the question is:
do we have intimate contact in the field?

GEOMEMBRANE WRINKLES

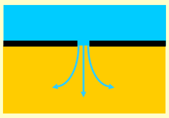


INTIMATE CONTACT

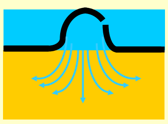


WRINKLE

greater area for leakage



The geosynthetic provides a solution . . .



and, also, brings a challenge.

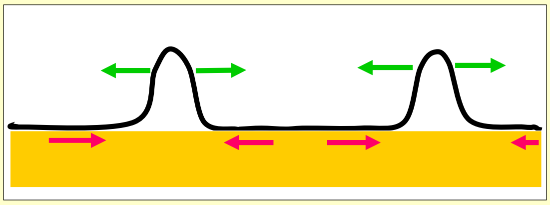
But, the challenge is met: methods have been developed to predict the rate of leakage through composite liners with wrinkles.

Why wrinkles in HDPE geomembranes?

- **Wrinkles are caused by the large coefficient of thermal expansion of HDPE.**
- **But PVC also has a large coefficient of thermal expansion.**
  [and we do not see wrinkles in PVC geomembranes]

A rational analysis will give the answer.

GEOMEMBRANE WRINKLES



Bending forces = Friction forces

Stiff geomembranes (HDPE)

- Due to HDPE stiffness, bending forces are large.
- Large friction forces are required to balance the large bending forces.
- Large spacing between wrinkles is required to generate the large friction forces.
- Since spacing is large, there are only few wrinkles.
- Since there are only few wrinkles, they must be high to accommodate a given thermal expansion.
- In conclusion, a stiff geomembrane exhibits few wrinkles. Since they are few, they must be high.

The same analysis shows that PVC geomembranes, which are flexible, have a very large number of very small wrinkles. As a result, they appear to be flat.

[we do not "see" them]

The bending-friction mathematical model gives the following results for HDPE geomembranes:

- Spacing between wrinkles: 3 m or more.
- Height of wrinkles: 10 cm or more.

These values are consistent with observations.

LESSON LEARNED

The wrinkle problem can be minimized by using flexible geomembranes with a high interface friction angle.

The challenge presented by geomembrane wrinkles for the effectiveness of composite liners is met in two different ways:

- **Methods for evaluating the rate of leakage for composite liners with geomembrane wrinkles**
- **Understanding of the parameters that govern wrinkles.**

But, there is another challenge associated with composite liners:

DESICCATION AND CRACKING OF THE CLAY COMPONENT OF A COMPOSITE LINER

CLAY DESICCATION PRIOR TO GEOMEMBRANE INSTALLATION

CRACKED CLAY UNDER GEOMEMBRANE

This phenomenon was unexpected.
Before it was observed, it was believed that the geomembrane would prevent clay desiccation.

CRACKED CLAY UNDER GEOMEMBRANE

This phenomenon was observed in the case of composite liners exposed for some time on landfill sideslopes.

DESICCATION OF CLAY UNDER GEOMEMBRANE

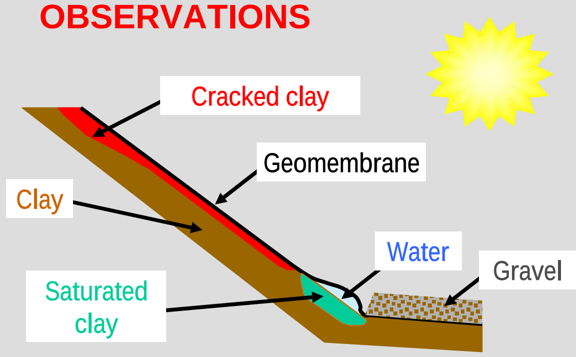
MECHANISM

ESSENTIALLY DAY- NIGHT CYCLES

- **DURING THE DAY**: Air entrapped in geomembrane wrinkles becomes saturated with water vapor that evaporates from the clay.
- **DURING THE NIGHT**: Vapor condenses and water migrates toward toe of slope.
- **AFTER SOME TIME**: Clay desiccates and cracks along the slope. Clay becomes saturated at toe of slope.

DESICCATION OF CLAY UNDER GEOMEMBRANE

OBSERVATIONS



To avoid the clay desiccation problem, in the case of a composite liners exposed on slopes, GCLs can be used.

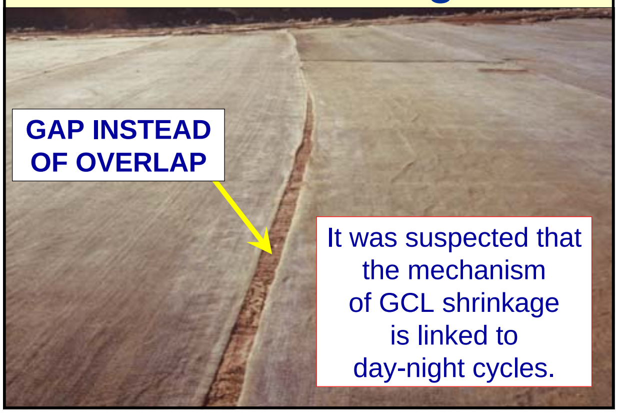
The clay desiccation problem is solved thanks to a geosynthetic, the GCL.

This is what was believed until GCL shrinkage was observed.

Again, a geosynthetic solution is followed by a challenge associated with the geosynthetic.

GCL SHRINKAGE

GCL Shrinkage



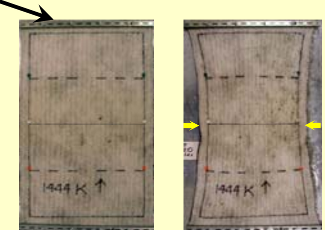
Specimens of GCL were subjected to temperature-humidity cycles simulating day-night conditions.

CLAMP

Before the cycles

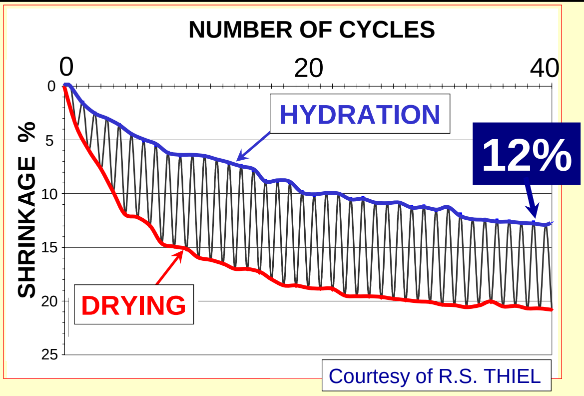
After 20 cycles

Constant length between the clamps



CLAMP

Courtesy of R.S. THIEL



12% of 5 m wide panel is 0.6 m shrinkage.

This study does not exactly model the situation in the field:

- **oven drying is probably more drastic than drying conditions in the field; and**
- **the amount of water added in the laboratory is probably greater than in the field.**

However, this study shows that shrinkage may result from drying-hydration cycles.

This study in progress already makes it possible to identify the types of GCL that are less susceptible to shrinkage and will make it possible to develop GCLs that are less susceptible to shrinkage.

At this point, one could think that geosynthetic solutions are not very effective because every geosynthetic solution is associated with a challenge that decreases the merit of the solution.

But, each challenge is less drastic than the preceding challenge, and the efforts converge toward better solutions.

For example, GCL shrinkage is a lesser problem than the cracking of compacted clay. It can be solved by using wide overlaps.

In a growing number of applications, GCLs replace compacted clay as the mineral component of composite liners.

But, GCLs lack thickness to be a diffusion barrier for organic contaminants.

Again, a geosynthetic solution and a challenge associated to it.

I did simple calculations of advective flow and diffusion through liners.

- **Two types of composite liners: GM/CCL and GM/GCL.**
  [In both cases, I considered typical numbers of defects through the geomembrane component.]
- **Also: CCL alone.**

ADVECTION AND DIFFUSION

CONTAMINANT	COMPACTED CLAY (CCL)	COMPOSITE LINER with typical defects	
		GM-CCL	GM-GCL
INORGANIC	1000 Ad	1 Ad-Di	1 Di
ORGANIC	1000 Ad	100 Di	10,000 Di

Solution for organic contaminants:
sorption and biodegradation
in an attenuation layer (a few meters of soil).

Considering the limitations of composite liners, a double liner can be justified.

ADVANTAGES OF DOUBLE LINERS

- **Redundancy**
- **Monitoring**
- **Quasi zero head on the secondary liner (drastic reduction of advective flow)**
- **Possibility of extracting gas from the leakage collection layer (elimination of organic contaminant migration by diffusion in gas phase from primary to secondary liner)**

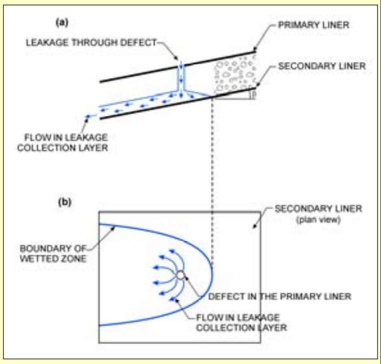
CONDITIONS FOR SUCCESSFUL LEAKAGE COLLECTION LAYER

- **achieve quasi-zero head of liquid**
- **allow vapor extraction**

To meet these conditions, the leakage collection layer must not be saturated with liquid.

Saturation may result from concentrated leak, if both components of the primary liner, the geomembrane and the GCL, are punctured at the same location.

LIQUID DEPTH DUE TO CONCENTRATED LEAK THROUGH THE PRIMARY LINER



$$Q = k\ t_{peak}^2$$

Numerical applications of this equation show that we need leakage collection layers with more flow capacity than usually considered.

The development of geosynthetics with high hydraulic transmissivity should be considered by manufacturers.

Leakage detection is possible only if the collected liquid is not lost in the underlying layers.

Therefore, the leakage collection layer must be underlain by a geomembrane.

However, there are still regulations that only require clay under the leakage collection layer.

These regulations should be changed.

As we have seen, we know all the conditions and we have the solutions for a good double liner.

QUESTION: should we always prefer a double liner to a single liner?

(the single liner being, of course, a composite liner)

While we should always use a double liner for hazardous waste, there are many situations where a single composite liner is adequate for municipal solid waste landfills.

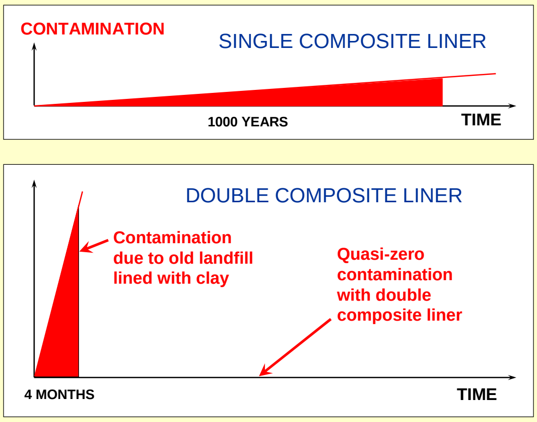
There may even be cases where a double liner is detrimental.

Where can this be?

SINGLE vs. DOUBLE LINER
IN UNDER-EQUIPPED AREA

- **Existing landfill lined with clay only**
- **A new landfill is to be constructed**
- **Two liner systems are considered:**
  - **single composite**
  - **double composite**

PROBLEM: 4-month delay with double composite



LESSON LEARNED

- **In an area, if the only existing landfill is not lined with a composite liner (or, even more so, is not lined at all), a landfill with a single composite liner should be constructed immediately.**
- **It would be counterproductive to wait for constructing a better landfill: this would cause more ground contamination.**

This is true even if the composite liner is constructed with local soil, instead of standard clay ($k = 10^{-9}$ m/s).

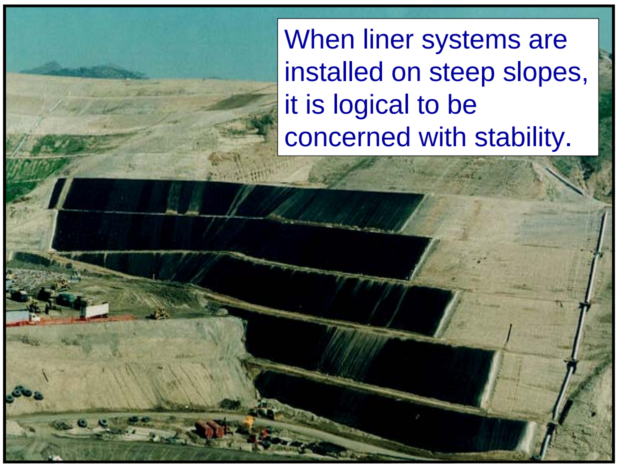
LESSON LEARNED

- **The best liner in a country may not be the best liner in another country.**
- **Exporting good practice may not be good.**

Clearly, landfill design must be site specific.

The best liner must, of course, be installed in a stable landfill.

We will see again the association of solution and challenge.



Experience shows that waste instability can happen with dramatic consequences.

WASTE SLIDE DUE TO LEACHATE RECIRCULATION

Here, both environmental scientists and geotechnical engineers can learn a lesson.

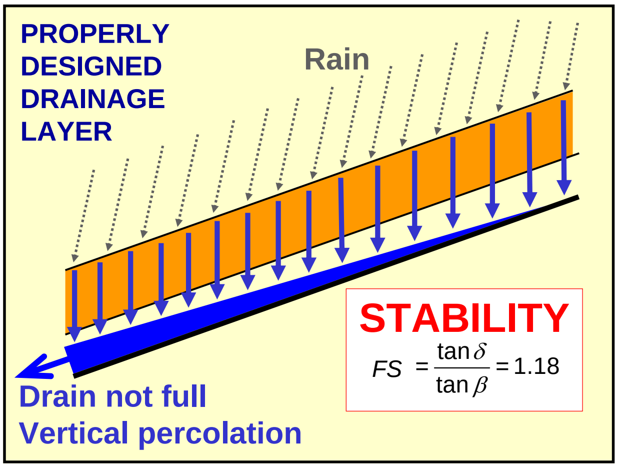
Environmental scientists who plan to do leachate recirculation should learn from geotechnical engineers that an increase in liquid content greatly impairs stability.

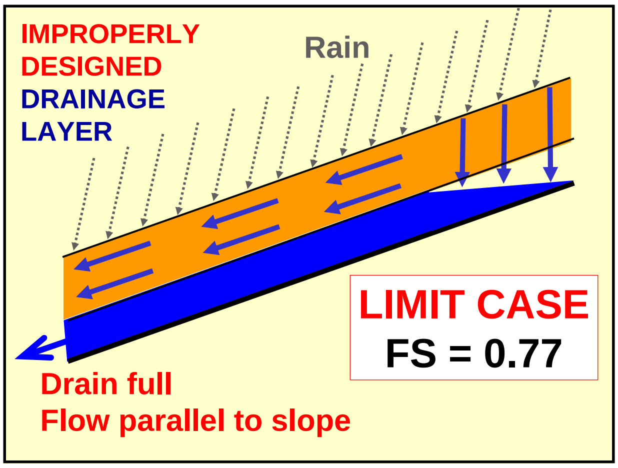
Here, both environmental scientists and geotechnical engineers can learn a lesson.

Geotechnical engineers (who know that water is detrimental to soil stability) should learn that the detrimental impact of water on stability is greater for waste than for soil due to the difference in density between waste and soil.

Since water is detrimental to stability, drainage is important in landfill covers.

Analysis of Failure of Landfill Cover



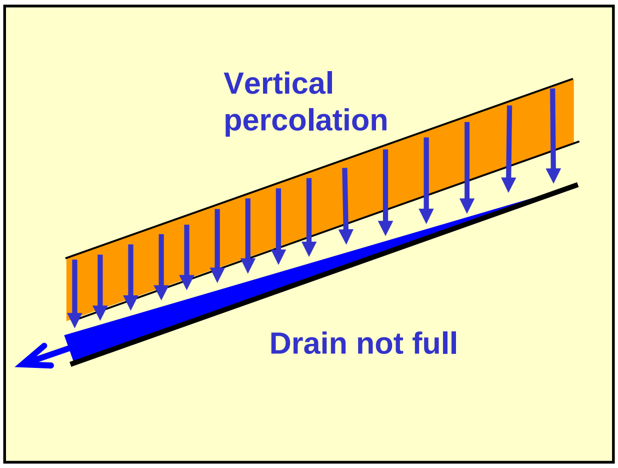


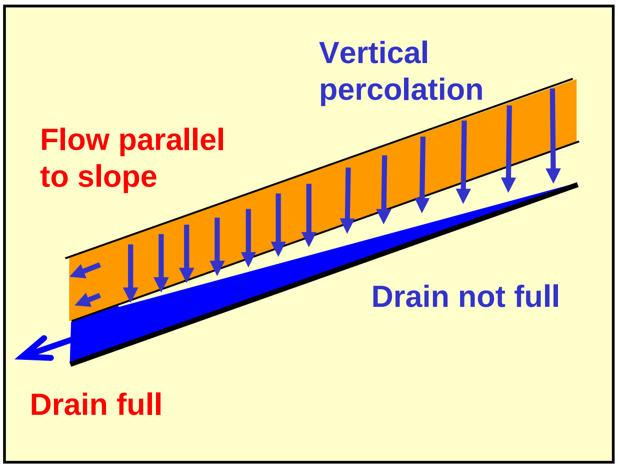
Geotechnical engineers are familiar with these two factors of safety, which are obtained using steady-state flow calculations.

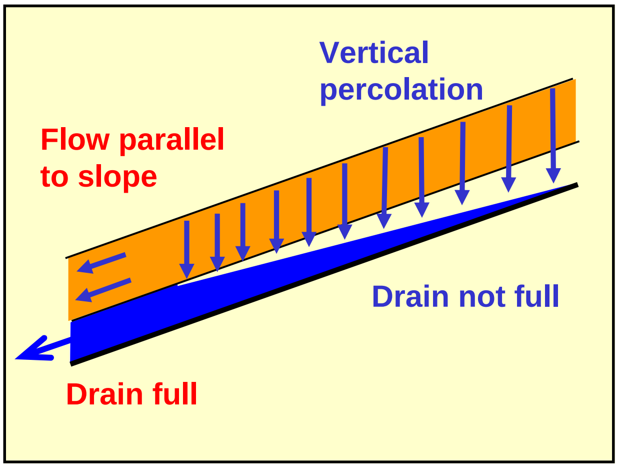
$$Q_{IN} = Q_{OUT}$$

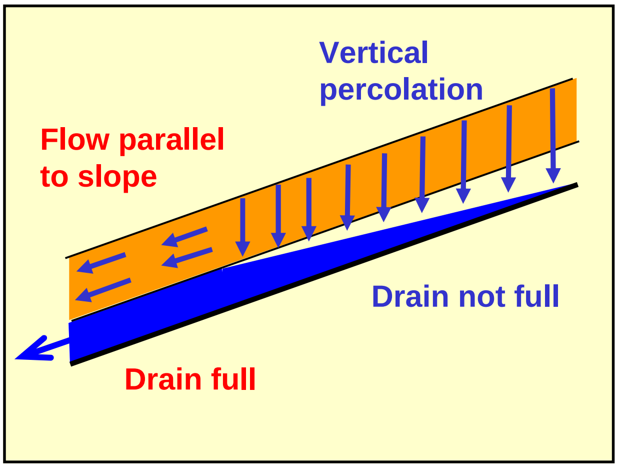
Now I will show the scenario leading to instability, considering transient flow.

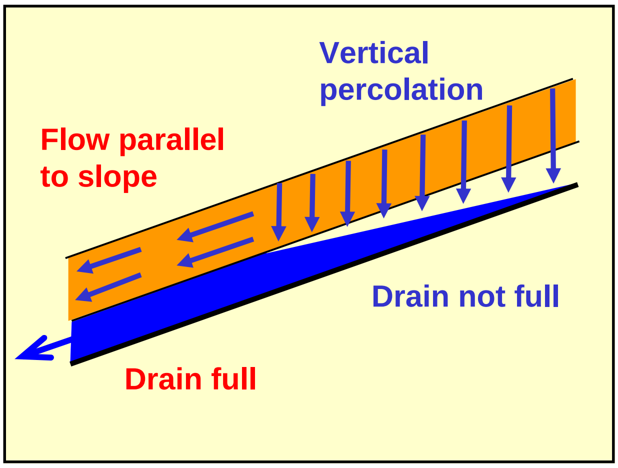
$$Q_{IN} = Q_{STORED} + Q_{OUT}$$

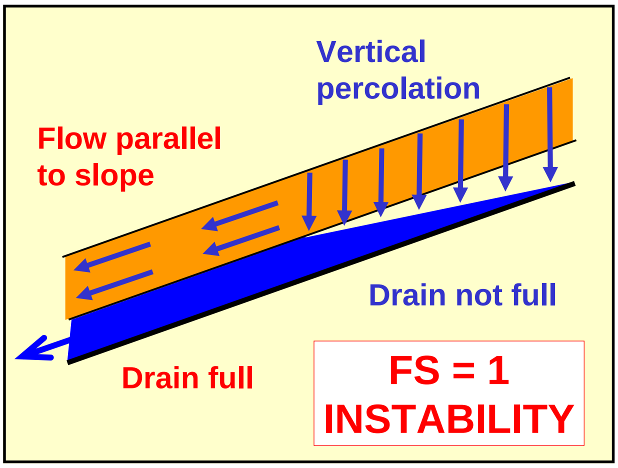




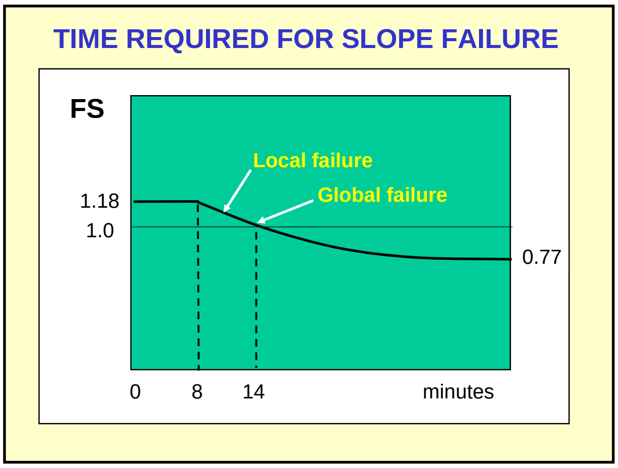








How much time does it take to reach instability?



TIME REQUIRED FOR THE DRAINAGE LAYER TO BE FULL AT THE TOE

$$FS = \frac{\tan\delta}{\tan\beta} \quad \text{if}$$

$$\hat{t} \leq \frac{n\, t_D\, L}{2\,\theta \sin\beta \cos\beta} \ln\left(\frac{1}{1 - \dfrac{\theta \sin\beta}{q_h\, L}}\right)$$

To be published

$n\, t_D$ is the volume of voids per unit area of the drainage layer, i.e. the storage capacity of the drainage layer.

$Q_{IN} = Q_{STORED} + Q_{OUT}$

STORAGE CAPACITY AND TIME TO FAILURE

- **The storage capacity of a granular drainage layer is 20 times that of a geonet.**
- **In case of improper design, if time to failure is 15 minutes with geonet, it is 5 hours with granular drainage layer.**
- **If the rainfall lasts 2 hours, the granular drainage layer will survive, the geosynthetic drainage layer will not.**

This may explain some of the observed landfill cover failures.

Geosynthetics are less forgiving than granular drainage layers in case of incorrect design.

How can we deal with this drawback of geosynthetics with respect to granular drainage layers?

- **Design drainage layers with large factor of safety.**
- **Therefore, use high-transmissivity geosynthetics.**

A different strategy for cover stability is to have no cover soil, i.e. to have an exposed geomembrane as a landfill cap.

Here, the challenge is the risk of uplifting of the geomembrane by the wind, but this challenge has been met.

A similar challenge is the risk of instability of soil covers caused by landfill gas pressure under the geomembrane.

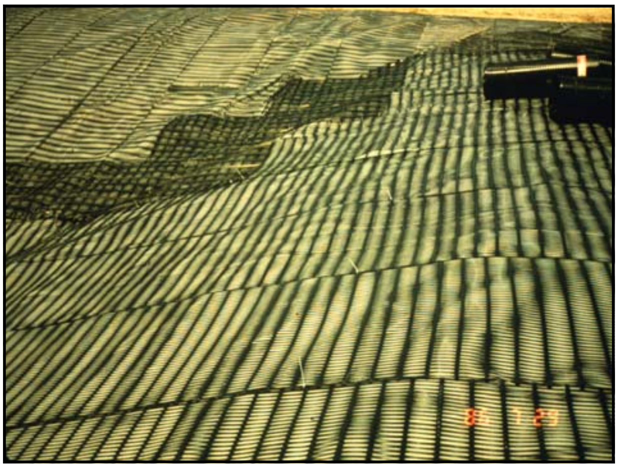
Courtesy of G.N. RICHARDSON

This is another challenge that has been met, as design methods to evaluate the impact of gas pressure on stability have been developed.

However, this is a difficult problem because a relatively small gas pressure can cause cover instability.

This mode of failure may become more frequent with increased gas generation due to leachate recirculation.

The stability of soil covers, can be improved by geogrid reinforcement.



ANCHORAGE OF GEOGRID AT CREST OF SLOPE

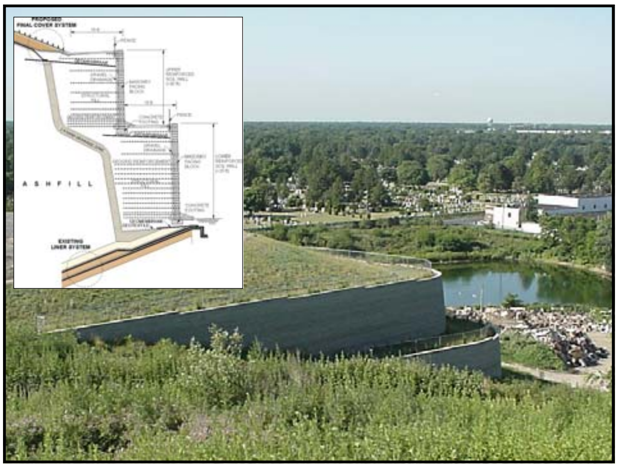
Since load is transferred to the top, strong anchorage is needed.

This may limit the application to slopes that are not too long.

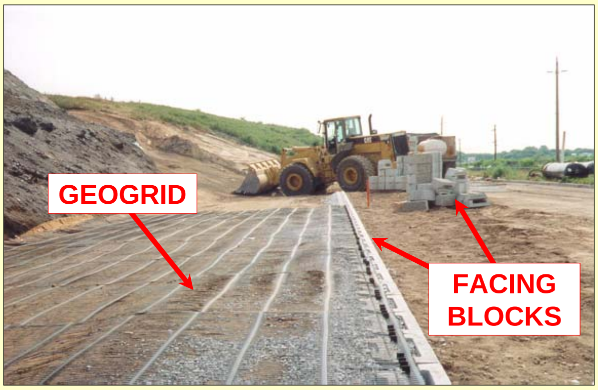
No such limitation exists with multilayer reinforced-soil structures, because each layer ensures its own stability.

EXAMPLES OF USE OF MULTILAYER REINFORCED-SOIL STRUCTURES TO CONSTRUCT LANDFILLS WITH STEEP LATERAL SLOPES

LANDFILL WITH MULTILAYER REINFORCEMENT

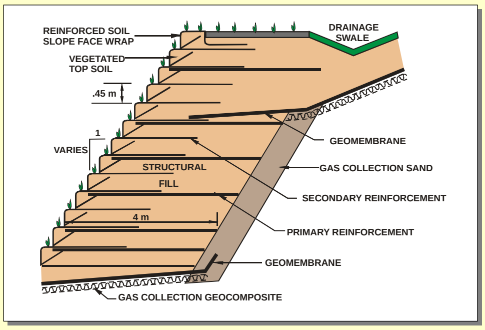


PLACEMENT OF GEOGRIDS

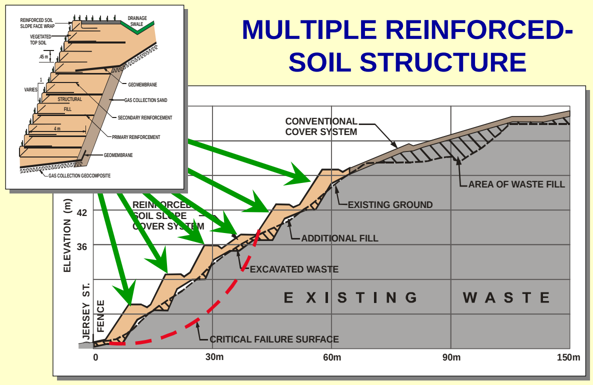


VERTICAL CONCRETE BLOCK FACE

STEEP FACE WITH GRASS
Geogrid Reinforcement Arrangement



MULTIPLE REINFORCED-SOIL STRUCTURE



Babylon Landfill, New York

CONCLUSION

Even though geosynthetics are obvious materials for landfills, their use has been associated with challenges.

CONCLUSION

The fact that the challenges were met gives credibility to the geosynthetic solutions.

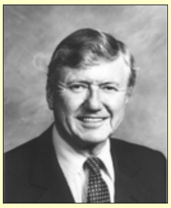
CONCLUSION

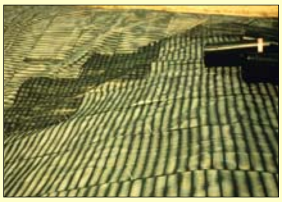
The efforts made to meet the challenges have led to the development of innovative designs and innovative products.

CONCLUSION

The geosynthetics discipline has brought innovation in an engineering field that tends to be dominated by prescriptive design and by regulations.

F. Brian Mercer
1927-1998





CONCLUSION

**Geosynthetics,
the most important development
in geotechnical engineering
at the end of the past century,
serve the most important cause
of this century,
the environment.**

Thank you