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Porto, Portugal

Fifth Victor de Mello Lecture

LEAKAGE CONTROL USING GEOMEMBRANE LINERS

By

J.P. GIROUD

JP GIROUD VICTOR DE MELLO LECTURE

LEAKAGE CONTROL USING GEOMEMBRANE LINERS

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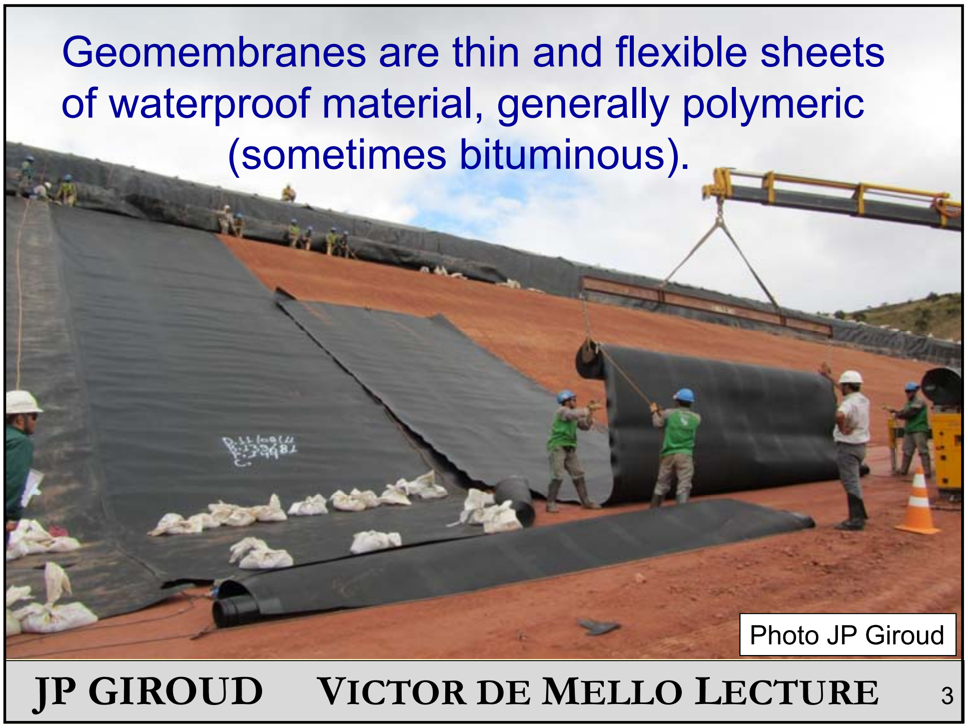
Geomembranes are thin and flexible sheets of waterproof material, generally polymeric (sometimes bituminous).
Photo JP Giroud
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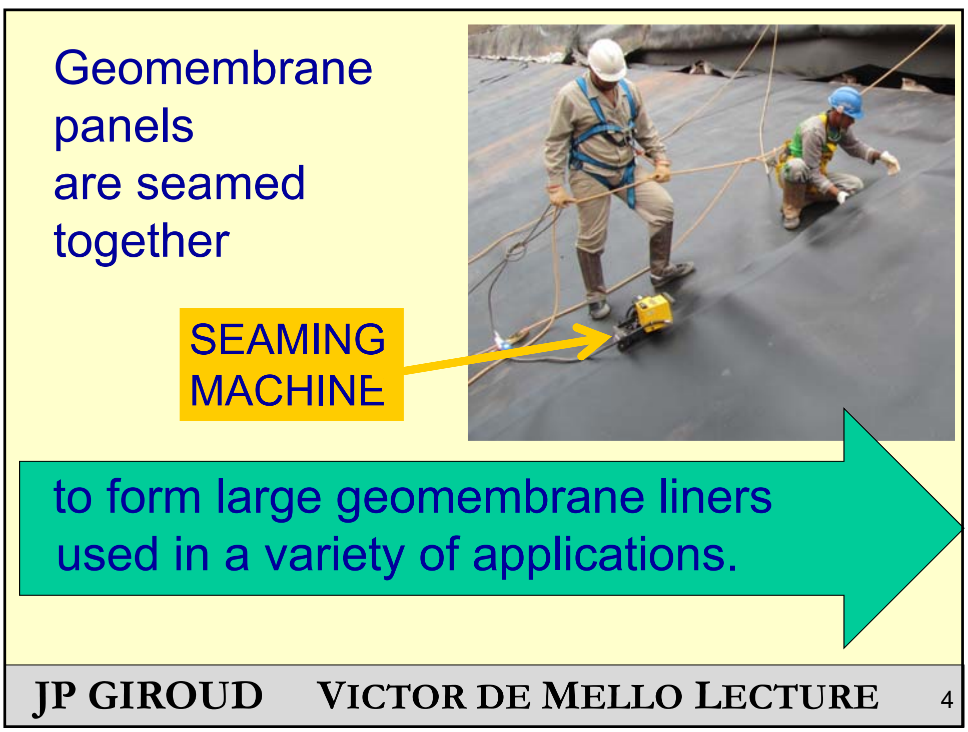
Geomembrane panels are seamed together
SEAMING MACHINE
to form large geomembrane liners used in a variety of applications.
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WASTE DISPOSAL LANDFILL
Courtesy SOLMAX
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Courtesy
Firestone
RESERVOIR
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EMBANKMENT DAM

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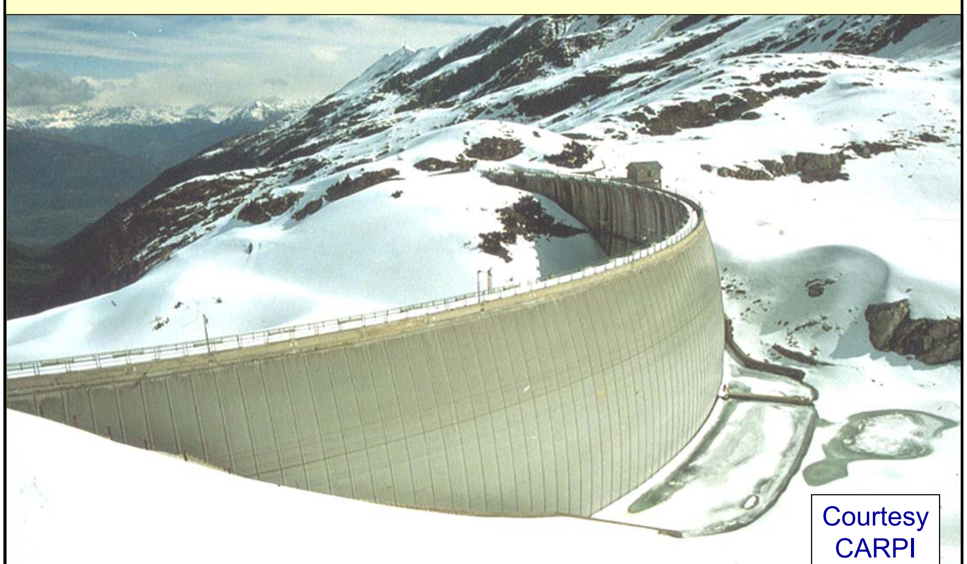
CONCRETE DAM



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JP GIROUD VICTOR DE MELLO LECTURE 9

The **polymeric compounds** used in geomembranes can be considered **impermeable**.

For example, the **standard tests** performed to determine geomembrane acceptance are equivalent to a **coefficient of permeability** of less than **10^{-14} m/s**.

In comparison, **other liner materials** are **more permeable**.

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PERMEABILITY OF INTACT MATERIALS

COMPARED TO THE <10^{-14} m/s "PERMEABILITY" OF GEOMEMBRANES

- Cement concrete, ideal — 10^{-12} m/s
- Cement concrete in field — 10^{-10} m/s to 10^{-8} m/s
- Roller compacted concrete — 10^{-8} m/s to 10^{-6} m/s
- Bituminous concrete, ideal — 10^{-9} m/s
- Bituminous concrete in field — 10^{-8} m/s
- Clay layer, ideal — 10^{-9} m/s
- Clay layer in field — 10^{-8} m/s
- Bentonite — 10^{-11} m/s

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Based on this discussion, geomembranes can be considered **quasi impermeable**.

Therefore, one may think that there is **no leakage** with geomembrane liners.

As a result, there would be no need for a **lecture on leakage control** using geomembrane liners.

But: *Impermeability on a small scale does not guarantee impermeability on a large scale.*

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In the field, **all liners leak**,
including geomembrane liners.

Leakage can be reduced
by a variety of measures
at the design stage and
at the construction stage.

But some leakage is always likely
and this fact should be recognized.

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Considering that
geomembranes are perfectly waterproof,
thereby **ignoring leakage**,
would be a **major mistake**
for two reasons:

- This would raise **unrealistic expectations** and would preclude the development of **realistic specifications**.
- Leakage has numerous **detrimental consequences**, which must be dealt with.

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Leakage is detrimental for several reasons:

- Loss of valuable liquid (water, pregnant solution).
- Difficulty in maintaining an acceptable level (pump storage facilities, sport and recreation ponds, decorative ponds).
- Contamination of ground and ground water.
- Deterioration of **geotechnical conditions** (erosion, dissolution, subsidence, softening, instability).
- Liner damage (e.g. uplift of geomembrane liner, geomembrane rupture on eroded support).

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EXAMPLES OF CONSEQUENCES OF LEAKAGE

DETRIMENTAL CONSEQUENCE	CONTAINMENT OF WATER	CONTAINMENT OF MINING PREGNANT SOLUTION	CONTAINMENT OF WASTED LIQUID
Loss of valuable liquid	YES	YES	NO
Contamination of ground	NO	YES	YES
Geotechnical damage	YES	YES	YES

With leakage,
there is **always a risk of geotechnical damage**.
However, the focus is too often
on liquid loss and ground contamination.

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It is important to note that leakage is not only an **economic problem** (loss of liquid)
or an **environmental problem** (contamination),
but also an **engineering problem** when leakage causes:

- Deterioration of soil under the liner; and, as a result,
- Impairment of liner integrity.

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Clearly, leakage is a serious problem and it must be addressed.

This is worth a lecture !

So, let's analyze
the mechanisms of leakage
associated with geomembrane liners.

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There are

TWO MAIN MECHANISMS OF LEAKAGE ASSOCIATED WITH GEOMEMBRANE LINERS

- LEAKAGE **THROUGH** THE GEOMEMBRANE which is essentially due to **holes** in the geomembrane,
- LEAKAGE **AROUND** THE GEOMEMBRANE at **attachments** of geomembrane with appurtenant structures.

We will address these two mechanisms successively.

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HOLES IN GEOMEMBRANE DUE TO CONSTRUCTION

- Holes from **geomembrane installation**
  - Tear and puncture by workers
  - Inadequate seams between geomembrane panels
- Damage due to **placement of materials** on top of the geomembrane
  - Puncture by stones placed on geomembrane
  - Weight and movement of construction equipment
  - Direct tear by construction equipment

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These holes must be
found and repaired.

Repairing holes is relatively easy.

Finding holes is a challenge.

The first idea that comes to mind
is to conduct a **ponding test**
which consists in filling with water
the geomembrane-lined reservoir
and measuring the **drop of water level**.

This method has many drawbacks:

- Impractical and time consuming
  due to large amount of water required,
- Not accurate due to evaporation and
  to the very small impact of leakage on water level,
- Does not find leaks, but only leakage.

CASE HISTORY OF PONDING TEST

The water level drop was specified
to be less than **6 mm** in 14 days.

- Ponding test after liner installation: **66 mm**.
- First sequence of reservoir emptying, visual inspection, repair of the identified holes, and ponding test: **22 mm**.
- Second sequence: **112 mm**.
- Third sequence: **23 mm**.
- Fourth sequence: **130 mm**.

The leakage was increasing in spite of repairs !

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Leakage increased for at least two reasons:

- **Damage** caused to the geomembrane by the team walking on the geomembrane to perform the visual inspection, and by the crew performing the repairs.
- **Stresses** induced in the geomembrane by repeated displacement of the geomembrane due to cycles of emptying and filling of the reservoir.

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CASE HISTORY OF PONDING TEST

After several months thus wasted,
the geomembrane liner was removed
and replaced by a new geomembrane liner
installed by a **new installer**.

This new geomembrane liner
met the specified leakage rate
at the **first ponding test**.

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COMMENTS ON THIS CASE HISTORY

- **Visual inspection** does not find all holes.
- Many holes were found at the geomembrane **attachments to appurtenant structures and pipes** having a complex geometry.
- Based on observations, **filling/emptying cycles** caused **stresses** on the geomembrane, next to appurtenant structures and pipes.
- Excessive traffic by **workers doing repairs can damage the geomembrane**.

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LESSONS LEARNED FROM THIS CASE HISTORY

- **Good workmanship is essential** to ensure a small rate of leakage.
- Appurtenances must be designed with a **geometry** that facilitate attachment of geomembranes.
- If a reservoir is subjected to **frequent drawdowns**, the liner should be designed accordingly.

This is a good lesson for **design engineers**: they must treat geomembrane liners as seriously as they treat geotechnical issues.

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Geotechnical engineers, who carefully take into account the impact of **rapid drawdown** on slope stability, **should take into account** the impact of multiple filling/emptying cycles on geomembrane liners.

Also, engineers should design appurtenant structures that ensure **good performance** of the **attached geomembranes**.

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The usual way to improve liner quality
and, in particular, to find holes
is **construction quality assurance**.

Construction quality assurance consists of
inspections and measures,
by a team independent
from the geomembrane installer,
during installation of geomembrane
and overlying materials.

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Typical construction quality assurance activities aimed at **finding holes** in the geomembrane include:

- Nondestructive tests on seams
  to find gaps in seams.
- Visual inspection of the entire geomembrane liner
  to find:
  - **punctures and tears** in the geomembrane
    and
  - **gaps in attachments** of geomembrane to structures.

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Nondestructive testing of seam

Visual inspection of geomembrane

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These typical construction quality assurance activities (seam testing and visual inspection) may be sufficient in the case of **first-class projects**, characterized by:

- **Excellent workmanship**; and
- **Excellent working conditions**.

This is the case for sophisticated applications, such as **geomembrane-lined dams**.

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But, experience shows that
these **typical construction quality assurance activities** (seam testing and visual inspection)
are not sufficient
in the case of usual projects,
such as **landfills** and **many reservoirs**
where they miss a number of holes.

In such projects, it is recommended to perform
electric leak location surveys
in addition to construction quality assurance.

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The principle of
electric leak location surveys is simple.

Most geomembranes are electrical insulators.

Therefore, **electric current will pass**
if there is a **hole** in the geomembrane
or a **gap** in an attachment to
an appurtenant structure.

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In the past two decades,
the **electric leak location technology**
has made **significant progress**.

Today, electric leak location
can be performed:

- on a **bare** geomembrane,
- on a geomembrane **under water**,
- or on a **layer of soil**
  overlying a geomembrane.

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Electric leak location
on a **bare** geomembrane

Electric leak location
on a **layer of soil**
overlying a geomembrane

Courtesy
A. Beck

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When a geomembrane
is **covered by a layer of soil**,
it is important to perform
electric leak location survey,
not only after geomembrane installation,
but also
after placement of the soil layer
because holes in the geomembrane
are often caused by soil placement.

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Finding such large holes is easy.

More importantly, what is the
minimum size of holes that can be found
by the electric leak location technique ?

With current technology (2016),
the **minimum size of holes**
that can be found is approximately:

- **1 mm** for a **bare geomembrane**
- **5 mm** under **0.5 m of soil**

Electric leak location can find small holes, but not all.

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All the holes found are repaired.

In the case of a bare geomembrane
the result, **after repair**,
is an installed geomembrane liner
with only holes smaller than about 1 mm.

In the case of a geomembrane
covered with a layer of soil,
the electric survey must be performed twice:

- A **first time**
  at end of geomembrane installation,
  thereby eliminating holes larger than 1 mm.
- A **second time**
  after placement of the soil layer,
  thereby eliminating holes
  larger than the detection limit
  (e.g. 5 mm, assuming a 0.5 m thick soil layer)
  that were caused by placement of the soil layer.

The above discussion showed
how to reduce occurrence of holes
by measures taken **during construction**.

A complementary approach is
to take precautions at the **design stage**.

MEASURES AT THE DESIGN STAGE

A general characteristic of these measures
is to **associate materials**:

- Association **geomembrane/geotextile**,
  the geotextile **protecting the geomembrane**
  from adjacent materials.
- Association **geomembrane/clay**
  to form a **composite liner**.
- Association
  geomembrane/drainage layer/geomembrane
  thereby forming a **double liner**.

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GEOMEMBRANE PROTECTION

The state of practice is to use **nonwoven geotextiles** for geomembrane **protection**.

First use of a geotextile protecting a geomembrane 1971

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Nonwoven geotextiles are available with different thicknesses (related to mass per unit area).

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There is wide discrepancy between practices in different countries [*expressed in mass per unit area of geotextile*]:

- USA: 500 g/m^2 considered heavy
- Europe: more of the order of 1000 g/m^2
- In technically advanced cases 2000 g/m^2

The next slide shows the use of a very heavy nonwoven geotextile protection.

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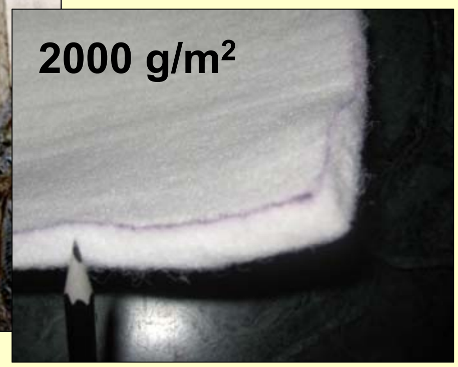
On the face of a masonry dam,
a very heavy nonwoven geotextile
was used between masonry and geomembrane.

Camposecco Dam, Italy



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MEASURES AT THE DESIGN STAGE

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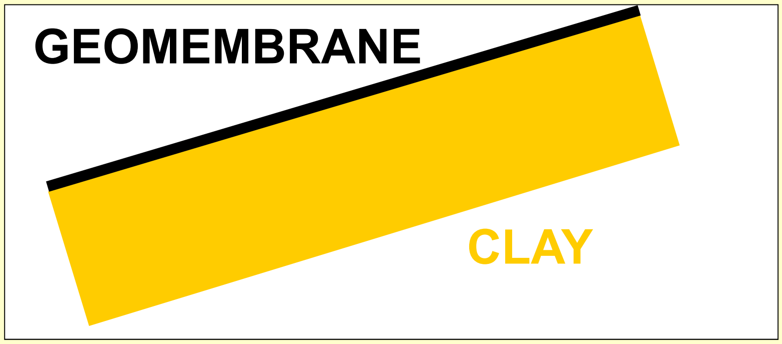
COMPOSITE LINER



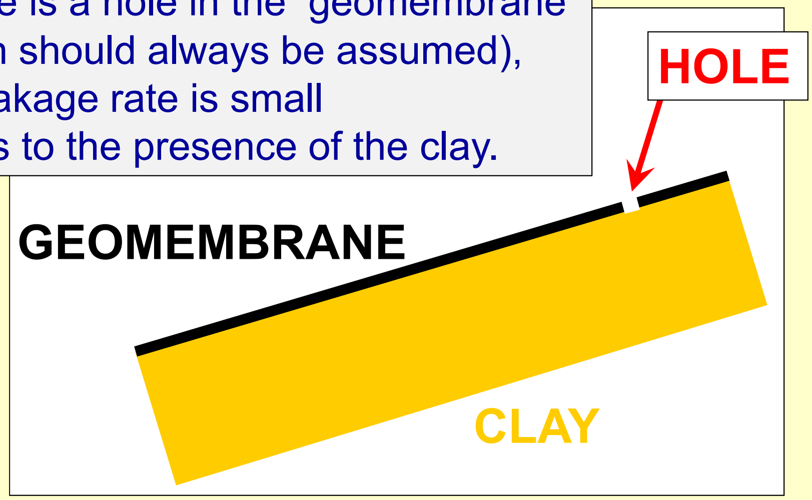
A composite liner associates two complementary materials, a geomembrane and a layer of clay (compacted clay or bentonite geocomposite).

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.

as shown by theory and tests

Why is a composite liner that good?

If there is a hole in the geomembrane (which should always be assumed), the leakage rate is small thanks to the presence of the clay.



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

This concept, proposed in 1989 by Giroud and Bonaparte, is recognized as the cornerstone of the effectiveness of composite liners.

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

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GEOMEMBRANE WRINKLES

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Wrinkles happen
with certain types of geomembranes
due to
high **coefficient of thermal expansion**
and
high **bending stiffness**.

Wrinkles must be eliminated
(through appropriate construction practice)
to ensure **intimate contact**
between the geomembrane and the clay
and fully benefit from the composite liner effect.

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Composite liners are excellent for controlling leakage, but there is a **major problem** with composite liners used in liquid containment applications.

Composite liners must be **ballasted**
to prevent the geomembrane from being **uplifted**
by liquid that could accumulate
between the two components,
geomembrane and **clay**.

From this viewpoint,
there is a big difference between
solid waste landfill and **liquid containment**.

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In the case of a **solid waste landfill**,
the situation is **ideal** for a composite liner:

- **Low liquid head** on liner (of the order of 0.1 m), therefore small leakage rate and no significant risk of accumulation of liquid between geomembrane and clay.
- **High load**, which prevents significant accumulation of liquid between geomembrane and clay and prevents geomembrane uplift (if there is any tendency for uplifting).

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In the case of a **reservoir**, in general,
the use of a composite liner is **questionable**:

- **High liquid head** on liner (e.g. 5 to 100 m), therefore high leakage rate and high risk of accumulation of liquid between geomembrane and clay.
- **Low load or zero load** on the geomembrane, which makes it easy for liquid to accumulate between geomembrane and clay.

Therefore,
if a composite liner is used for liquid containment,
there is a high risk of uplifting the geomembrane.

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Many **geotechnical engineers**
have learned about geomembranes
while designing **landfills**.

They use for liquid containment
what they have used for landfills
without recognizing fundamental differences.

Geotechnical engineering is not about
designing by cutting and pasting.

Geotechnical engineering is about thinking.

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General rule:
do not put two independent liners
directly on top of each other
(*unless they are sufficiently ballasted*).

Water (liquid and/or vapor) and **air**
will **accumulate** between the two liners.

The upper liner
(especially if it is a geomembrane)
will be **uplifted** and damaged.

This has been observed many times.

For example, here is a geomembrane,
placed directly on top of an asphaltic liner.
The geomembrane was uplifted
by water and air entrapped
between the two liners.

Photo J.P. Giroud

To sum up:

The two components of a composite liner,
the geomembrane and the clay,
must **be in intimate contact**
to effectively control leakage
and must be **maintained in intimate contact**
by appropriate loading
to prevent water from accumulating
between the two components.

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Considering that **composite liners**
are difficult to use
in liquid containment facilities
(as opposed to solid waste landfills),
another design measure
can be considered:
The use of a **double liner**.

Remember,
this was the third measure listed earlier.

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MEASURES AT THE DESIGN STAGE

A general characteristic of these measures is to **associate materials**:

- Association **geomembrane/geotextile**, the geotextile **protecting the geomembrane** from adjacent materials
- Association **geomembrane/clay** to form a **composite liner**
- Association **geomembrane/drainage layer/geomembrane** thereby forming a **double liner**

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A double liner system consists of two liners

(primary liner and secondary liner)

separated by a drainage layer acting as *leakage collection and detection layer*.

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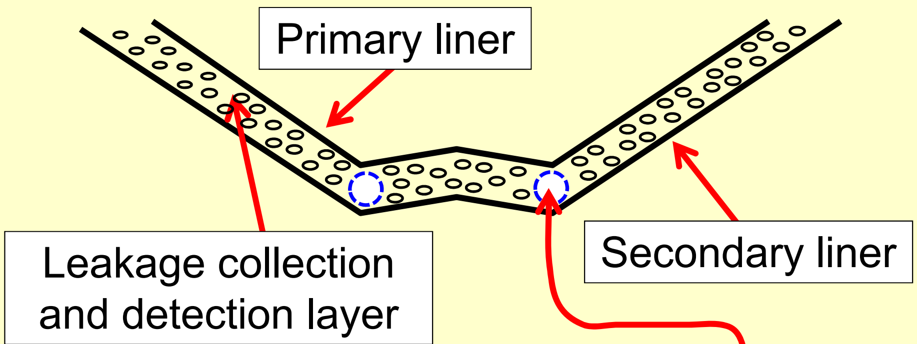
SCHEMATIC REPRESENTATION OF A DOUBLE LINER SYSTEM



The leakage collection and detection layer includes pipes that evacuate the collected leakage.

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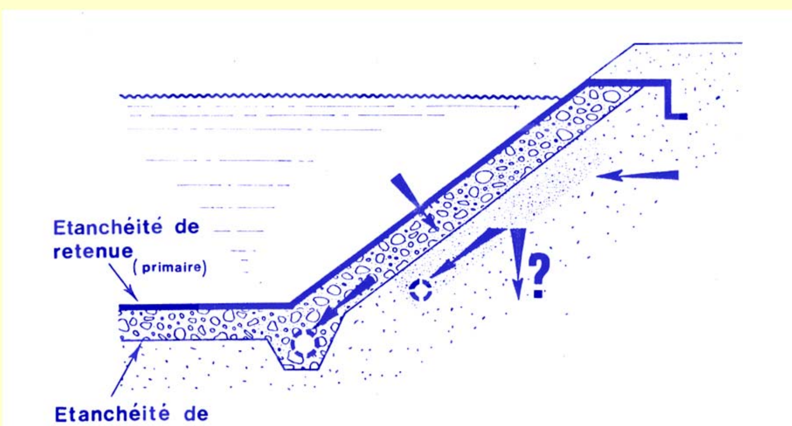
Here is the original drawing published in 1973 presenting the **double liner concept**.



(Giroud 1973)

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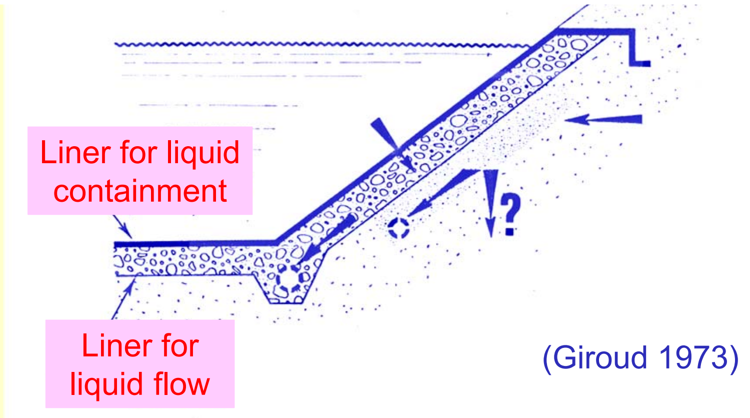
In this original drawing, the terminology was



This terminology clearly indicates that,
while the primary liner is subjected to high head,
the secondary liner is exposed to very low head.

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The essential feature of a double liner is
the very small hydraulic head
on the secondary liner,
which ensures that
there is very little leakage into the ground.

In addition,
double liners have many other advantages.

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ADVANTAGES OF DOUBLE LINERS

- Leakage through the primary liner is detected and the rate of leakage can be measured.
- Leaking liquid is collected
  - If liquid is contaminant, it can be treated,
  - If liquid is valuable, it can be pumped back into the reservoir.
- No liquid accumulation between the liners; therefore, no geomembrane uplift.

Also, it is possible
to fill the reservoir with water,
totally or partly,
to evaluate the leakage collected
by the leakage collection system,
which is faster and more accurate
than performing a ponding test.

Now a double liner case history

The first double liner constructed with two geomembranes is still in service forty years later.

Constructed in 1974

Photo J.P. Giroud

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The water **reservoir** was located on a **steep slope**.

The **steep slope**

The **reservoir**

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The slope

The geotechnical study showed that **leakage** from the reservoir could impair the **stability** of the slope.

Here is the **chemical plant**

Slope stability was essential
because there was a large **chemical plant**
at the toe of the steep slope,
50 meters lower than the reservoir.

To minimize leakage into the ground,
a **double liner system** was selected.

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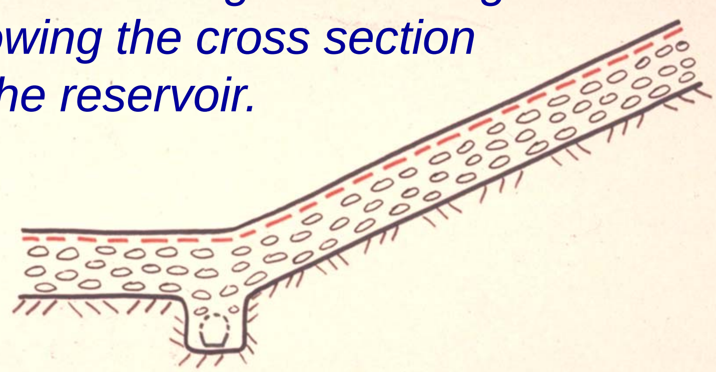
Here is the original drawing showing the cross section of the reservoir.



Original drawing by J.P. Giroud

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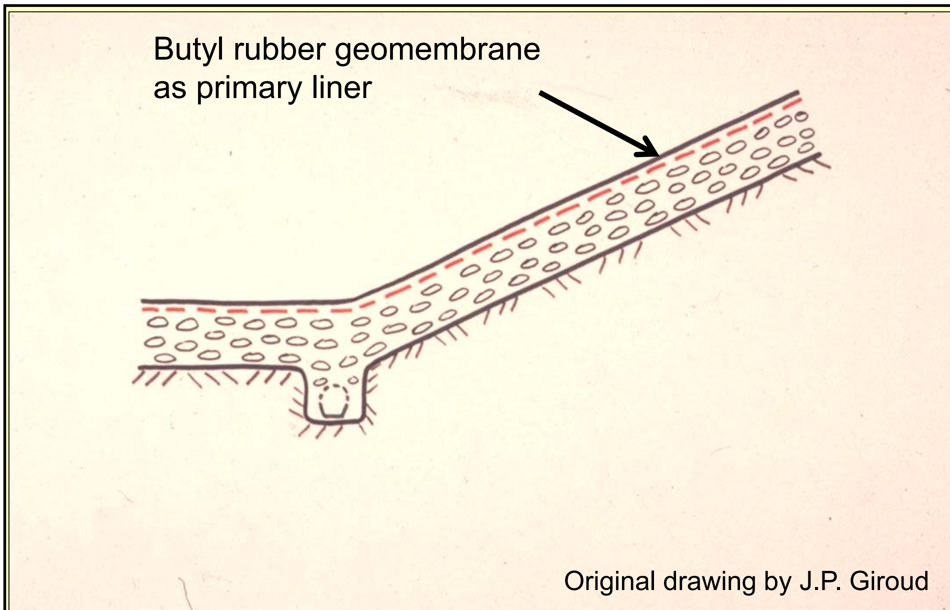

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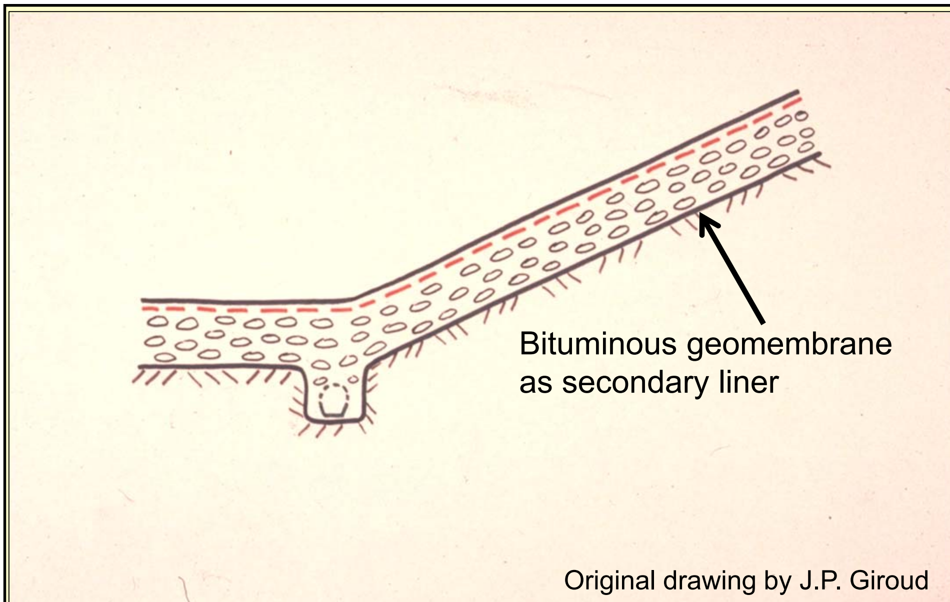
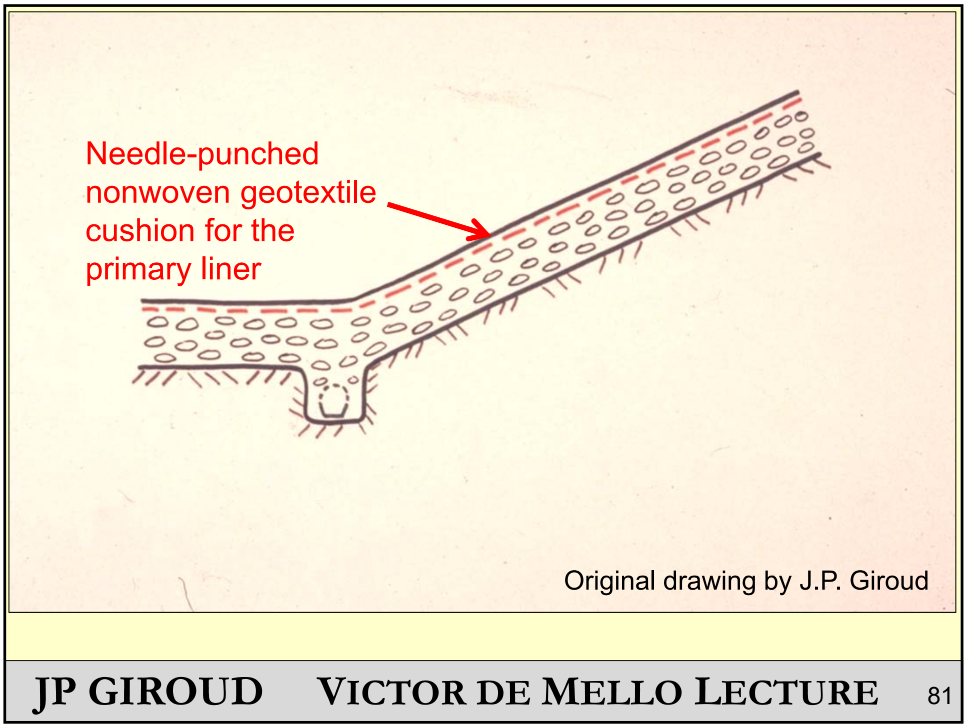
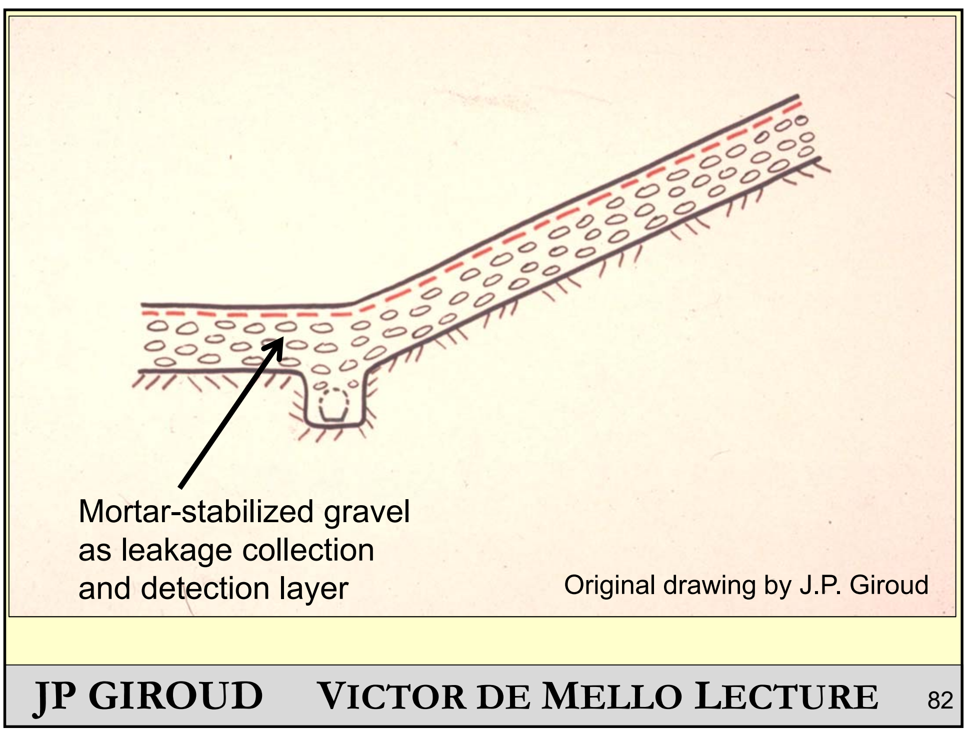
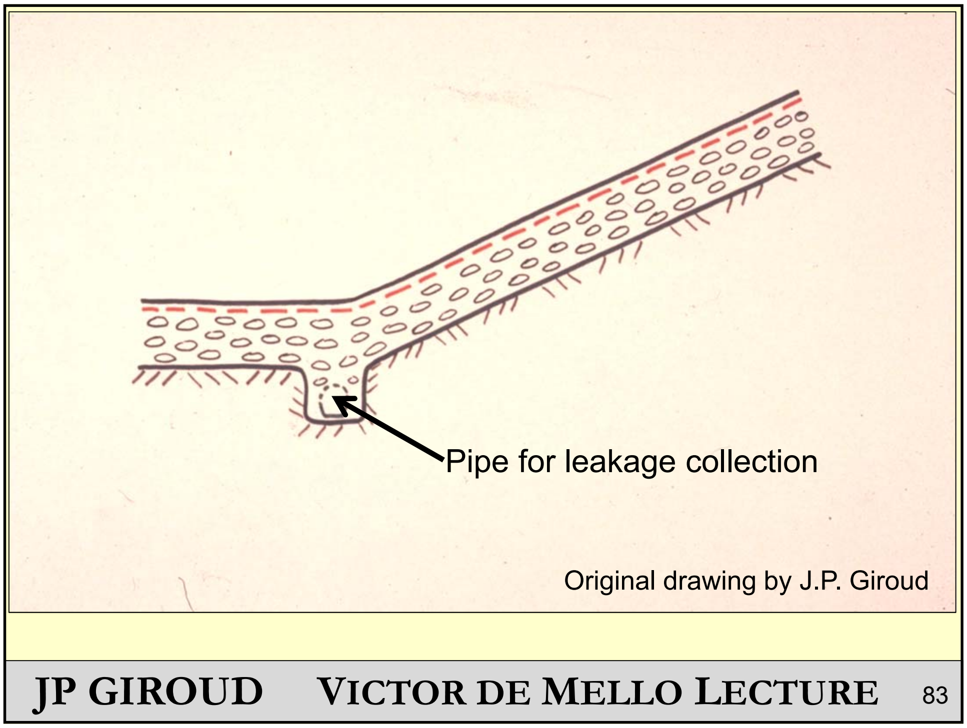
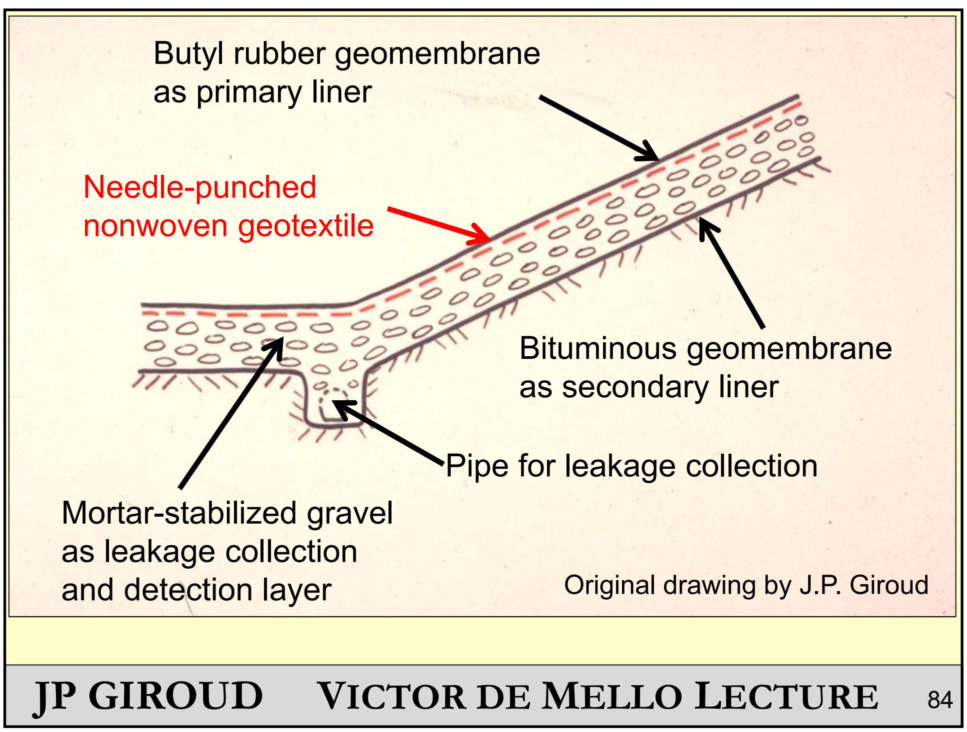


JP GIROUD VICTOR DE MELLO LECTURE 80

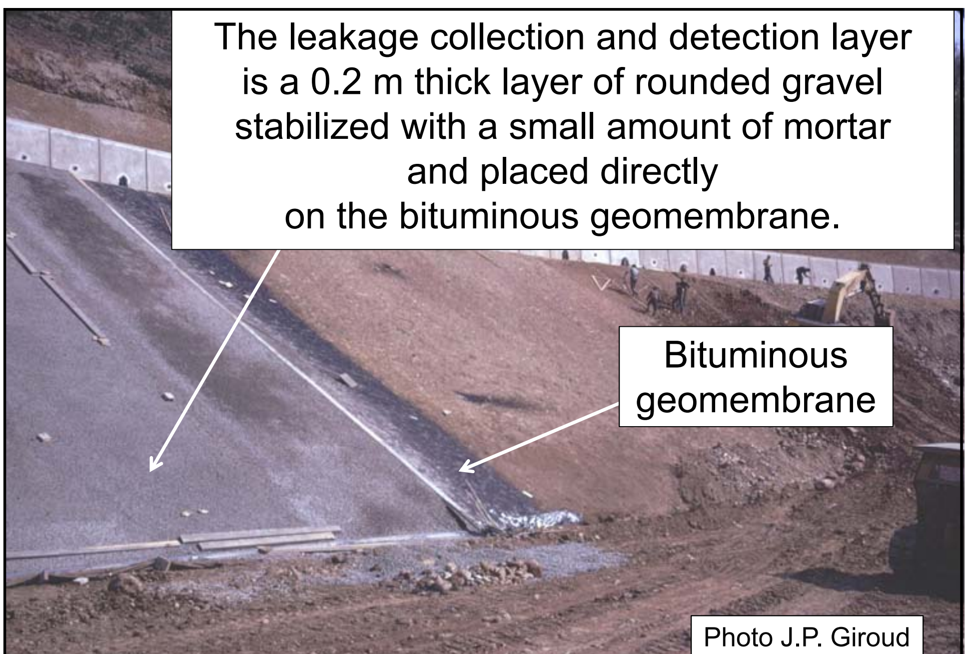

Needle-punched nonwoven geotextile cushion for the primary liner
Original drawing by J.P. Giroud
JP GIROUD VICTOR DE MELLO LECTURE 81

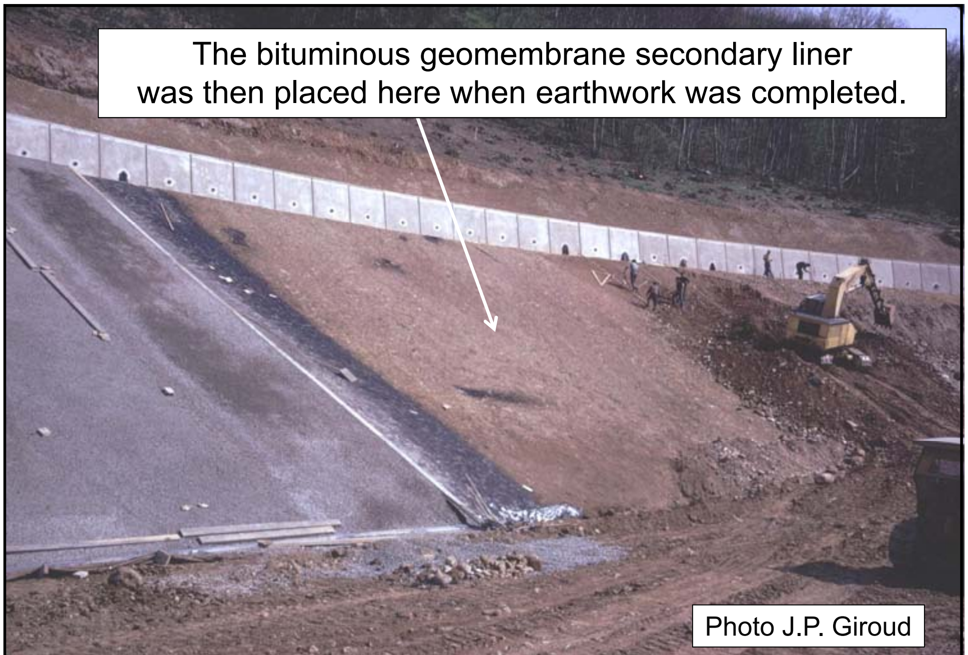

Mortar-stabilized gravel as leakage collection and detection layer
Original drawing by J.P. Giroud
JP GIROUD VICTOR DE MELLO LECTURE 82


Pipe for leakage collection
Original drawing by J.P. Giroud
JP GIROUD VICTOR DE MELLO LECTURE 83


Butyl rubber geomembrane as primary liner
Needle-punched nonwoven geotextile
Bituminous geomembrane as secondary liner
Pipe for leakage collection
Mortar-stabilized gravel as leakage collection and detection layer
Original drawing by J.P. Giroud
JP GIROUD VICTOR DE MELLO LECTURE 84

The construction phases
are presented
on the following slides.





JP GIROUD VICTOR DE MELLO LECTURE 87

JP GIROUD VICTOR DE MELLO LECTURE 88

JP GIROUD VICTOR DE MELLO LECTURE 89

The selection of the mass per unit area of the geotextile protecting the geomembrane resulted from **pressure vessel tests** where the geomembrane/geotextile system was tested on a sample of the mortar-stabilized gravel.

Such tests were not common at the time (1973).

Courtesy D. Fayoux

JP GIROUD VICTOR DE MELLO LECTURE 90


Butyl rubber geomembrane
Nonwoven geotextile
Leakage collection and detection layer
Photo J.P. Giroud
JP GIROUD VICTOR DE MELLO LECTURE 91


COMPLETED RESERVOIR
Photo J.P. Giroud
JP GIROUD VICTOR DE MELLO LECTURE 92

PERFORMANCE DURING 42 YEARS

- Only one incident happened: **leakage** was detected by the leakage collection and detection system 30 years after construction.
- The exact **location of the leak** was found thanks to air bubbles moving up to the reservoir water surface.
- The leak was small as reported by divers.
- The leak was **near the water intake structure**.

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Location of the leak in 2004

JP GIROUD VICTOR DE MELLO LECTURE 94

JP GIROUD VICTOR DE MELLO LECTURE 95

CONCLUSIONS FROM THE CASE HISTORY

- The double liner system worked.
- The performance of the geomembrane, 42 years after installation is remarkable for a type of geomembrane that is no longer supplied today because it has been superseded by more durable geomembranes.
- Careful design is rewarded by performance.

JP GIROUD VICTOR DE MELLO LECTURE 96

Regarding design, it is important to note that the reason for using a double liner was **not economical** (loss of liquid) and was **not environmental** (soil contamination).

The reason was to eliminate the risk of slope instability

Clearly **the reason was geotechnical**.

A lesson to be remembered by geotechnical engineers.

JP GIROUD VICTOR DE MELLO LECTURE 97

In this project, the detection of leakage was, in fact, a good thing.

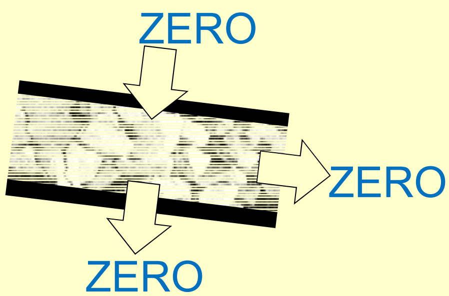
- The **leak was small** as observed by the divers.
- The fact that a small leak was detected indicates that the **secondary liner was in good condition** (at least on the path of the leaking water).

This eliminates, in this project, the classical suspicion:

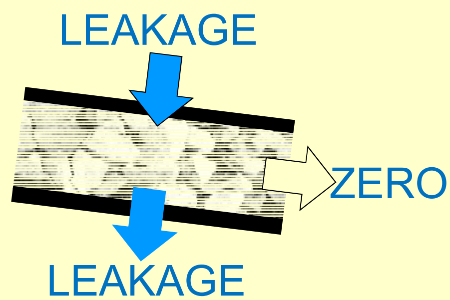
JP GIROUD VICTOR DE MELLO LECTURE 98

*There is always a **potential suspicion** with double liners:*

Does zero leakage detected means that the primary liner is **very good ?**



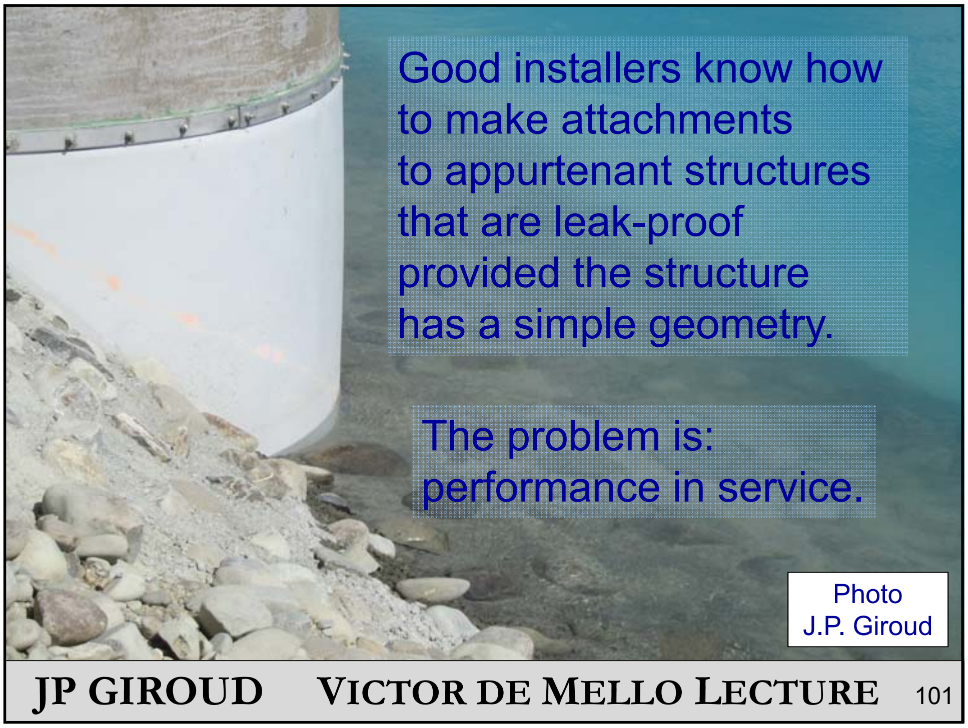
or the secondary liner is **very bad ?**

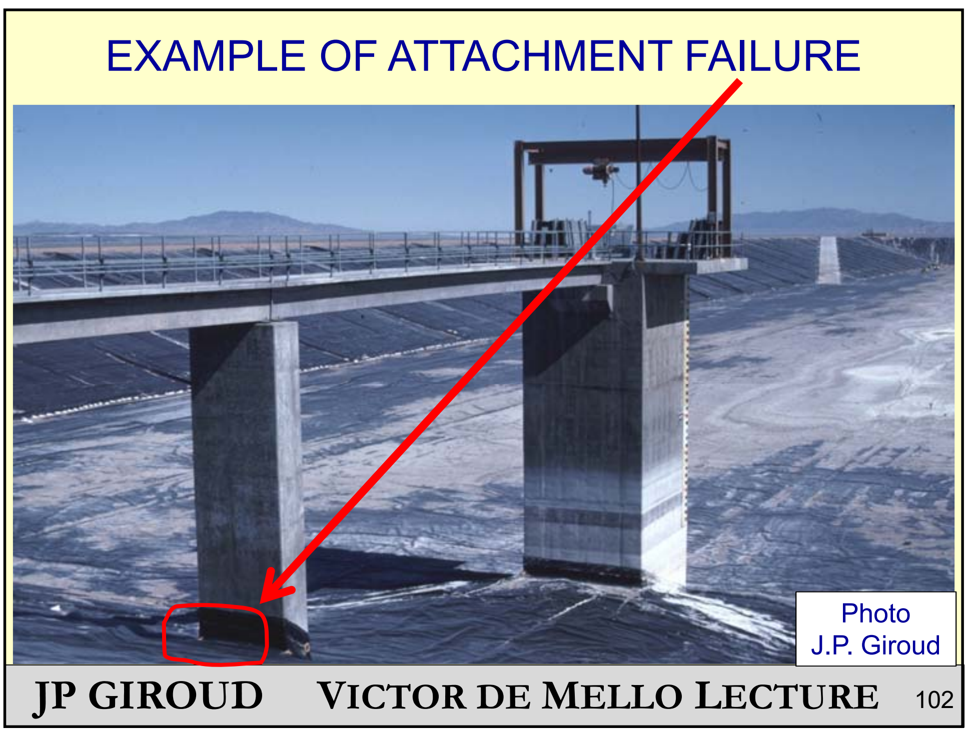


We indicated earlier that there are essentially two mechanisms of leakage associated with geomembranes:

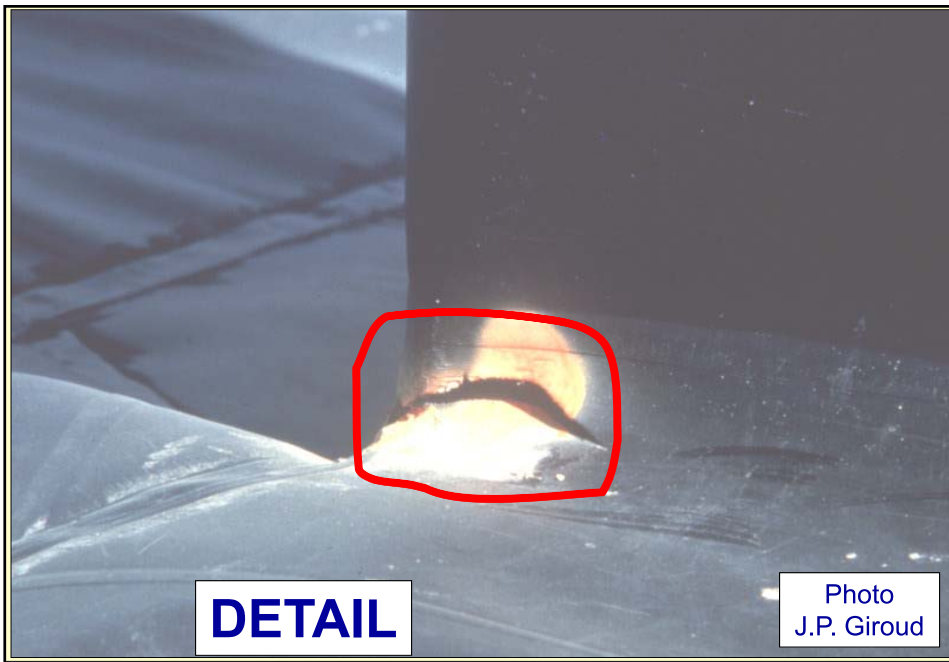
- Holes in the geomembrane, which we have addressed so far; and
- Bypass at attachments of geomembrane with appurtenant structures, which we will address now.

Let's now discuss leakage due to liquid flow at attachments to appurtenant structures.


Good installers know how
to make attachments
to appurtenant structures
that are leak-proof
provided the structure
has a simple geometry.
The problem is:
performance in service.
Photo
J.P. Giroud
JP GIROUD
VICTOR DE MELLO LECTURE
101


EXAMPLE OF ATTACHMENT FAILURE
Photo
J.P. Giroud
JP GIROUD
VICTOR DE MELLO LECTURE
102

JP GIROUD VICTOR DE MELLO LECTURE 103



JP GIROUD VICTOR DE MELLO LECTURE 104

A significant fraction
of observed **leakage**
of geomembrane-lined facilities
occurs at the **attachments**
between the geomembrane
and rigid appurtenant structures.

JP GIROUD VICTOR DE MELLO LECTURE 105

More important than
inadequate sealing
at the time of construction,
the main **cause of leakage**
at geomembrane attachments
is **geomembrane failure**
due to large **differential settlement**
between the embankment
that supports the geomembrane
and the rigid structure.

JP GIROUD VICTOR DE MELLO LECTURE 106

The two aspects to be considered when dealing with attachments :

- **Geomembrane selection,**
- **Shape of the rigid structure.**

Brief presentation of theoretical analysis

JP GIROUD VICTOR DE MELLO LECTURE 107

An analysis of stresses and strains
in a **geomembrane next to a rigid structure**
shows that the likelihood
of geomembranes **rupture**
caused by **differential settlement**
is a function of the **tension-strain curve**
of the geomembrane.

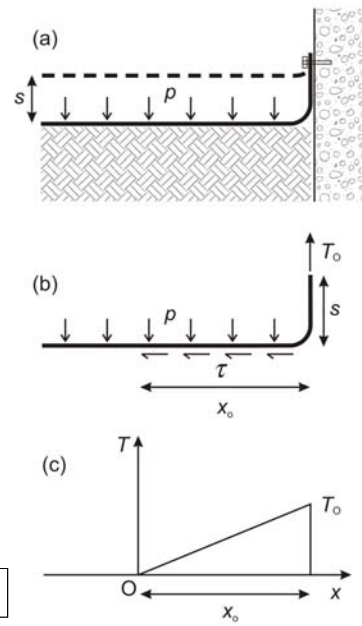
The analysis is illustrated in the next slide.

JP GIROUD VICTOR DE MELLO LECTURE 108

Settlement

Stresses on the geomembrane

Tension in the geomembrane



Giroud & Soderman 1995

JP GIROUD VICTOR DE MELLO LECTURE 109

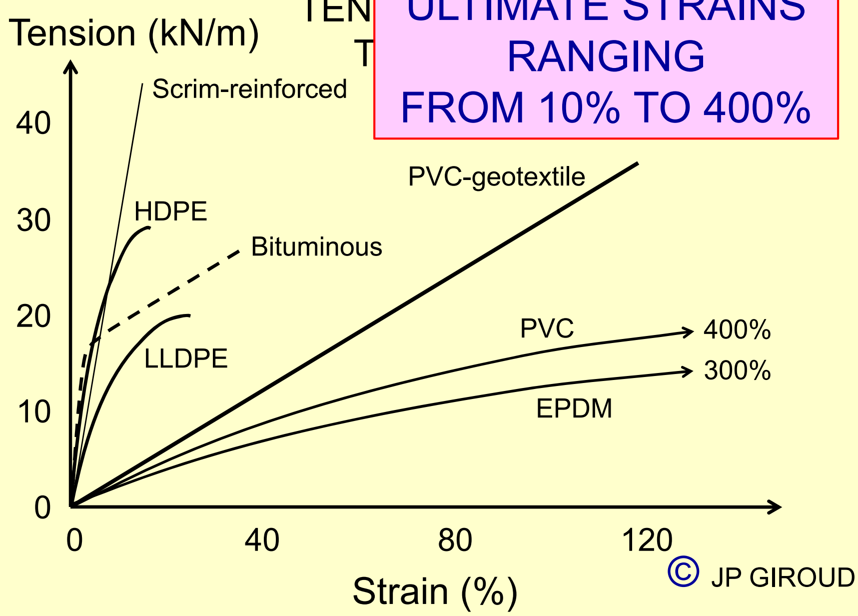
While the various available geomembranes
are **all quasi-impermeable**
and, therefore, quasi- equivalent
from the view point of impermeability,
they are **very different**
from the viewpoint of **mechanical properties**.

The following graph illustrates
the huge variety of tension-strain curves
of currently available geomembranes.

JP GIROUD VICTOR DE MELLO LECTURE 110

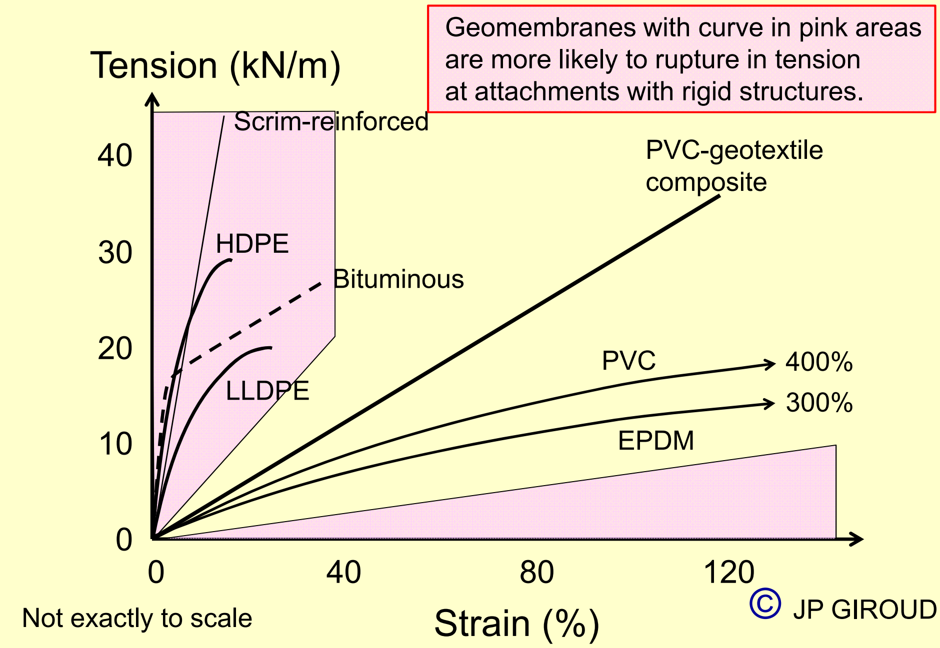
TEN
T

ULTIMATE STRAINS RANGING FROM 10% TO 400%



The analysis (not described here) shows that
the **most rigid** geomembranes
and the **most deformable** geomembranes
are **more likely to rupture**
next to an attachment
than geomembranes
with intermediate tension-strain curves.

This is illustrated in the next slide.



JP GIROUD VICTOR DE MELLO LECTURE 113

Two aspects:

- Geomembrane selection,
- **Shape of the rigid structure.**

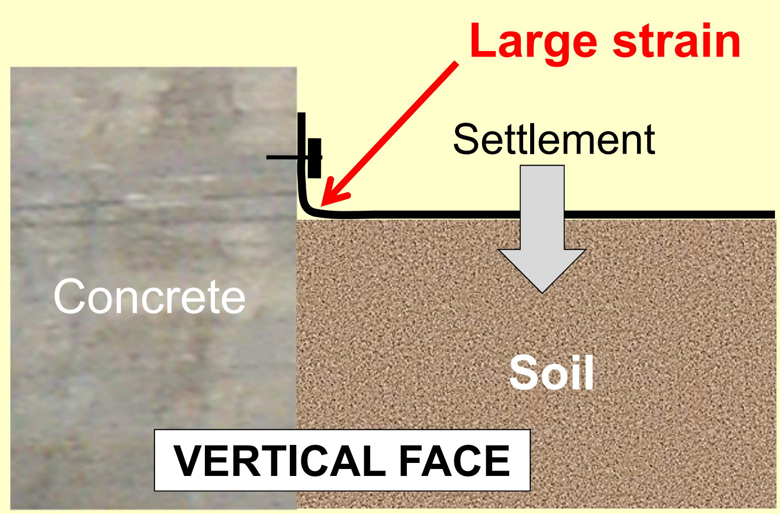
JP GIROUD VICTOR DE MELLO LECTURE 114

To **minimize differential settlement**, it is recommended to **avoid** constructing rigid structures with **vertical walls**.

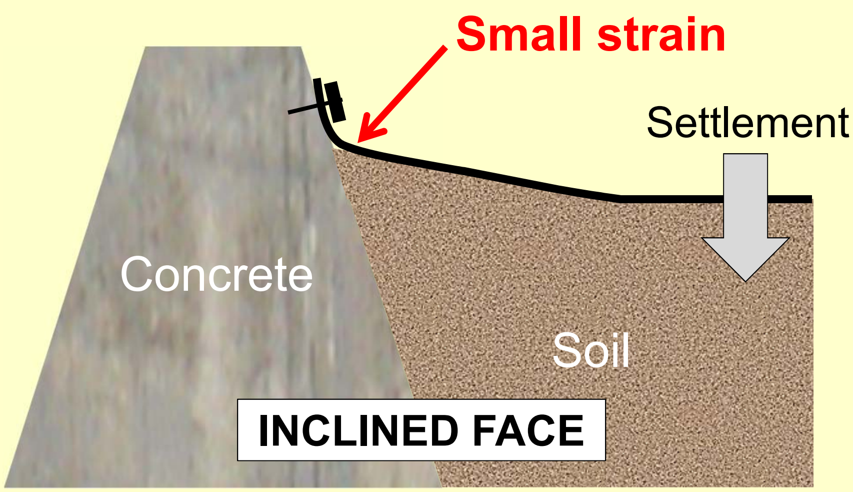
Settlement of soil is more progressive in the vicinity of structures constructed with **inclined walls**.

This is illustrated in the following slides.

INADEQUATE CONCRETE STRUCTURE



ADEQUATE CONCRETE STRUCTURE



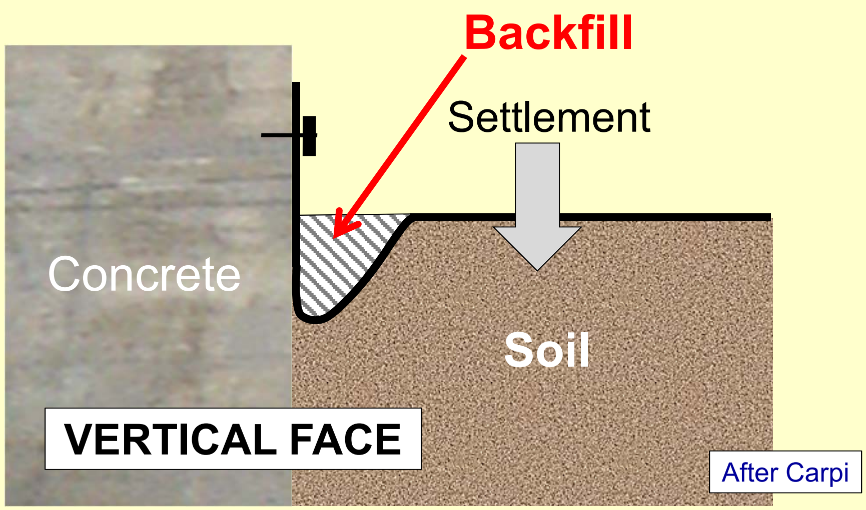
JP GIROUD VICTOR DE MELLO LECTURE 117

Even though I have repeated this recommendation for 30 years, most structures to which geomembranes are attached have vertical walls !

But there is a solution in the case of vertical walls, as shown in the next slide.

JP GIROUD VICTOR DE MELLO LECTURE 118

SOLUTION WITH VERTICAL WALLS

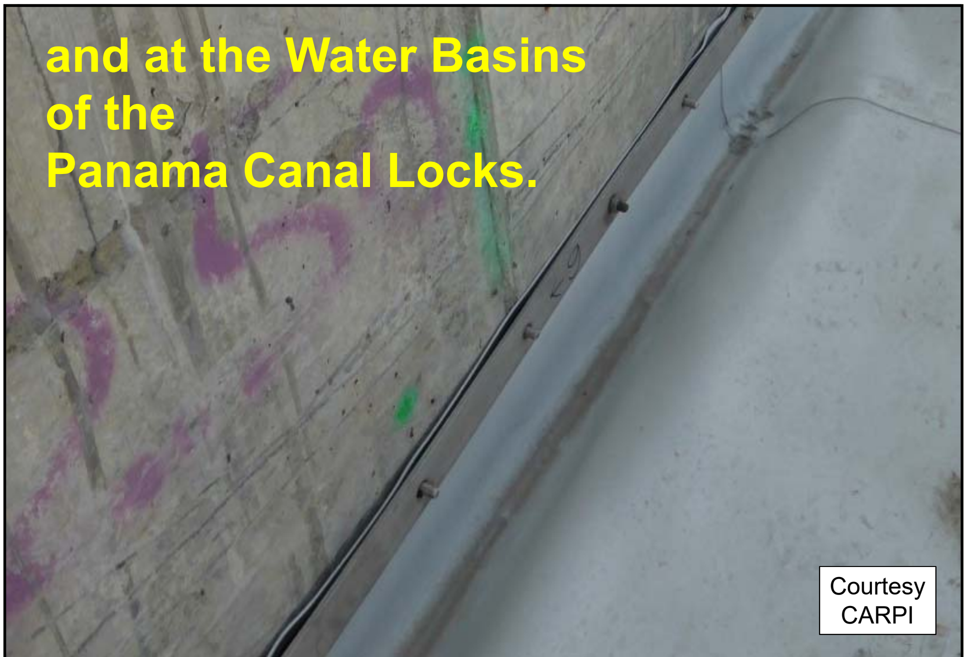


JP GIROUD VICTOR DE MELLO LECTURE 119

The solution
presented
in the preceding slide
has been used,
for example,
at the toe
of the Bovilla Dam
geomembrane liner . . .

Courtesy
CARPI

JP GIROUD VICTOR DE MELLO LECTURE 120



JP GIROUD VICTOR DE MELLO LECTURE 121

After these discussions
on how to **design and construct**
a geomembrane liner
that controls leakage
as well as possible,
let's review **monitoring results**.

JP GIROUD VICTOR DE MELLO LECTURE 122

There is significant experience
with leakage rates in the case of **landfills**,
because many landfills have a **double liner**
and, therefore, it is possible to **monitor**
the **leakage** though the primary liner.

Some typical **leakage rates for landfills**
in the United States,
will be compared to
leakage rates for reservoirs
lined with geomembranes.

JP GIROUD VICTOR DE MELLO LECTURE 123

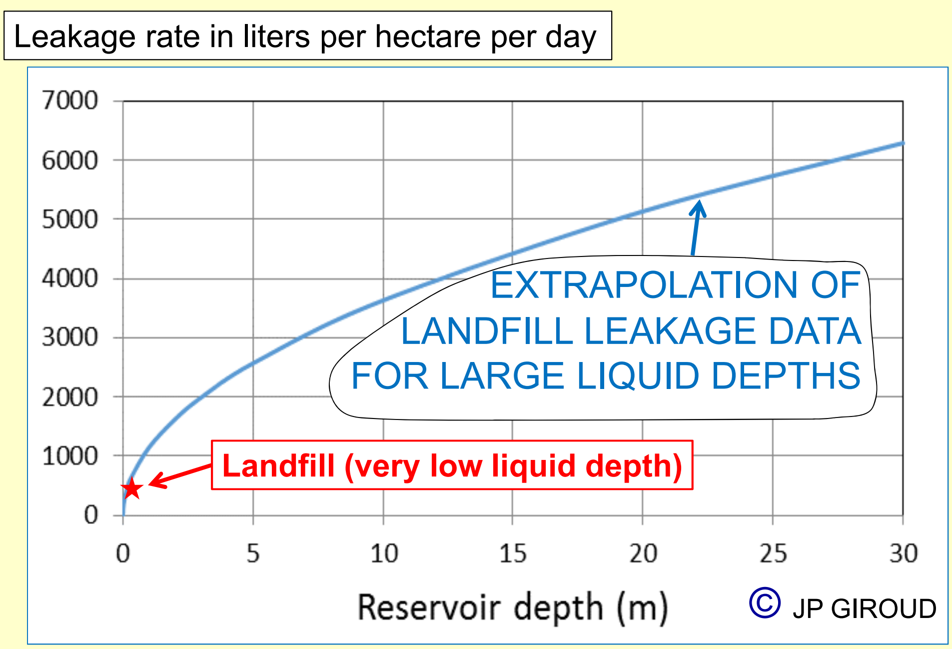
Such comparison is **potentially questionable**
because of **major differences**
between landfills and reservoirs:

- The liquid **depth in landfills is very small** compared to the liquid depth in reservoirs.
- In the US, **landfill design is strictly regulated** and, as a result, all landfills are relatively similar. In contrast there is a **wide range of designs** and **construction conditions** for reservoirs,
  - from small to large,
  - with and without appurtenant structures,
  - with more or less construction quality assurance.

JP GIROUD VICTOR DE MELLO LECTURE 124

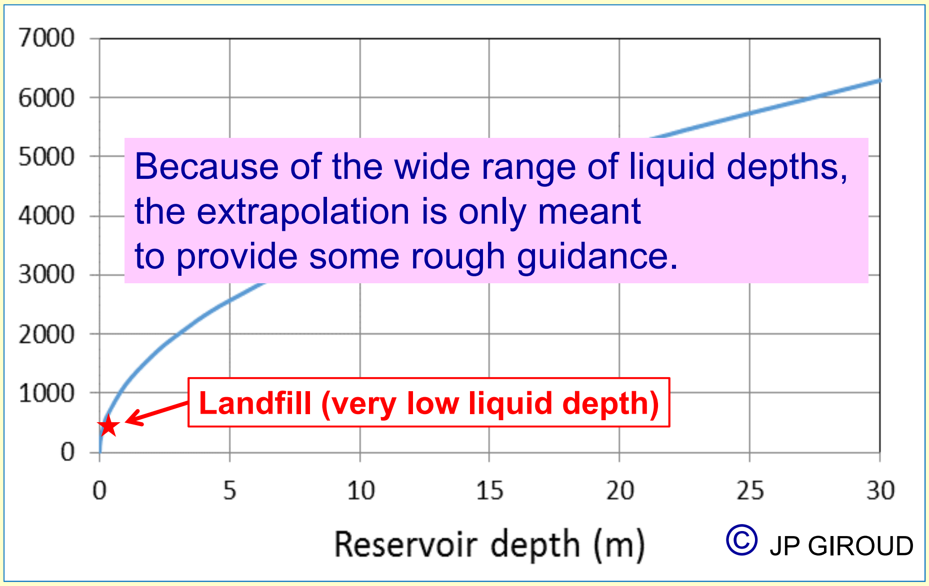
Nevertheless, I will use here a method that I have proposed to **extrapolate** landfill leakage data to geomembrane liners (*geomembrane alone, not composite liner*) exposed, in reservoirs, to hydraulic heads greater than those acting in landfills (see Peggs & Giroud 2014).

JP GIROUD VICTOR DE MELLO LECTURE 125



JP GIROUD VICTOR DE MELLO LECTURE 126

Leakage rate in liters per hectare per day



JP GIROUD VICTOR DE MELLO LECTURE 127

This table presents **typical leakage rates** from **landfills** and **reservoirs** lined with a geomembrane alone (i.e. no composite liner), as well as extrapolated leakage rates from the preceding graph.

lphd = liter per hectare per day

Type of containment	Average depth	Measured leakage	Extrapolation
	m	lphd	lphd
Landfill	0.03	50-1000	200
Reservoir	5	2000 to 100,000	3,000

The extrapolation (shown in the preceding graph) is based on a landfill leakage rate of 200 lphd for an average hydraulic head of 30 mm.

JP GIROUD VICTOR DE MELLO LECTURE 128

The main comment that can be made
is that the tabulated values
are **far from zero leakage rate**.

However, it should be noted that
10,000 liters per hectare per day
correspond only to
a water level drop of 1 mm per day.

Small, but not zero.

JP GIROUD VICTOR DE MELLO LECTURE 129

The following comments can be made
on the tabulated leakage rates:

- There is some consistency between extrapolated values and measured values.
- The range of measured leakage rates for reservoirs is very broad.
- One of the reasons for the broad range is the wide variety of working conditions.

JP GIROUD VICTOR DE MELLO LECTURE 130

For example, for a 5 m deep reservoir,
a rate of leakage of **less than 0.5 mm/day**
can be achieved with **perfect conditions**:

- Firm and smooth supporting soil
- Geotextile protection as needed
- Dry and clean working conditions
- Moderate temperature and no wind
- No interference from the general contractor
- No appurtenant structures
- Cooperation between good geomembrane installer and good quality assurance team.

Whereas a rate of leakage of 5000 lphd
(**0.5 mm/day** water level drop)
can be achieved under **perfect conditions**,
as indicated on the preceding slide,
a rate of leakage as high as 100,000 lphd
(**10 mm/day** water level drop)
or even higher
may happen in **many typical projects**
where one or more
of the "**perfect conditions**" **are not met**.

And a last question:

How effective
are geomembranes
for controlling leakage through dams?

To answer this question
it is essential to understand
that the **goal of controlling leakage**
in the case of **dams**
is not exactly the same
as the **goal of controlling leakage**
in **landfills** and **reservoirs**.

JP GIROUD VICTOR DE MELLO LECTURE 133

First, it is important to note that
the **geometry of geomembrane-lined dams**
is different from
the geometry of geomembrane-lined
landfills and reservoirs:

- In the case of **landfills and reservoirs**,
  the liquid is **completely contained** by the liner.
- In the case of **dams**, the liquid is, in great part,
  in contact with the natural ground
  and, therefore, a significant fraction of
  leakage takes place into the ground.

JP GIROUD VICTOR DE MELLO LECTURE 134

In addition to the fact that,
in the case of geomembrane-lined dams,
most leakage takes place around the liner
and **not through the liner**,

a **minimum flow rate** should be kept
in the river **downstream** of the dam,
in particular for environmental considerations.

For these two reasons,
a **zero-leakage goal is not relevant**
to geomembrane-lined dams.

JP GIROUD VICTOR DE MELLO LECTURE 135

Another consideration is important
in the case of geomembrane-lined dams.

Leakage should be controlled
to **prevent deterioration by water**
of the body of the dam.

This depends on the type
of geomembrane-lined dam,
as discussed in the following slides.

JP GIROUD VICTOR DE MELLO LECTURE 136

The relative importance of
the two leakage control goals,

- **leakage reduction**
  and
- **prevention of deterioration of the dam body**,

depends on the type of dam.

JP GIROUD VICTOR DE MELLO LECTURE 137

Three types of geomembrane-lined dams must be considered:

- **two types of new dams:**
  - Embankment dams;
  - Roller compacted concrete dams;
- **and old concrete or masonry dams rehabilitated with a geomembrane facing.**

JP GIROUD VICTOR DE MELLO LECTURE 138

Alternatively, geomembrane-lined dams can be classified as follows:

- **Embankment dams:**
  - Rockfill dams
  - Earth dams
- **Concrete dams**
  - Roller compacted concrete dams
  - Conventional concrete dams (and masonry dams)

JP GIROUD VICTOR DE MELLO LECTURE 139

The potential mechanisms of deterioration of the dam body by water can be put in two categories:

- **Progressive deterioration of the dam material** due to the presence or the flow of water and
- **Instability of the dam** due to a detrimental effect of water pressure.

The actual mechanisms depend on the type of dam.

JP GIROUD VICTOR DE MELLO LECTURE 140

In the case of **embankment dams**,
the two potential **mechanisms**
of dam body deterioration
by water
(*material deterioration and instability*)
depend on the type of dam.

Earth dams and rockfill dams are considered.

In the case of earth dams:

- The **progressive material deterioration**,
  if it occurs,
  is by **internal erosion** ("piping").
- **Instability of the dam**,
  if it occurs,
  is caused by **high pore water pressure**
  in the downstream part of the dam.

It is **not safe**
to rely only on a geomembrane liner
to prevent
internal erosion and instability
in an earth dam.

This is discussed
in the following slide.

As a **general rule**,
a dam lined with a geomembrane
should be designed in such a way
that **no catastrophic failure**
should occur in the case
of a **major breach in the geomembrane liner**,
at least during the time necessary
to empty the reservoir
and repair the geomembrane.

This applies in particular to earth dams,
as they are the most likely
to experience catastrophic failure.

To prevent failure of an embankment dam:

- It is important to **eliminate leakage through the dam**, thanks to the geomembrane, which **reduces** leakage and thanks to the drainage system that **collects** the leakage (that flows through holes in the geomembrane and leakage coming from the geomembrane periphery) and **conveys it downstream** of the dam.
- It is important to **monitor leakage**, which is possible thanks to the drainage system.
- It is important to **promptly repair** the geomembrane if leakage has been detected, which is now possible underwater.

JP GIROUD VICTOR DE MELLO LECTURE 145

In the case of **earth dams**
the **risk of internal erosion and instability**
(*both related to water in the dam body*)
is high.

In contrast:

In the case of well-designed **rockfill dams**
the **risk of internal erosion and instability**
is low.

JP GIROUD VICTOR DE MELLO LECTURE 146

After evaluating
the risk of **deterioration**
of an embankment dam body
by water,
let's evaluate
the importance of **leakage reduction**
in embankment dams.

JP GIROUD VICTOR DE MELLO LECTURE 147

In the case of embankment dams,
the relative importance of
the two leakage control goals:

- **leakage reduction**
  and
- **prevention of dam body deterioration**

depends on the type of dam.

Rockfill dams and earth dams
are considered.

JP GIROUD VICTOR DE MELLO LECTURE 148

In the case of
geomembrane-lined **rockfill dams**:

- The **permeability** of the dam materials is **high** and the **risk** of dam body deterioration by water (internal erosion and instability) is **low** (*assuming the rockfill embankment is properly designed*).
- Therefore, the **leakage reduction** goal of the lining system is the main goal.

JP GIROUD VICTOR DE MELLO LECTURE 149

In the case of **earth dams**
that are sufficiently permeable
to justify the use of a geomembrane liner
for leakage reduction,
the **risk of internal erosion and instability**
(*both related to water in the dam body*)
may be high.

Therefore, the two goals of leakage control (*leakage reduction and prevention of deterioration of the dam body*) are both important in the case of earth dams.

JP GIROUD VICTOR DE MELLO LECTURE 150

After embankment dams,
let's discuss concrete dams.

JP GIROUD VICTOR DE MELLO LECTURE 151

Remember what we said earlier:

The potential mechanisms
of deterioration of the dam body by water
can be put in two categories:

- **Progressive deterioration of the dam material**
  due to the presence or the seepage of water
  and
- **Instability of the dam**
  due to a detrimental effect of water pressure.

These mechanisms will now be reviewed for concrete dams.

JP GIROUD VICTOR DE MELLO LECTURE 152

In concrete dams, dam body deterioration can result from the following mechanisms:

- **Deterioration of the dam material**
  may be due to:
  - Alkali-aggregate reaction in the presence of **water**
  - Leaching of cement by seeping **water**
  - Freeze-thaw cycles (obviously linked to **water**)
- **Instability of the dam**
  may be caused by
  water pressure in cracks and lift joints.

JP GIROUD VICTOR DE MELLO LECTURE 153

Alkali-aggregate reaction deserves a discussion:

- In modern concrete, aggregate is generally inert.
- However, some aggregate (especially aggregate containing silica) reacts with alkali hydroxide in concrete, thereby forming a gel that swells when it absorbs **water**.
- The swelling pressure deteriorates the concrete.

JP GIROUD VICTOR DE MELLO LECTURE 154

In the case of **concrete dams**:

- For all of the reasons mentioned earlier (*alkali-aggregate reaction, leaching of cement, freeze thaw, instability due to water pressure*) the body of the dam must be kept **dry**.
- This is achieved by **associating a geomembrane and a drainage system**.
- The drainage system collects leakage water and water drained from the dam body (if any).
- And it conveys the collected water to the downstream side of the dam.

Based on the preceding discussion,
it is important to **keep the dam body dry**
in concrete dams,
in particular when there is a risk of
alkali-aggregate reaction.

This is particularly true in the case of the **rehabilitation of old concrete dams** where alkali-aggregate reaction has started a long time before rehabilitation is undertaken.

In the case of
the rehabilitation of old concrete dams,
keeping the dam body dry means:

- Not only, to drain the **water leaking** through holes in the geomembrane and the **water seeping** from the periphery of the geomembrane,
- But, also, to progressively drain **water** that has **accumulated in the dam** over the years.

JP GIROUD VICTOR DE MELLO LECTURE 157

As I said before:

Keeping the **dam body dry** is achieved by combining a **geomembrane** and a **drainage system**.

The **flow capacity** of the drainage system should be sufficient to convey *with no excessive pressure buildup* :

- water **leaking** through geomembrane holes;
- water **leaking** through the attachments of the geomembrane to the peripheral plinth;
- water **seeping** from the abutments;
- and, also, **water that progressively drains from the dam body**.

JP GIROUD VICTOR DE MELLO LECTURE 158

In **RCC dams**, the potential
for **leakage through the dam** is high, because:

- the **permeability** of the dam material is high, because roller compacted concrete typically has a low cement content;
- water tightness of the **contraction joints** is difficult to achieve; and
- the **interfaces between lifts** of compacted concrete provide preferential paths for water.

Therefore, **leakage reduction** is an essential goal of the geomembrane facing of RCC dams.

JP GIROUD VICTOR DE MELLO LECTURE 159

But, in RCC dams, there is a risk of
progressive degradation of concrete
due to leaching of cement by seeping water
and, in some cases, by alkali-aggregate reaction.

Therefore, in RCC dams, the **two goals**
of a lining system are both essential:

- **Leakage reduction**,
  and
- **Prevention of dam body deterioration**.

JP GIROUD VICTOR DE MELLO LECTURE 160

In the preceding discussions,
the association of
a drainage layer with a geomembrane
has been mentioned for collecting water
leaking through the geomembrane
in order to keep the dam body dry.

In fact,
a drainage layer behind the geomembrane
is also needed for another reason.

In all cases where
a **geomembrane** is located
at, or near, the **upstream face** of a dam,
a **drainage layer** is necessary
beneath the geomembrane
to prevent the presence of water
under the geomembrane,
which could **uplift the geomembrane**
in case of rapid drawdown
of the reservoir water.

Based on the foregoing discussions,
there is **generally a drainage system**
associated with a geomembrane
on the **upstream face of dams**,
including:

- a drainage layer under the geomembrane; and
- collector pipes leading to a gallery or an outlet.

One may expect that this system can be used to **monitor leakage** through the geomembrane liner; however the situation is complex.

JP GIROUD VICTOR DE MELLO LECTURE 163

COMMENTS ON LEAKAGE MONITORING

Water collected in the drainage system is **not only leakage** through the geomembrane or leakage at the geomembrane connections with appurtenant structures, but also (and in great part) **seepage from the abutments**.

In some dams with a drainage system composed of independent sections, careful analyses have shown that up to 90% of the collected water is, in fact, flowing from the abutments.

JP GIROUD VICTOR DE MELLO LECTURE 164

Therefore, the amount of **water collected by the drainage system of a dam cannot be interpreted as leakage** through the geomembrane,
unless there is
a **sophisticated drainage system** where waters from different sources are identified.

JP GIROUD VICTOR DE MELLO LECTURE 165

So, how can we answer the question asked 35 slides earlier:

How effective are geomembranes for controlling leakage through dams?

A tentative answer can be obtained by reviewing data from dam rehabilitation.

Examples of dam rehabilitation with a composite geomembrane/geotextile

JP GIROUD VICTOR DE MELLO LECTURE 166

Concrete exposed to water can be deteriorated by frost or alkali-aggregate reaction.

JP GIROUD VICTOR DE MELLO LECTURE 167

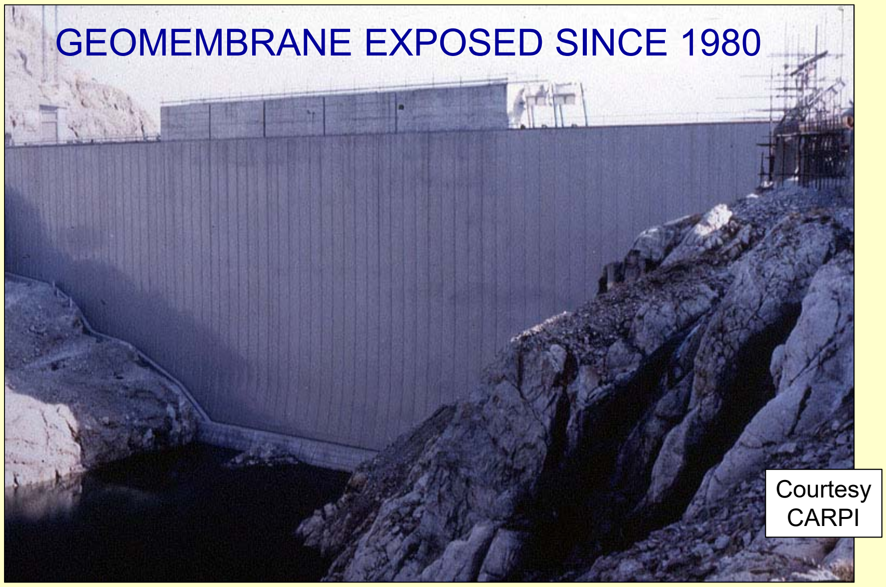
JP GIROUD VICTOR DE MELLO LECTURE 168

DAM FACE REHABILITATED USING A GEOMEMBRANE

JP GIROUD VICTOR DE MELLO LECTURE 169

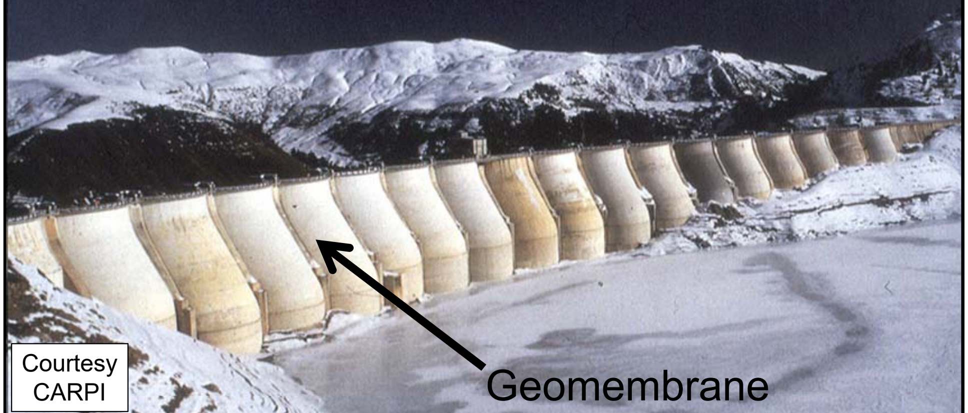
Other examples
of dam rehabilitation
are presented
in the following slides.

JP GIROUD VICTOR DE MELLO LECTURE 170



JP GIROUD **VICTOR DE MELLO LECTURE** 171

LA GIROTTE DAM, FRANCE
Constructed 1940, Repaired 1991



PVC geomembrane bonded to nonwoven

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LA GIROTTE DAM
Geomembrane placement
is possible on complex shapes.
Courtesy
CARPI
JP GIROUD
VICTOR DE MELLO LECTURE
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CONCRETE FACED ROCKFILL DAM
REHABILITATION
Courtesy
CARPI
2005 5 14
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VICTOR DE MELLO LECTURE
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Again the question: *How effective are geomembranes for controlling **leakage through dams**?*

Data from 8 dams rehabilitated using a geomembrane, shows that:

- The leakage rate **ratio** **before** and **after** rehabilitation ranges between **4 and 1200**.
- Most typical ratios are between **10 and 100**.

The wide range is probably due to different conditions at the geomembrane periphery.

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The preceding slide shows that there is a significant **reduction in leakage** when a geomembrane is used at the upstream face of a dam,

but it should be remembered that another benefit, which is often the **main benefit**, is that, thanks to the drainage system, the leakage is not seeping through the dam body, so the dam body is **dry**.

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There would be much more to say on this subject,
but it is time to conclude.

SUMMARY

- The consequences of leakage must be analyzed in order to select the proper liner system.
- Among the consequences of leakage, **geotechnical engineering consequences** (such as soil deterioration and instability) should not be forgotten.
- Engineers should be aware of the limits of the geomembrane technology to avoid writing unrealistic specifications that lead to more leakage.

SUMMARY

- Zero leakage through a single liner does not exist in the real world.
- Leakage through a single liner can be reduced by good workmanship, construction quality assurance and electric leak location survey.
- **Good workmanship** is the most important factor among the factors related to construction.
- Construction quality assurance and electric survey are not substitutes for good workmanship.

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SUMMARY

- Zero leakage through a single liner does not exist, but leakage can be controlled by associating liners, with or without drainage layers.
- There are limits to geomembrane liner technology; for example, placing two liners together requires intimate contact and appropriate loading; thus, composite liners often used in landfills are difficult to use for liquid containment.
- Double liners are effective in all applications.

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SUMMARY

- Impermeability of the liner material is necessary but not sufficient.
- **Mechanical properties** of geomembranes are important.
- There are huge differences between geomembranes regarding mechanical properties, leading to significant differences in performance.
- There are significant differences between dams on one hand and landfills and reservoirs on the other hand regarding leakage control.

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CONCLUSION

In all of the topics listed in the previous slides, geotechnical engineers can, and must, play a key role.

However, many of the failures that have occurred with geomembrane liners were linked to inadequate designs.

Too many engineers do not use all their skills when designing projects with geomembranes.

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Too many engineers have learned about geomembranes in designing landfills where the use of geomembrane liners is heavily regulated.

They believe the same designs apply to hydraulic structures such as reservoirs, dams and canals.

Technology transfer cannot be reduced to “cut and paste”.

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Here we need the Victor de Mello spirit !

Here we need engineers who think, not engineers who cut and paste.

Here we need engineers who learn and understand new materials.

Here we need the Victor de Mello vision !

JP GIROUD VICTOR DE MELLO LECTURE 184

I want to thank the committee members who appointed me for this prestigious lecture, thereby giving me an opportunity to express my gratitude to Victor de Mello.

He appointed me to create and chair the first technical committee of the ISSMFE on geotextiles and geomembranes.

Creating such a technical committee
was against the opinion
of some conservative members of the society,
but Victor knew better where the future was.

JP GIROUD VICTOR DE MELLO LECTURE 185

Thank you, President de Mello,
for your support 35 years ago.

Thank you, Victor de Mello,
for your inspiration today.

Thank you.

JP GIROUD VICTOR DE MELLO LECTURE 186

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