The 2023 Koerner Lecture

FROM ZERO LEAK
AT END OF GEOMEMBRANE INSTALLATION
TO ZERO LEAKAGE
IN SERVICE

By

J.P. GIROUD

2023 February 07

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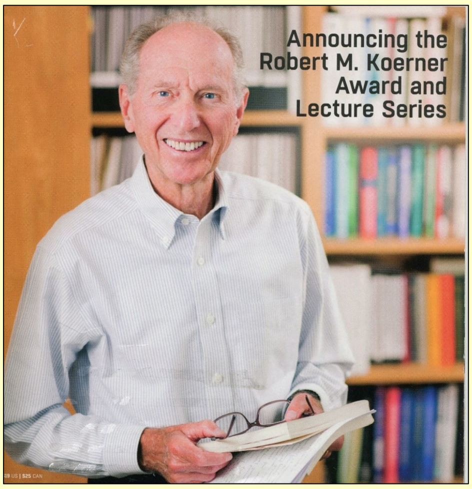

First, thank you Bob
for your immense contribution to our discipline.

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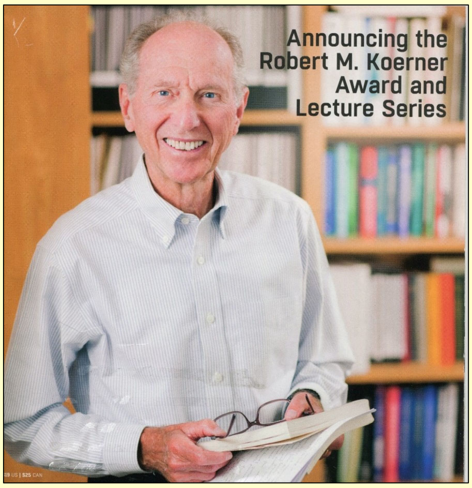

I am very honored to be a Koerner Lecturer.

George Koerner
2017

Barry Christopher
2019

Jie Han
2021

And I am very pleased to be in good company with former Koerner Lecturers.

FROM ZERO LEAK
AT END OF GEOMEMBRANE INSTALLATION
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In this lecture,
I will show that the remarkable *progress*
made in geomembrane **installation**
should inspire *progress* in **design**.

In the past five decades,
the use of **geomembranes**,
and other geosynthetics,
has been very beneficial to the environment,
in particular in **landfills**.

Geomembranes are also used successfully
for liquid containment,
which is **more challenging**
than waste containment
from the viewpoint of leakage,
in particular
because of **higher liquid pressure**.

The **first** reason of the success
of **geomembrane-lined** facilities
is the **availability** of high-quality geomembranes,
and other geosynthetics
used in association with geomembranes.

The **manufacturers** of geosynthetics
should be *congratulated* for this success,
which is the result of scientific achievements,
technological developments,
and **cooperation with users**.

In fact, as I often said, **without the manufacturers**,
there would be **no geosynthetics discipline** .

The **second** reason of this success
has been the *recognition* that is essential
for geomembranes to be **properly specified**.

The leading role played by Bob Koerner
and the Geosynthetics Research Institute
for **geomembrane specifications**
has been, and still is, essential.

Specifications are all the more important that
the success of geomembranes
has attracted **more manufacturers** worldwide.

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The **third** reason of the success
of geomembrane liners
is the *significant progress* made over five decades
in **geomembrane installation techniques**.

The geomembrane **installers**
should be congratulated,
as well as the **suppliers** of seaming equipment.

IAGI,
the International Association of Geosynthetics Installers,
through its **certification program**
has promoted *professionalism*
in the installation of geomembranes.

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The **fourth** reason of this success was the development of **construction quality assurance**.

It is pertinent, today, to mention
the *development of construction quality assurance*,
because both Bob Koerner and myself
were *early contributors* to this essential development.

While I created the first
construction quality assurance team with Joe Fluet
(*who, incidentally, was the first president of NAGS, the ancestor of IGS-North America*),
Bob codified the practice of CQA for the USEPA.

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Last, but not least, a major progress has been
the use of **electrical leak location** surveys,
thanks to **innovators**
and **providers** of electrical leak location services.

Today, thanks to electrical leak location,
quasi-zero leak at end of installation
is a possibility . . .

. . . provided that the **design**
of containment facilities is adequate
and **construction quality assurance**
of installation is strictly enforced.

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Clearly,
geomembranes have been very successful, and
so is the geosynthetics industry.

This success is in great part
the result of
the remarkable **spirit of cooperation**,
in our industry.

I always tell my friends, who work in other industries,
that it has been a blessing, for me,
to work for decades
in an industry where professionals cooperate so well.

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The International Geosynthetics Society (IGS),
its chapter, IGS-North America, and
the Geosynthetic Materials Association (GMA)
certainly promote the **spirit of cooperation**
that is the hallmark of our discipline.

Cooperation goes with exchange of information,
hence the great contribution of our publications,
Geosynthetics, *Geotextiles and Geomembranes*,
Geosynthetics International, *and conferences*.

After these comments on our industry,
let's focus on the subject of the lecture.

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FROM ZERO LEAK
AT END OF GEOMEMBRANE INSTALLATION
TO ZERO LEAKAGE
IN SERVICE

First,
the role of **design engineers** is essential.

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Design engineers should understand that
electrical leak location is essential
to ensure that the containment facility they design
will perform as intended.

Design engineers should cooperate
with electrical leak location providers
to ensure that the *designed liner configuration*
is such that electrical leak location
can be **successfully implemented**.

Design engineers should write
leakage **specifications that can be met**.

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Zero leakage is a legitimate target.
However, "**zero**" is **impossible to measure**.

Since zero leakage cannot be measured,
it is **pointless to specify zero leakage**.

Therefore, a rationally established,
acceptable leakage rate should be specified.

But, even if the specified *acceptable leakage rate*
is **reasonable**, this **is not sufficient**
if design and installation are inadequate.

This is illustrated by the following case history.

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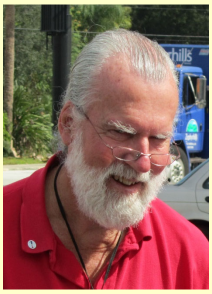
CASE HISTORY OF PONDING TEST

This case history is from my dear friend Ian Peggs
who has done so much for the quality
of installed geomembranes.



For a water reservoir,
the specified maximum leakage rate was
a water surface drop of **6 mm in 14 days**.

6 mm in 14 days is close to
an **acceptable leakage rate** of 500 gallons/acre/day,
which is typical for reservoirs.
Therefore, it was a **reasonable specification**.

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CASE HISTORY OF PONDING TEST

Compared to the specified **6 mm** in 14 days,
here are **ponding test results**:

- After liner installation: **66 mm**.
- **First** sequence of reservoir emptying, visual inspection, repair of holes: **22 mm**.
- **Second** sequence: **112 mm**.
- **Third** sequence: **23 mm**.
- **Fourth** sequence: **130 mm**.

All were above the specified 6 mm.

The leakage increased despite repairs !

CASE HISTORY OF PONDING TEST

The leakage increased for at least two reasons:

- **Damage** to the geomembrane
  by the team performing **inspections** and **repairs**;
  and
- **Stresses** induced in the geomembrane
  by *repeated displacements* of the geomembrane
  due to **cycles of emptying and filling**
  the reservoir
  to perform **inspections** and **repairs**.

CASE HISTORY OF PONDING TEST

Many holes were found
at the *geomembrane attachments*
to **appurtenant structures**
having a **complex geometry**.

Finally, a **new geomembrane liner**
was installed by a **new installer**.

And the specified leakage rate
was met at the **first ponding test**.

A **good installer** made a difference !

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Here are the lessons learned from this case history:

- Visual inspection **does not find** all holes.
- Activities of **workers**
  can damage the geomembrane.
- 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.
- Frequent reservoir **drawdowns**, that are not necessary for operations, **should be avoided**.

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The foregoing discussion of leakage evaluation by ponding tests, showed the **importance of design**.

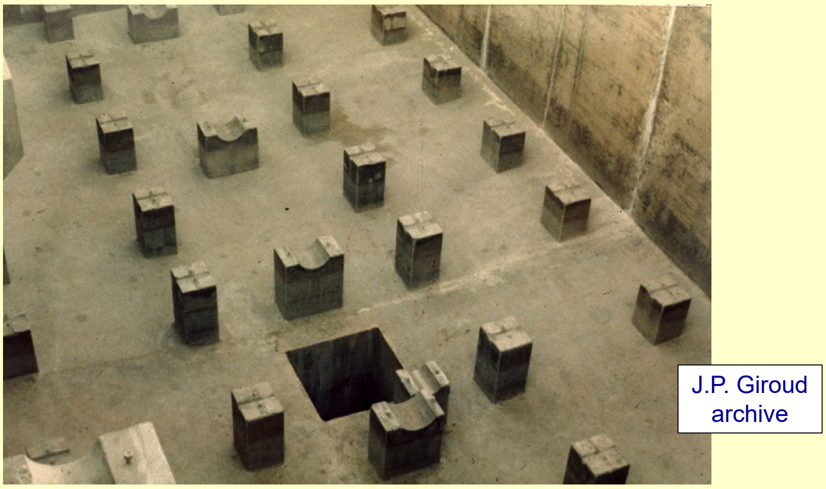
The following slides will illustrate the **importance of design** using case histories of **geomembrane failures**, which **generated leakage**.

In all cases, the **main cause of failure** was a **design error**.

The next **CASE HISTORY** shows that

THE DESIGN OF A CONTAINMENT FACILITY SHOULD BE SUCH THAT A GEOMEMBRANE LINER CAN BE INSTALLED WITHOUT EXCESSIVE DIFFICULTY.

How is it possible to install a geomembrane in this concrete reservoir with so many pedestals ?



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The answer is: with great difficulty.

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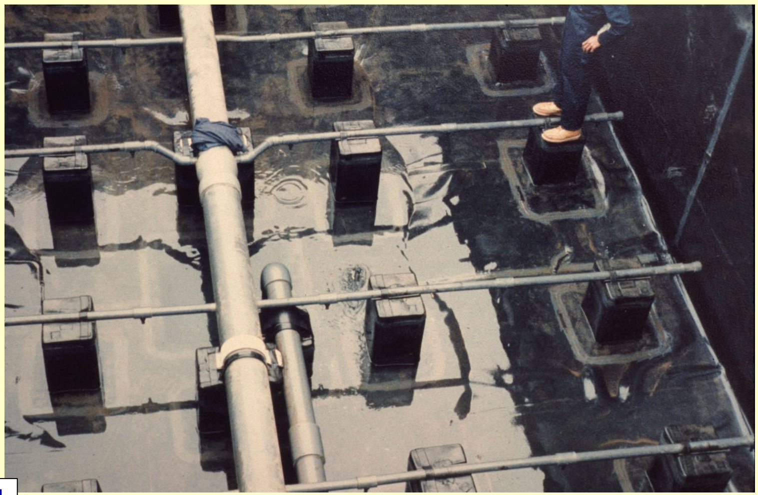
And the installed geomembrane . . .



J.P. Giroud archive

. . . had more than 100 holes.

The following comments can be made on this case history :

- The configuration of the reservoir was such that it was **inevitable to have many holes** in the geomembrane.
- Clearly, the cause of the holes was the **inadequate design**.

This case was from the 1980s in North America,
but the problem still exists, as shown in the next slide.

Here is an example, also in North America, but in 2022.

An acrobatic performance was needed to install the geomembrane.

Photo courtesy of R.S. Thiel

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Excessive leakage occurred in this reservoir and **extensive rework** was necessary.

Photo courtesy of R.S. Thiel

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Thanks to the rework, the leakage was significantly reduced, but not reduced to zero,

even though the installer was excellent and an expert field engineer was present.

Photo courtesy of R.S. Thiel

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Clearly, we saw examples of **designs** that make it **impossible**, *even for the best installers*, to achieve the goal of **zero leak** at end of installation.

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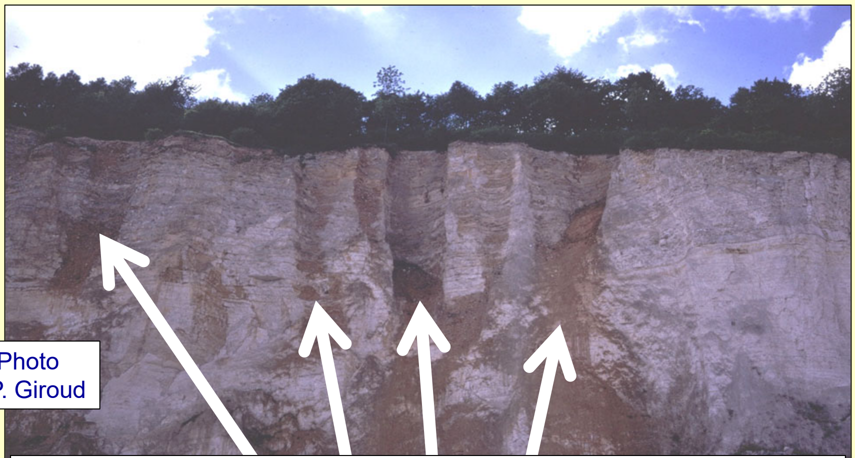
The next **CASE HISTORY** shows that

BOTH
DESIGN DETAILS
AND
CONCEPTUAL DESIGN
ARE IMPORTANT.

CASE HISTORY

- A water reservoir was constructed on a **thin layer** of natural soil overlying a **karstic formation** (*which is limestone with cavities*).
- The reservoir was close to an **abandoned quarry**, which provided an opportunity to **see the karstic formation**.

Here is the quarry
showing a cross section of the karstic formation.



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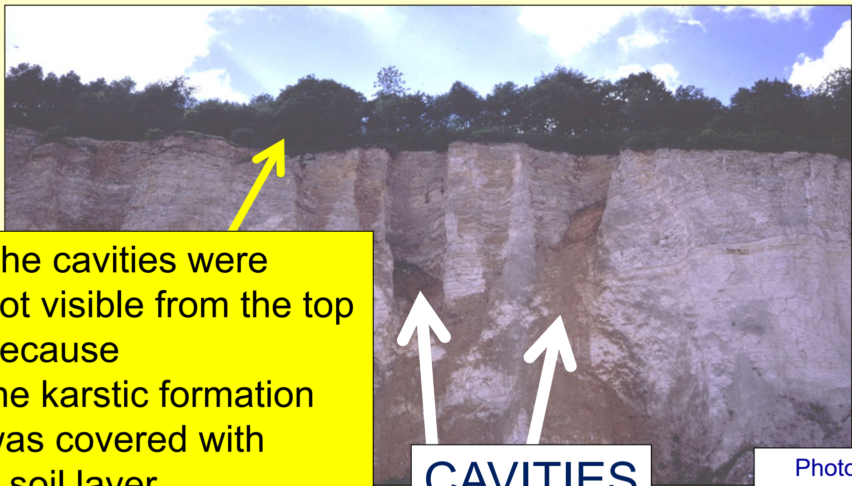
The reservoir was located on the top,
behind the trees, not far from the quarry.



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The quarry was observed only **when the failure** of the reservoir **was investigated**.

At the design stage,
there was **no geological study**
and the quarry was not observed.

Since the soil layer was hiding the cavities,
the designer of the reservoir
ignored the situation shown on
the **following cross section**.

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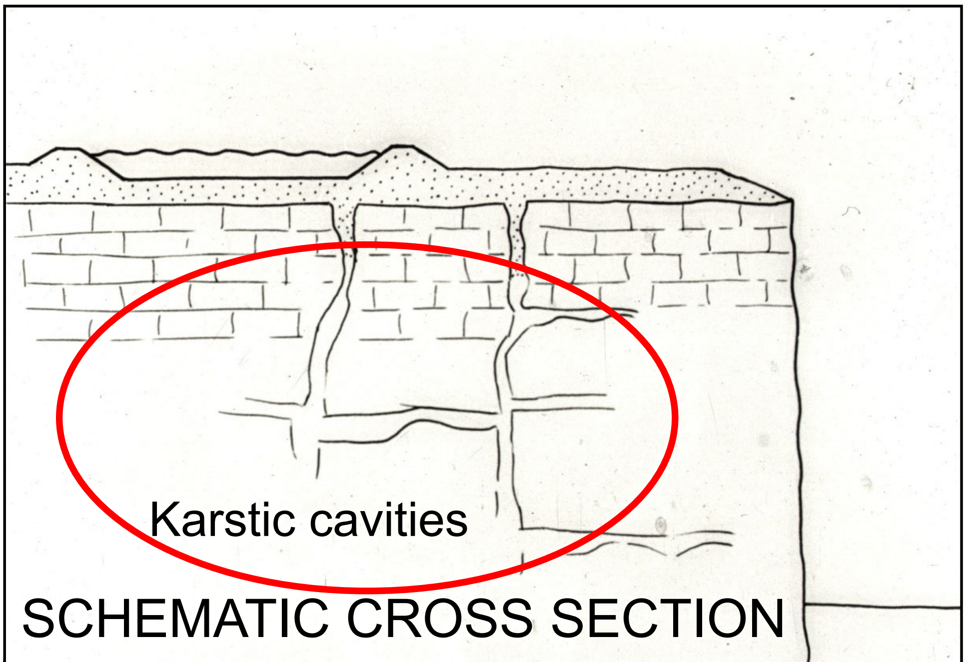

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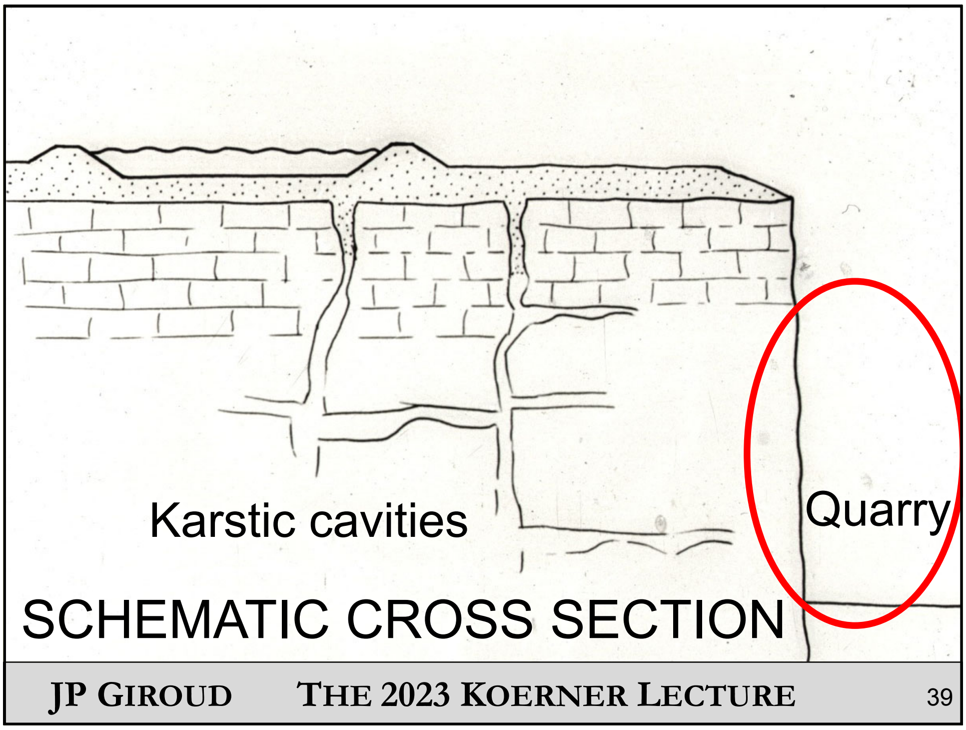
Karstic cavities
Quarry
SCHEMATIC CROSS SECTION
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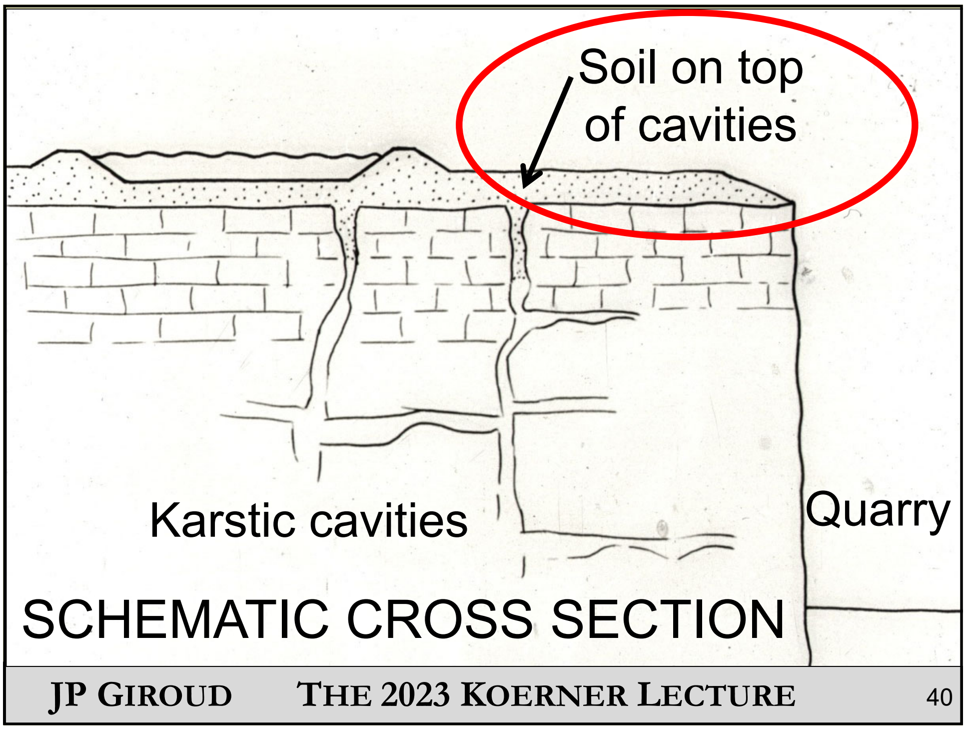
Soil on top
of cavities
Karstic cavities
Quarry
SCHEMATIC CROSS SECTION
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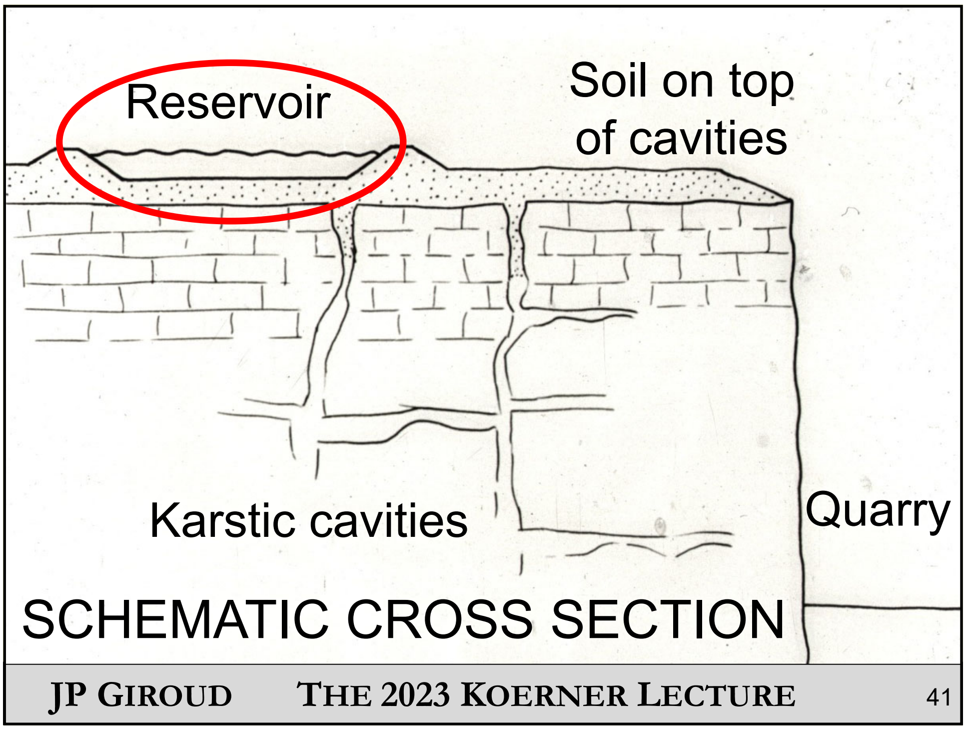

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THE RESERVOIR LINER SYSTEM

- The reservoir was lined with a single geomembrane.
- The geomembrane was underlain by a gravel leakage collection and detection layer **placed directly on the soil**.

> We will see that
> a **leakage collection and detection layer, placed directly on the soil, cannot prevent leakage into the ground.**

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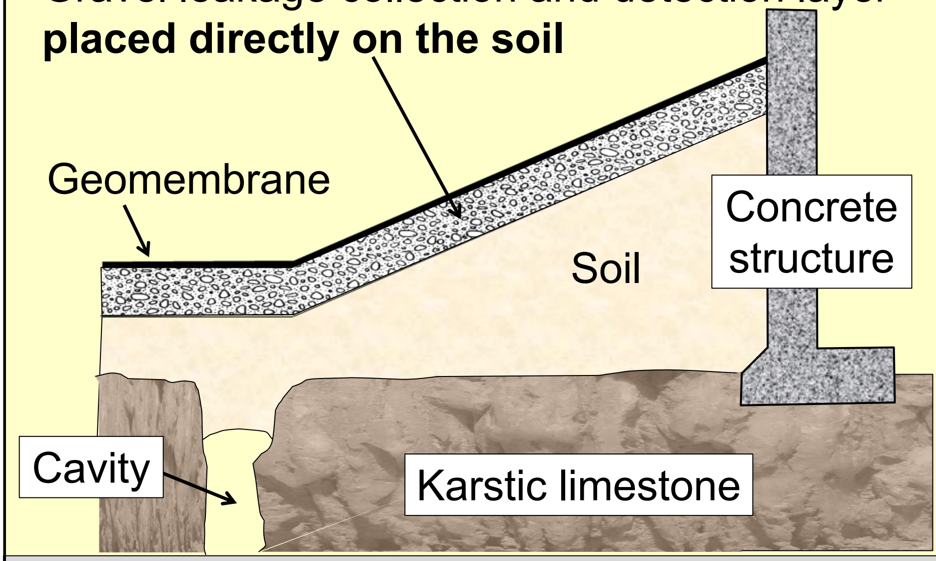
HERE WE SEE:
Gravel leakage collection and detection layer **placed directly on the soil**



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DESCRIPTION OF FAILURE

During the **first filling** of the reservoir,
leakage occurred
at a **defective connection**
between the geomembrane
and the **concrete structure**.

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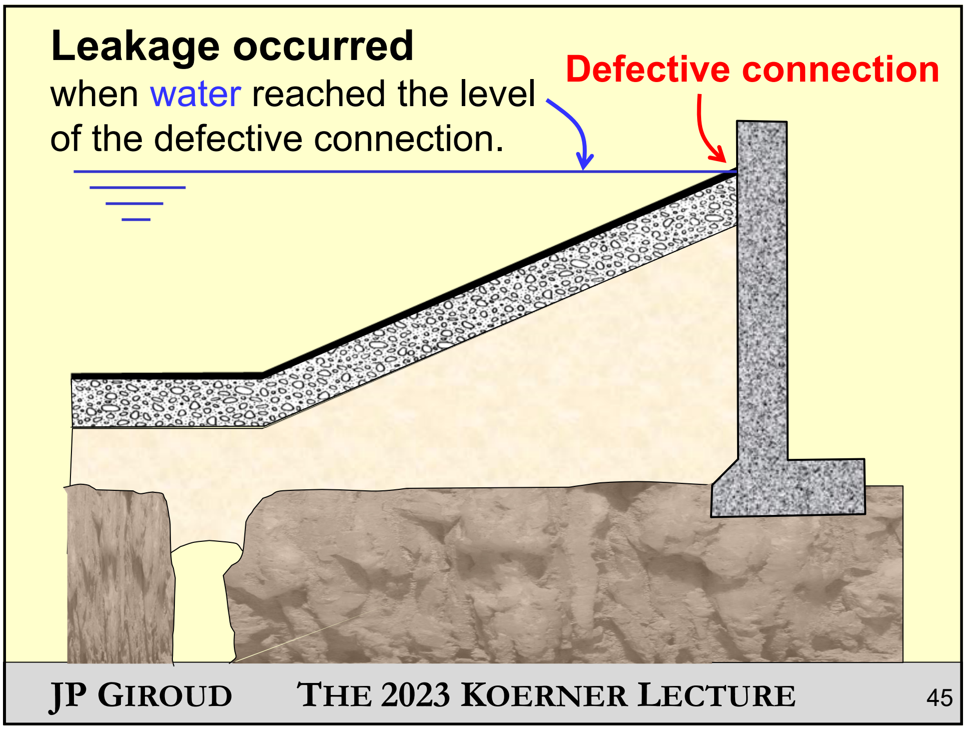
Leakage occurred
when water reached the level
of the defective connection.
Defective connection
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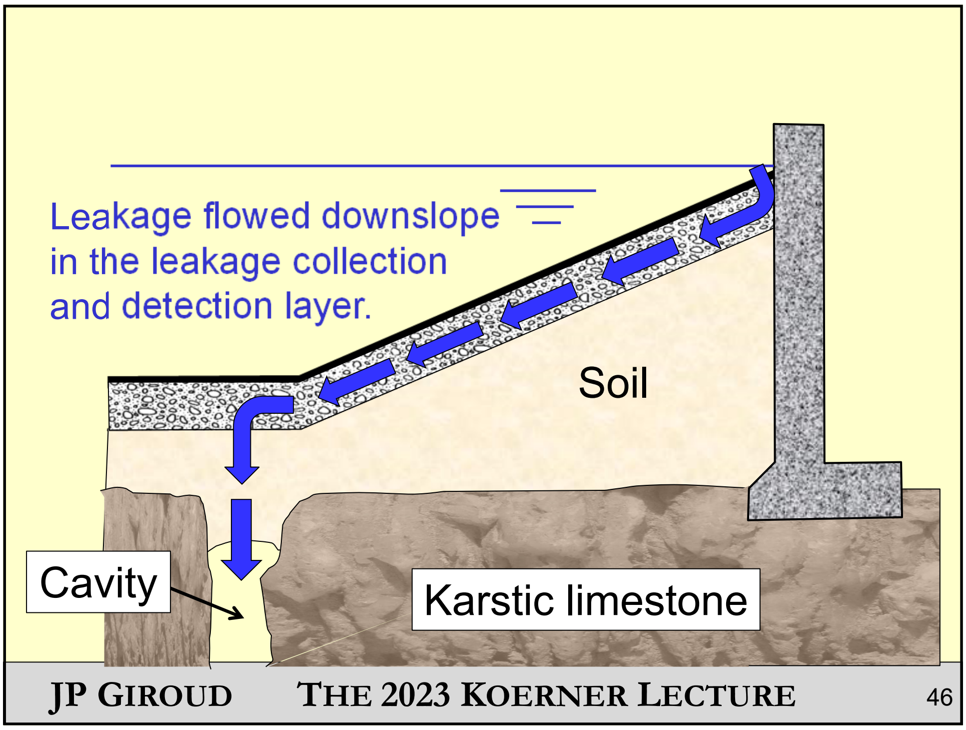
Leakage flowed downslope
in the leakage collection
and detection layer.
Soil
Cavity
Karstic limestone
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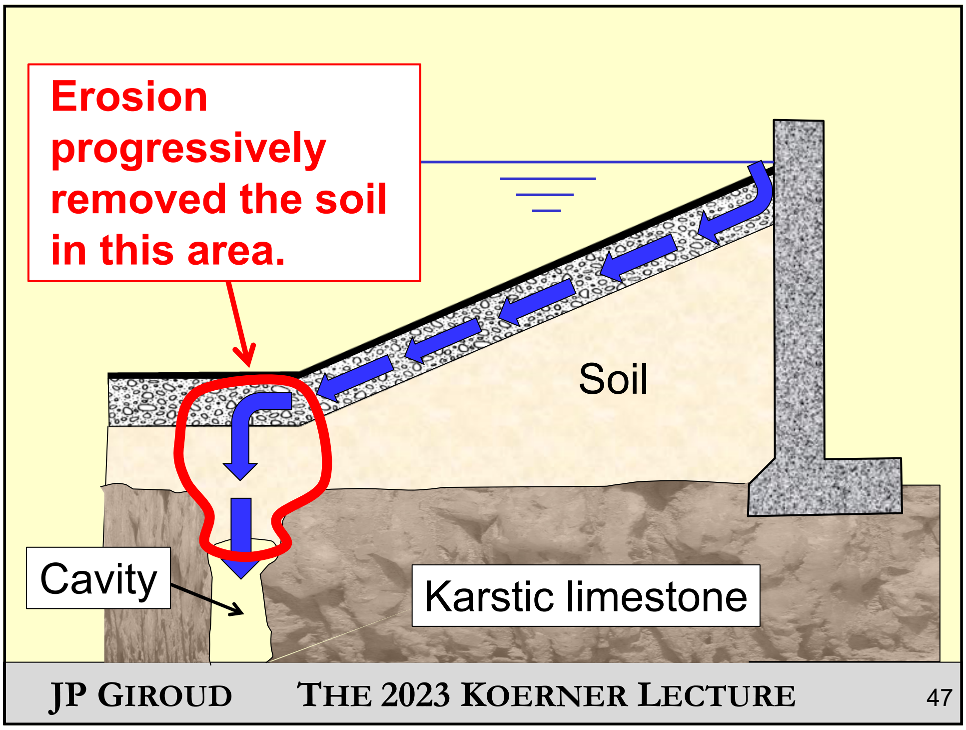
Erosion progressively removed the soil in this area.
Soil
Cavity
Karstic limestone
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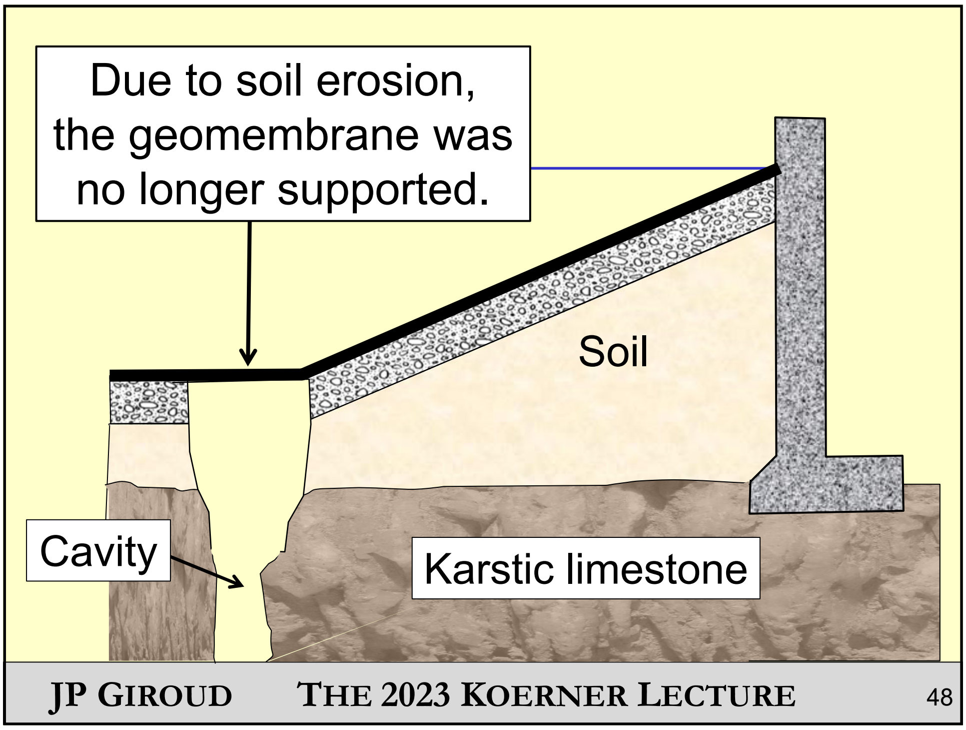
Due to soil erosion, the geomembrane was no longer supported.
Soil
Cavity
Karstic limestone
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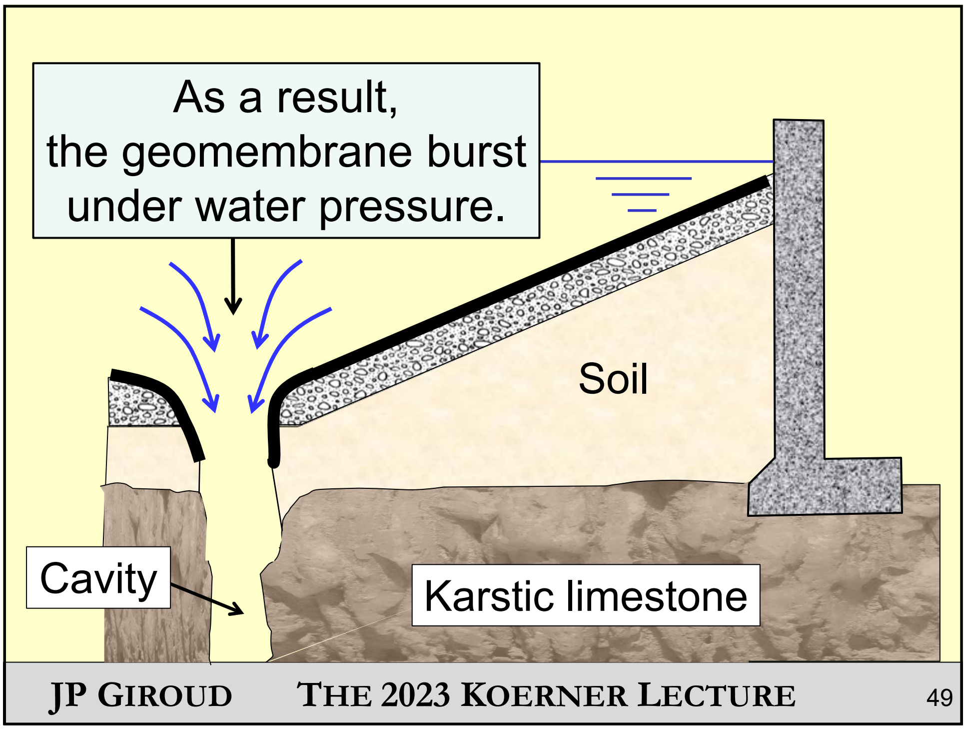
As a result,
the geomembrane burst
under water pressure.
Soil
Cavity
Karstic limestone
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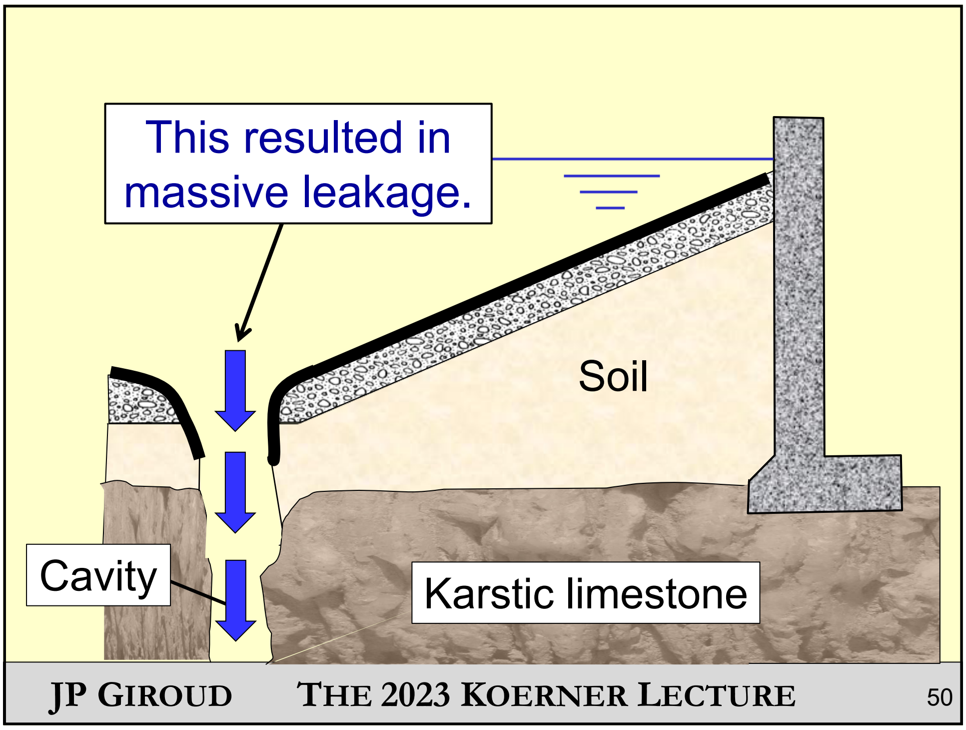
This resulted in
massive leakage.
Soil
Cavity
Karstic limestone
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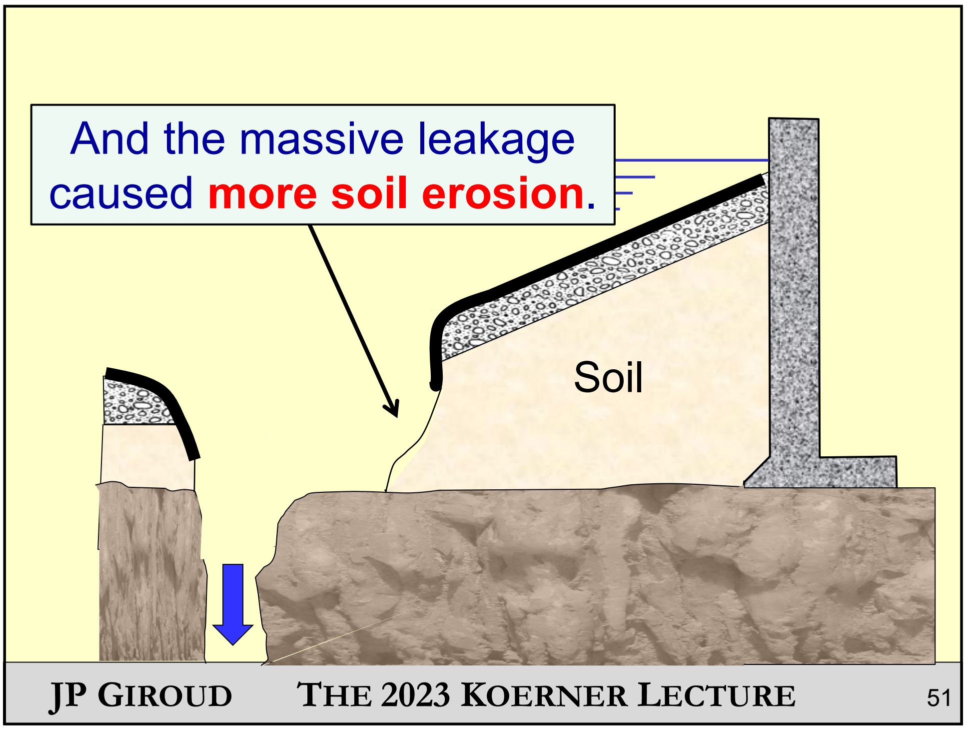
And the massive leakage caused more soil erosion.
Soil
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Here is a view of the reservoir after failure.
Several cubic meters of embankment disappeared into the cavity.
FAILURE AREA
Photo
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Here is a view of the failure area showing
the concrete structure to which the geomembrane was attached.

Photo
J.P. Giroud

The defective connection was here.

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Clearly, the **failure** mechanism
was **initiated by leakage** into the ground.

Therefore, the solution was to achieve
a *leakage rate into the ground* as
close as possible to "**zero leakage**".

I suggested a **double liner**,
but this was new (in 1972),
and the owner preferred to rely
on **reinforcement** to bridge the cavities.

The adopted repair solution included
both **double liner** and **reinforcement**.

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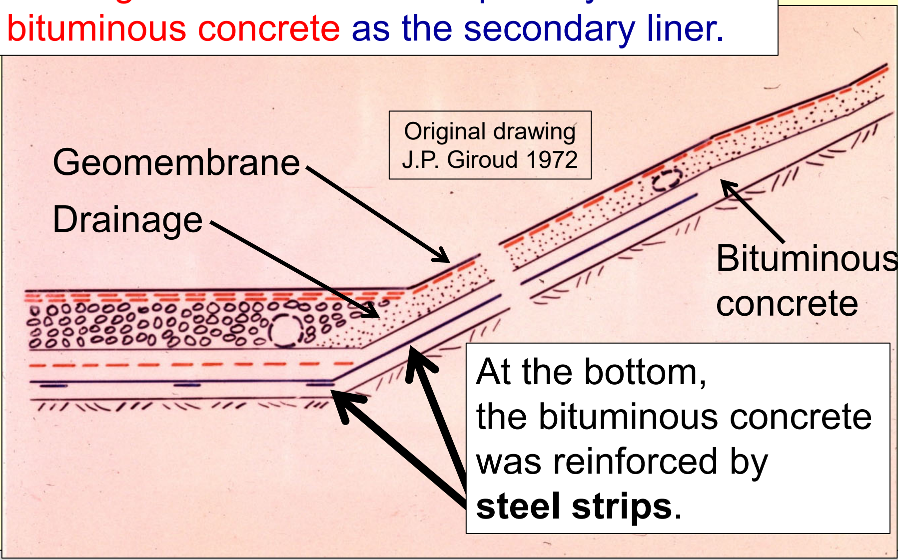
The repair consisted in a **double liner** with a geomembrane as the primary liner and bituminous concrete as the secondary liner.



At the bottom, the bituminous concrete was reinforced by **steel strips**.

The **secondary liner**, by **preventing water** collected by the leakage collection and detection layer **from infiltrating into the ground**,

was the best way to prevent the *same failure mechanism* from occurring again.

This was **the first double liner**, but not with two geomembranes (1972).

CONSTRUCTION OF THE REMEDIATION

Photo
J.P. Giroud

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STEEL STRIPS USED TO REINFORCE THE BOTTOM

Photo
J.P. Giroud

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COMMENTS ON THE REMEDIATION

- The key aspect of the repair was the **double liner**, because it addressed the **cause of the problem**, which was *leakage into the ground*.
- The **reinforcement** only addressed the ***consequence*** *of leakage*, which was erosion of geomembrane support. (*It was used to reassure the owner who did not trust the double liner*.)

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CONCLUSION OF THE CASE HISTORY

- A **detail** (poor connection) **triggered the failure.**
- But the **cause of the failure** was a **conceptual design flaw:** the leakage collection and detection layer **without a secondary liner.**
- And there was **negligence** regarding **soil investigation.**

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With an appropriate **design**,
a **detail**, the **defective connection**
between the geomembrane
and the concrete structure,
should have triggered **only a loss of water**,
not a major failure.

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The lessons learned from this case:

- With a geomembrane liner,
  a leak is always possible.
- Therefore,
  the **potential consequences of a leak**
  should **always** be **identified** and **evaluated**.
- If the consequences are unacceptable,
  the **design should be improved**.

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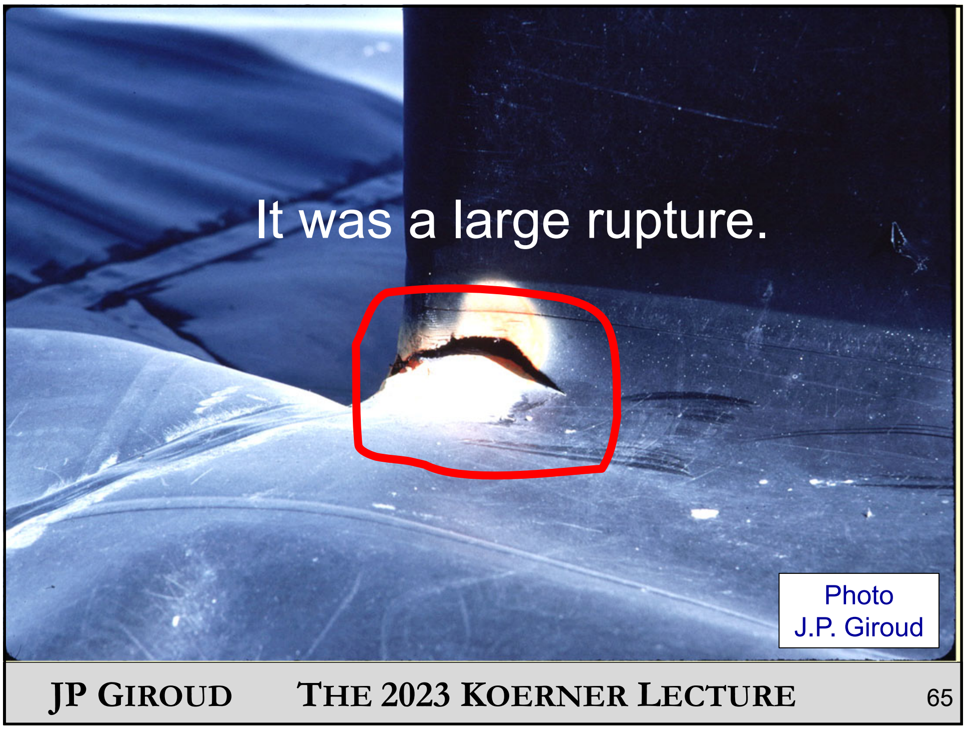
The next **CASE HISTORY** is
another example of
connection with concrete structure,
which illustrates:

ZERO LEAK AT INSTALLATION
BUT
SIGNIFICANT LEAK
AFTER GEOMEMBRANE DISPLACEMENT

The geomembrane failure occurred here,
at the toe of a concrete structure.

Photo
J.P. Giroud

From zero leak at end of geomembrane
installation to zero leakage in service


It was a large rupture.
Photo
J.P. Giroud
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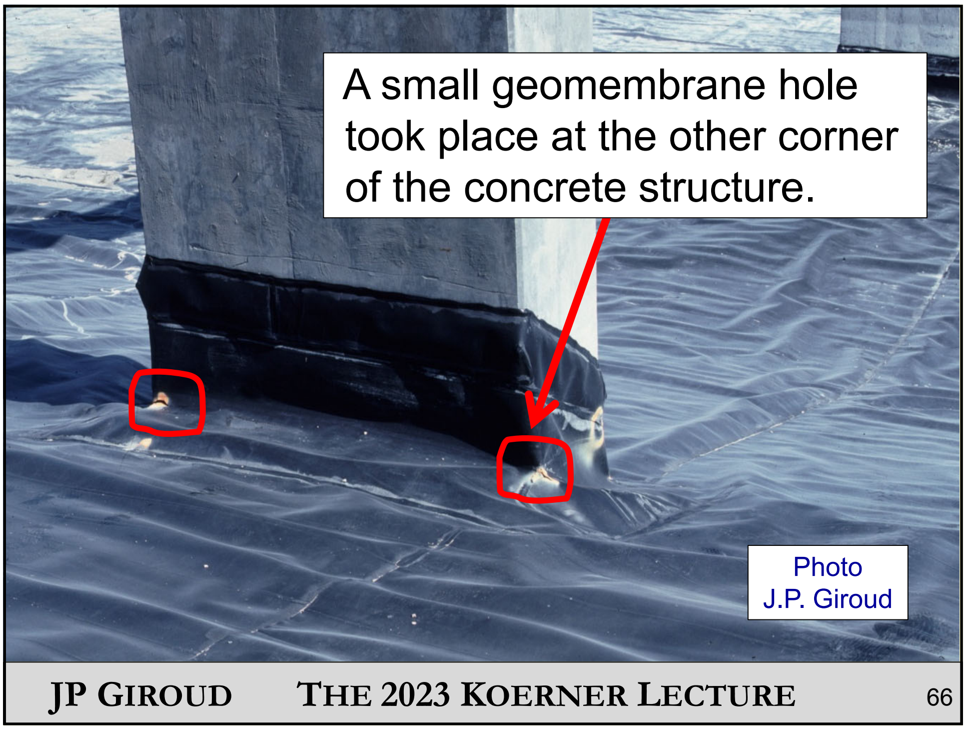
A small geomembrane hole took place at the other corner of the concrete structure.
Photo
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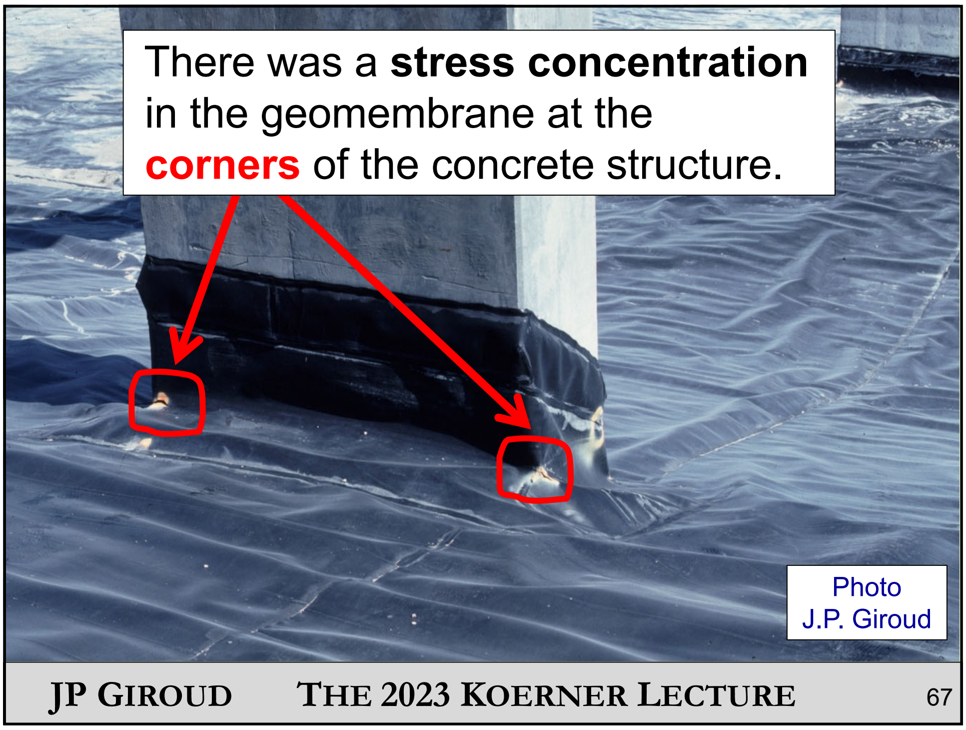
There was a **stress concentration** in the geomembrane at the **corners** of the concrete structure.
Photo J.P. Giroud
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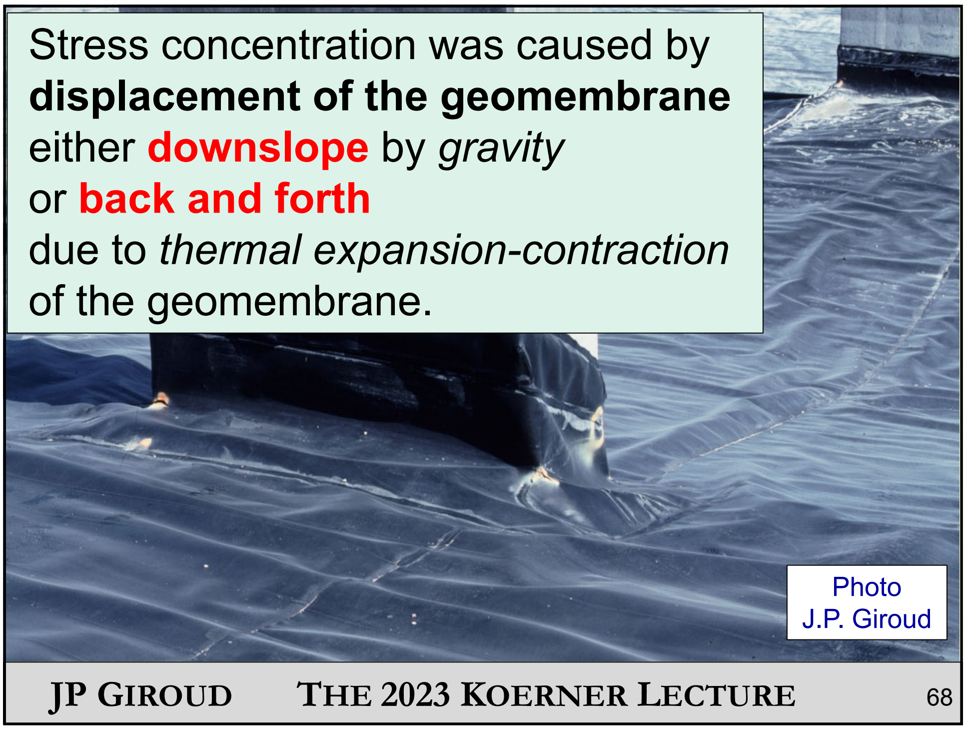
Stress concentration was caused by
displacement of the geomembrane
either **downslope** by *gravity*
or **back and forth**
due to *thermal expansion-contraction*
of the geomembrane.
Photo J.P. Giroud
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Even if there is **zero leak**
at a geomembrane-structure connection,
at the *end of geomembrane installation*,

leakage may occur in service
due to failure of the geomembrane
caused by concentrated stresses
induced in the geomembrane
next to the structure.

Stress concentration occurs at the connection between a **geomembrane** and a **rigid structure** for the following reasons:

- **displacement of the geomembrane**, for example, by gravity on slope, by wind or water uplift, or by thermal-expansion-contraction;
- **settlement of the soil** or any other soil deformation next to a rigid structure; and
- **displacement of the "rigid" structure**.

The last case is rare, but it does exist.

This wall moved toward the left . . .

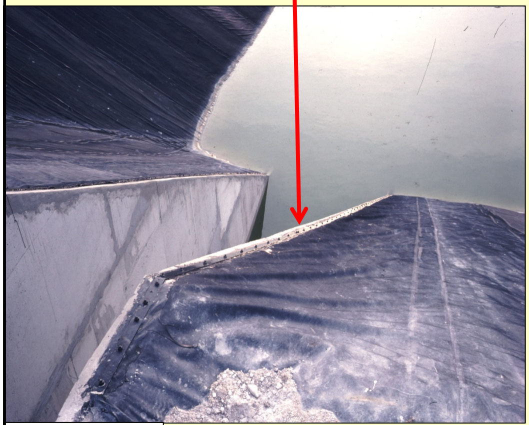
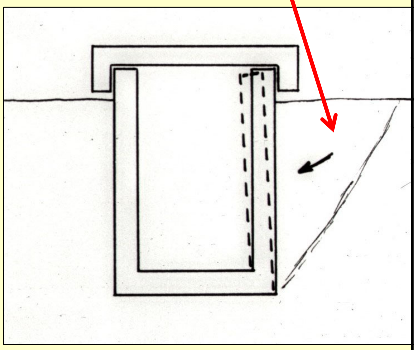


Photo J.P. Giroud

. . . because it did not resist the active soil pressure.



This was a **design error**.

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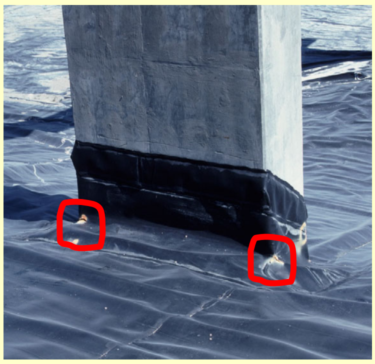
In addition to the risk of **stress concentration**, there is **another problem** with **right-angle corners**.



It is difficult to achieve a **watertight** connection between a geomembrane and a structure with **right-angle corners**.

Without watertight connections, the **zero-leak goal** at end of installation **cannot be achieved**.

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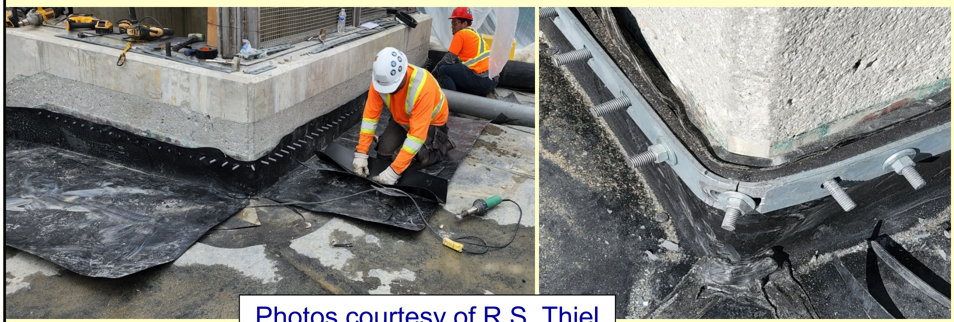
These photos illustrate
the **amount of care** needed
to attach a geomembrane
to a concrete structure
with **right-angle corners**.



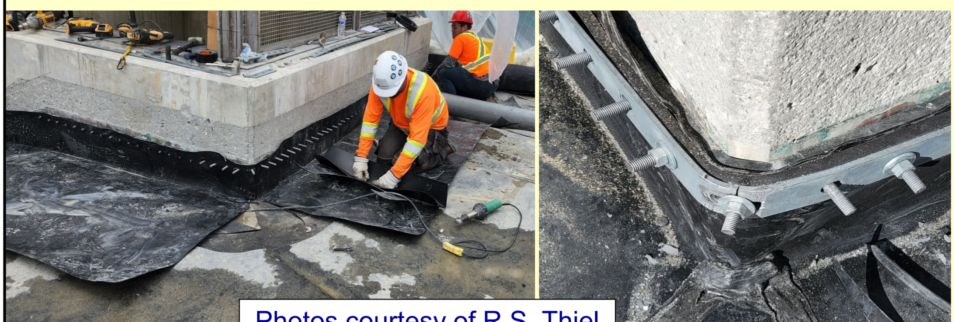
Photos courtesy of R.S. Thiel

JP GIROUD THE 2023 KOERNER LECTURE 73

73

Most structures do not need sharp corners.

Design engineers should **learn from the field**, and **cooperate** with geomembrane **installers**, to design concrete structures to which geomembranes can be easily attached.



Photos courtesy of R.S. Thiel

JP GIROUD THE 2023 KOERNER LECTURE 74

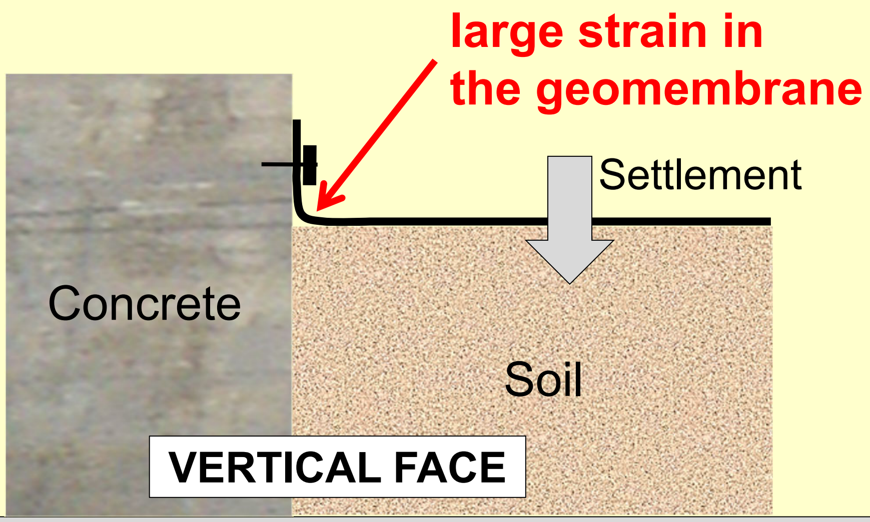
74

Another aspect of the **shape of concrete structures** to reduce the risk of stress concentration in the geomembrane is the **vertical profile** of the concrete structure.

In cases where stresses in the geomembrane may result from **differential settlement** between the structure and the adjacent soil (which supports the geomembrane) the **vertical profile of the structure** is important.

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

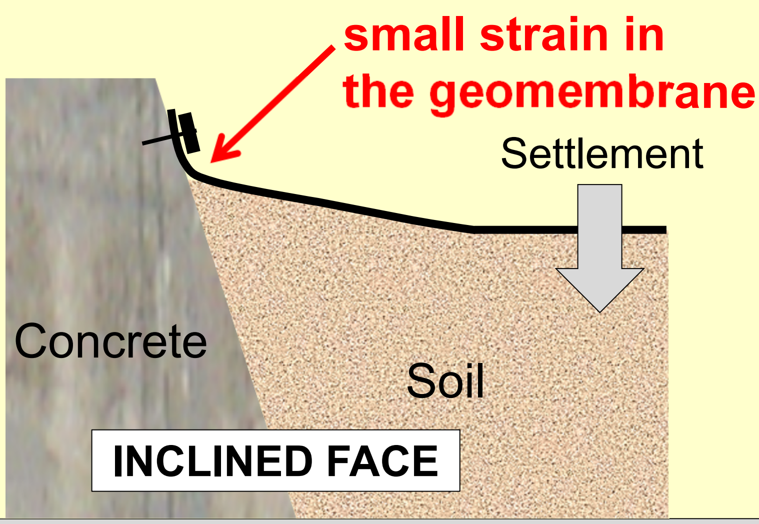
This concrete structure with **vertical wall** is inadequate *in case of soil settlement* because of



JP GIROUD THE 2023 KOERNER LECTURE 77

77

This concrete structure with **inclined wall** is adequate *in case of soil settlement* because it results in



JP GIROUD THE 2023 KOERNER LECTURE 78

78

To conclude this discussion
on the **shape of structures**
to which geomembranes are attached:

- concrete structures should have
no sharp corners
to *facilitate the construction*
of watertight connections
and to *minimize concentrated stresses*
in the geomembrane; and
- *if differential settlement can be expected*,
the concrete structure should have **inclined walls**.

JP GIROUD THE 2023 KOERNER LECTURE 79

79

The next CASE HISTORY
shows that

**UNDERSTANDING
GEOMEMBRANE PROPERTIES
IS
ESSENTIAL**

JP GIROUD THE 2023 KOERNER LECTURE 80

80

A large volume of water
was needed
for a physics experiment.

To contain the water ,
a large cavity
20 m x 20 m x 20 m
was excavated
in a **salt formation**
(*because salt,*
contrary to rock,
is not radioactive).

The reservoir
was to contain
the **purest water**
ever produced.

An **HDPE** geomembrane
was selected
for its **chemical inertia**,
to maintain
the water purity.

I was asked
to design the liner
for this
extraordinary reservoir.

Due to the solubility
of the salt,
I recommended
a **double liner**
with two
geomembranes.

JP GIROUD THE 2023 KOERNER LECTURE 83

83

For the leakage collection
and detection layer
between the
two geomembranes,
I selected a **geonet**
(*a new geosynthetic
at that time, 1980*)
because
(*contrary to gravel*)
it is **not radioactive**
and it could be
installed vertically.

JP GIROUD THE 2023 KOERNER LECTURE 84

84

This was the **first use** of a **geonet** for a leakage collection layer and the **first** **entirely geosynthetic** double liner system.

1980-1981

JP GIROUD THE 2023 KOERNER LECTURE 85

85

The reservoir had been excavated before designing the liner system.

The reservoir had **right-angle corners**.

This is another example of structural design done **without taking into account** the requirements of geomembrane installation and performance.

JP GIROUD THE 2023 KOERNER LECTURE 86

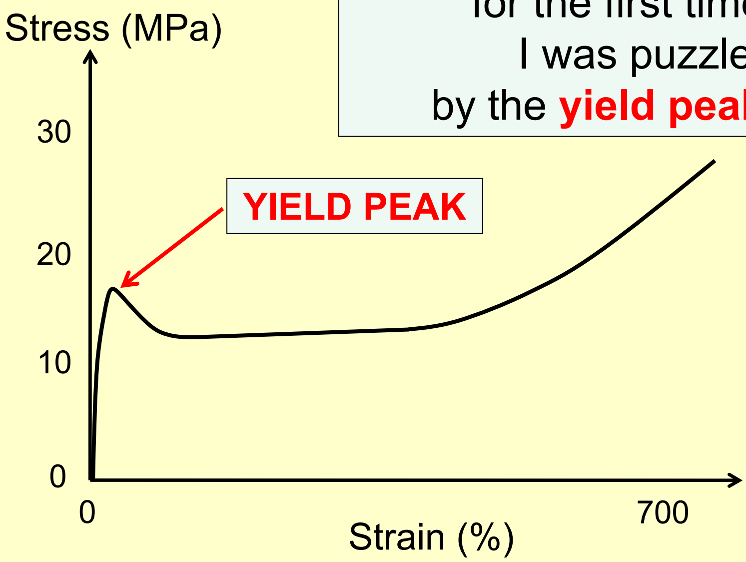
86

To design
this challenging project,
I asked for
the **stress-strain curve**
of the geomembrane.

This was
an extraordinary request.

At that time (1980),
it was not easy
to obtain
the stress-strain curve
of a geomembrane !

When I saw this curve
for the first time,
I was puzzled
by the **yield peak**.

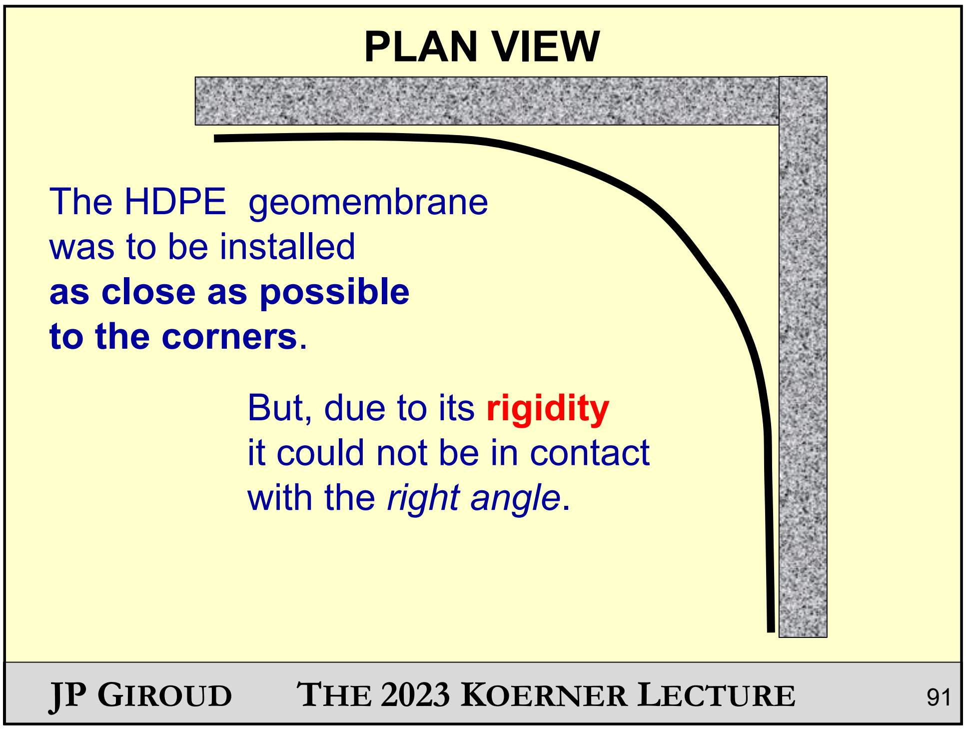


After a significant amount of thinking,
I understood that a geomembrane,
with a **scratch on its surface**
would fail when its **average strain**
is close to the **yield strain**
(*which we all know today*).

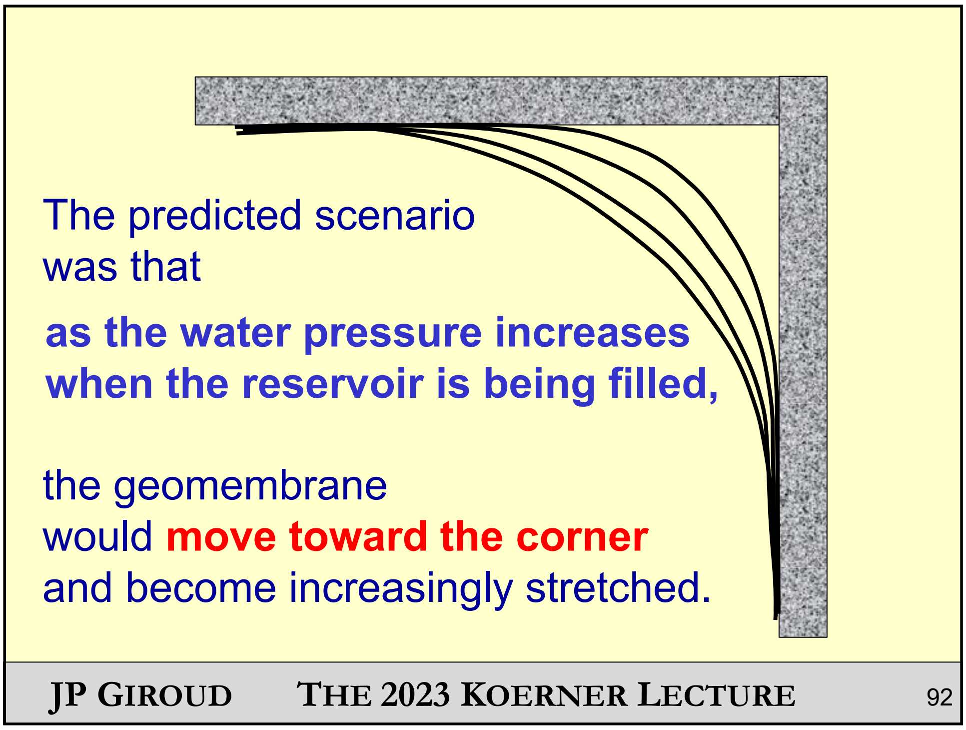
Then, I calculated the strain in the geomembrane
when it is **pushed into a corner**
by water pressure,
and I found that the strain in the geomembrane
was going to be **higher than the yield strain**.

Based on this analysis,
which was new at that time,
I predicted
that the geomembrane would fail
in a corner of the reservoir.

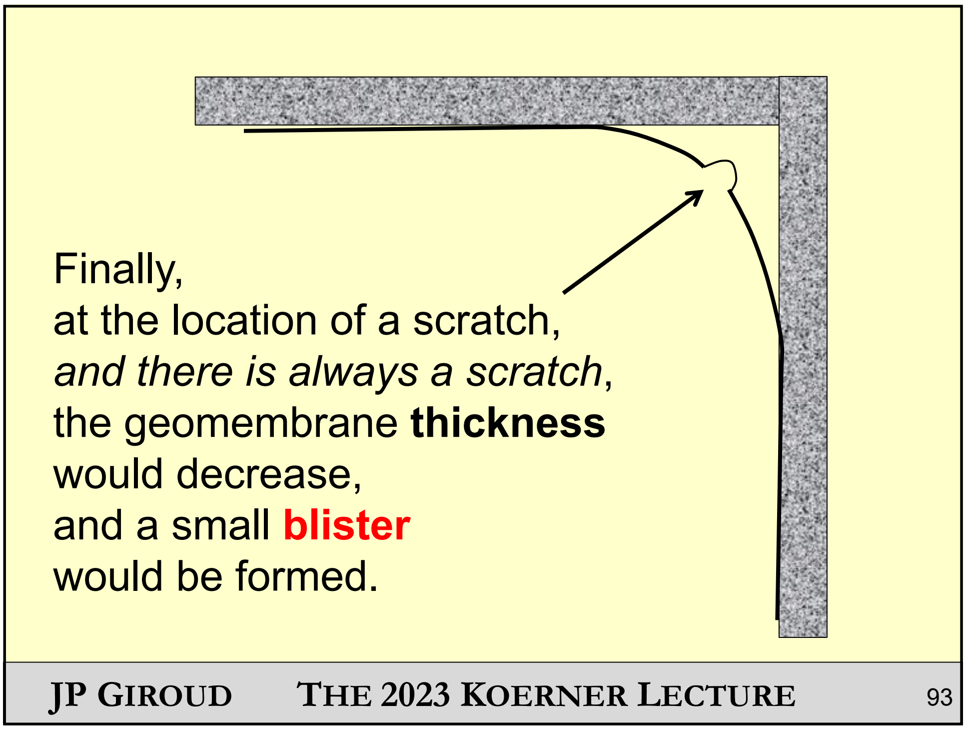
And I presented this prediction
in the design report,
along with the demonstration.


PLAN VIEW
The HDPE geomembrane
was to be installed
as close as possible
to the corners.
But, due to its rigidity
it could not be in contact
with the right angle.
JP GIROUD THE 2023 KOERNER LECTURE 91

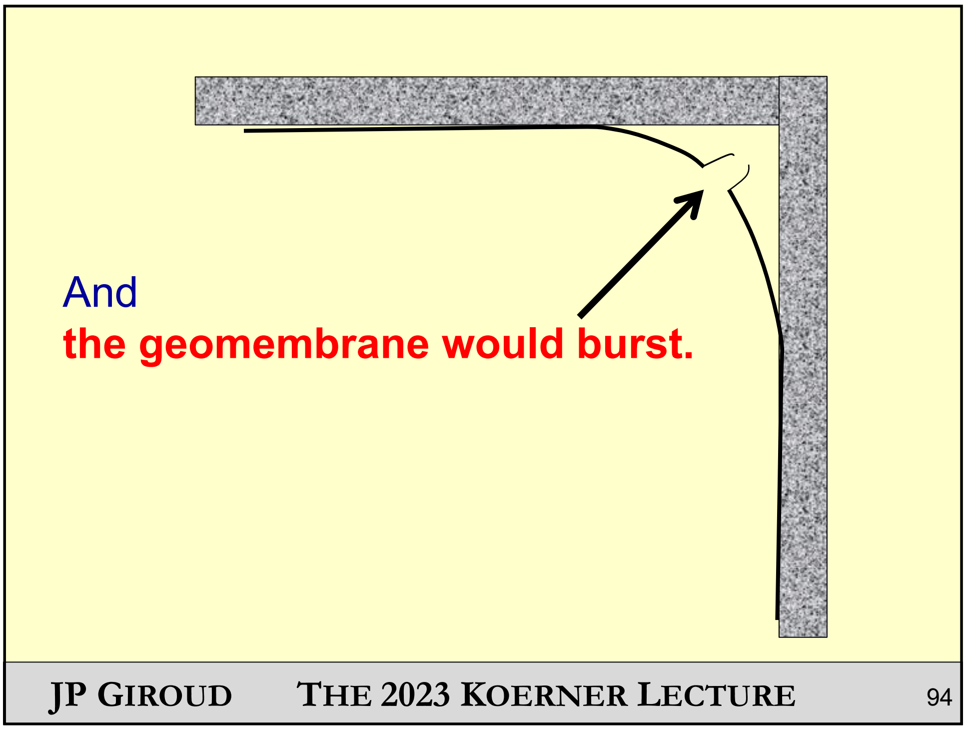
91


The predicted scenario
was that
as the water pressure increases
when the reservoir is being filled,
the geomembrane
would move toward the corner
and become increasingly stretched.
JP GIROUD THE 2023 KOERNER LECTURE 92

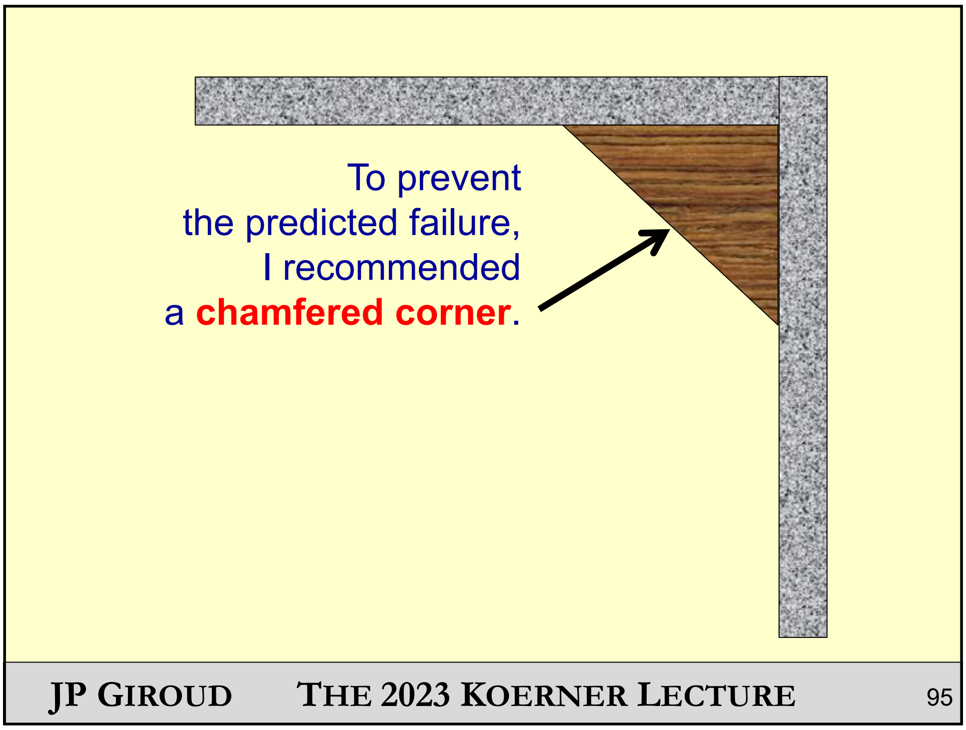
92


Finally,
at the location of a scratch,
and there is always a scratch,
the geomembrane **thickness**
would decrease,
and a small **blister**
would be formed.
JP GIROUD
THE 2023 KOERNER LECTURE
93

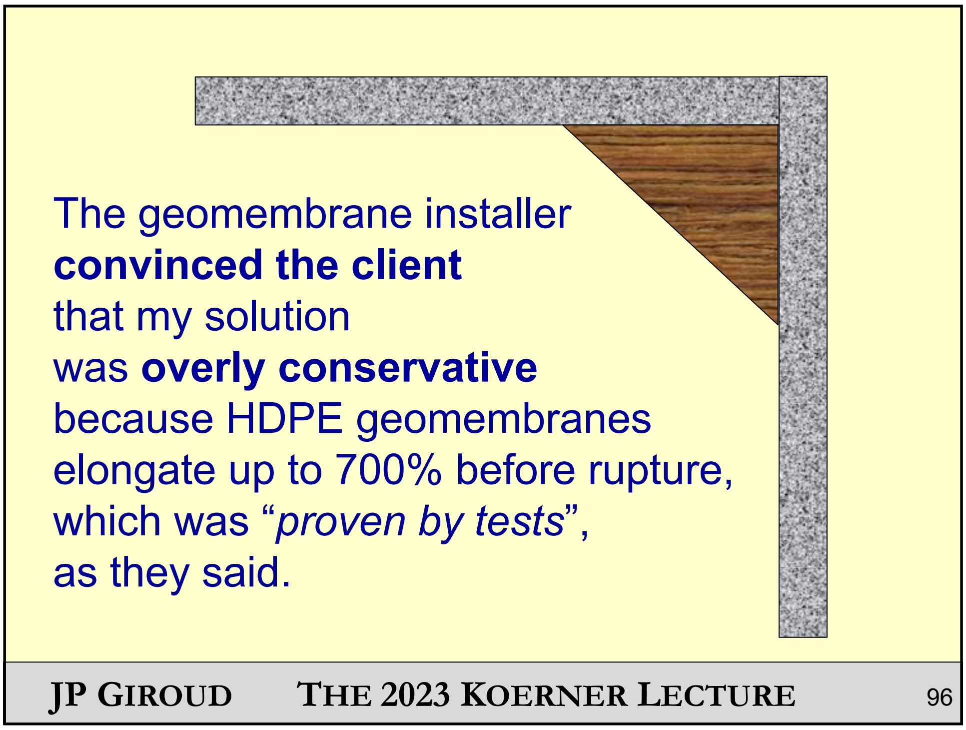
93


And
the geomembrane would burst.
JP GIROUD
THE 2023 KOERNER LECTURE
94

94


To prevent
the predicted failure,
I recommended
a chamfered corner.
JP GIROUD
THE 2023 KOERNER LECTURE
95

95


The geomembrane installer
convinced the client
that my solution
was overly conservative
because HDPE geomembranes
elongate up to 700% before rupture,
which was "proven by tests",
as they said.
JP GIROUD
THE 2023 KOERNER LECTURE
96

96

We know, today, that
HDPE geomembranes
can elongate
up to 700% before rupture
only under the ideal conditions of a laboratory test.

But this was not known in 1980.

JP GIROUD THE 2023 KOERNER LECTURE 97

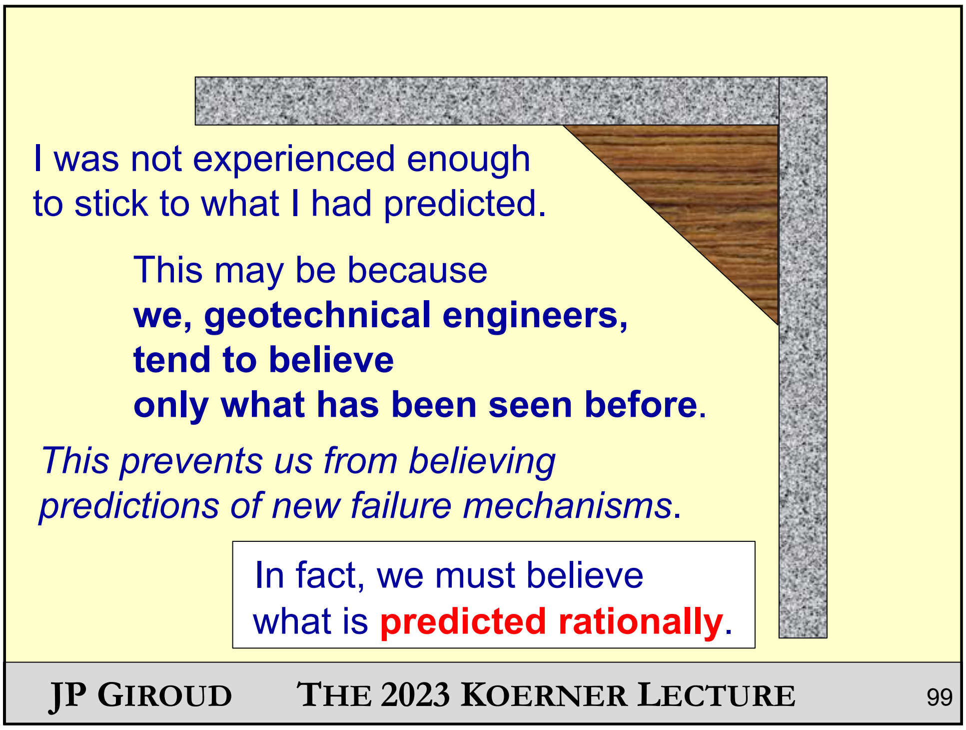
97

The most compelling argument
used by
the geomembrane installer
was that
the type of failure I predicted
had **never been observed**.

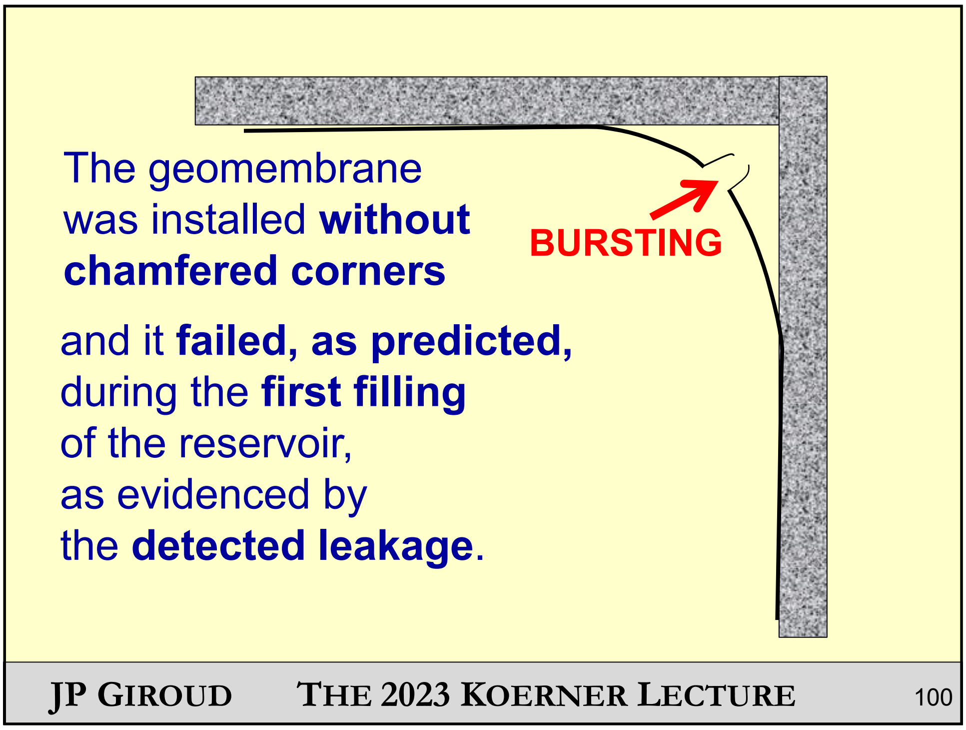
This convinced the client.

JP GIROUD THE 2023 KOERNER LECTURE 98

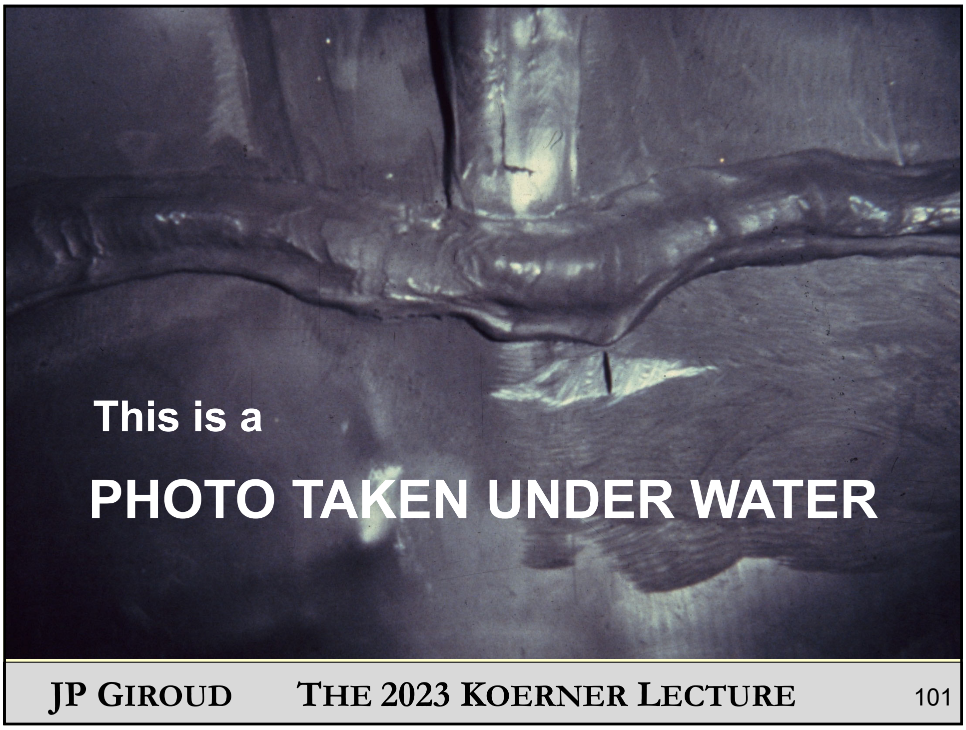
98


I was not experienced enough
to stick to what I had predicted.
This may be because
we, geotechnical engineers,
tend to believe
only what has been seen before.
This prevents us from believing
predictions of new failure mechanisms.
In fact, we must believe
what is **predicted rationally**.
JP GIROUD
THE 2023 KOERNER LECTURE
99

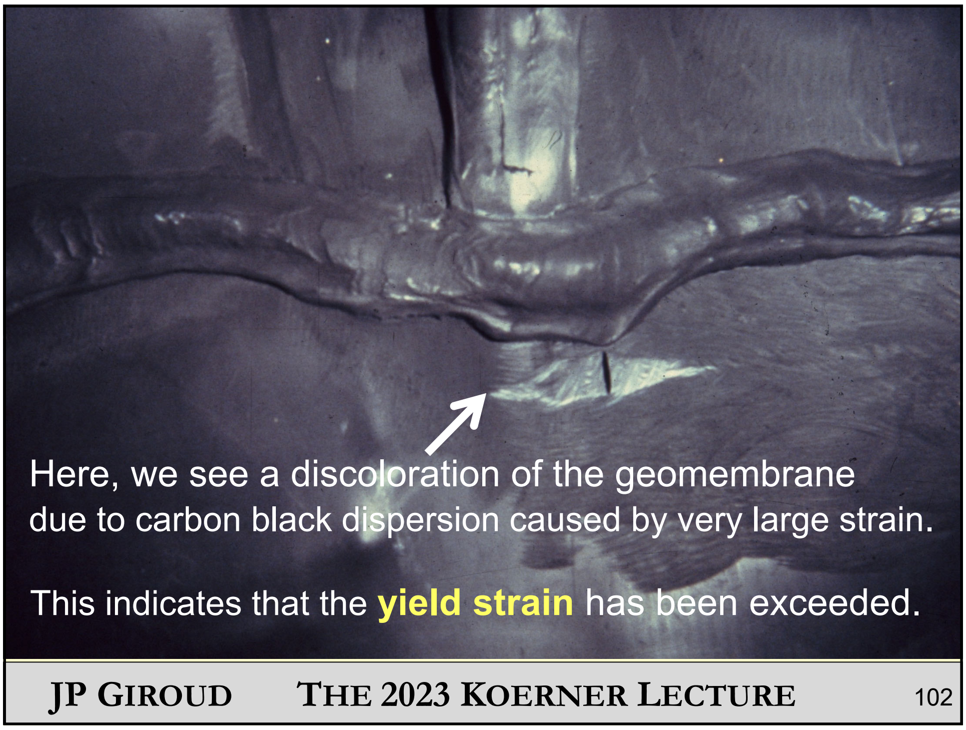
99


The geomembrane
was installed **without**
chamfered corners
BURSTING
and it **failed, as predicted,**
during the **first filling**
of the reservoir,
as evidenced by
the **detected leakage**.
JP GIROUD
THE 2023 KOERNER LECTURE
100

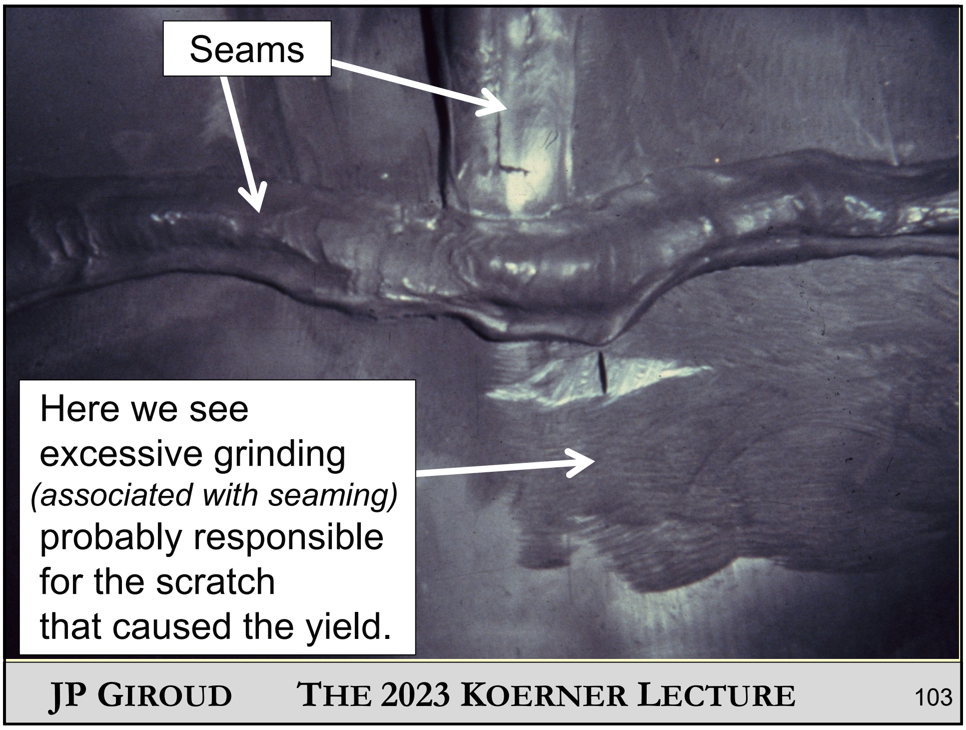
100


This is a
PHOTO TAKEN UNDER WATER
JP GIROUD
THE 2023 KOERNER LECTURE
101

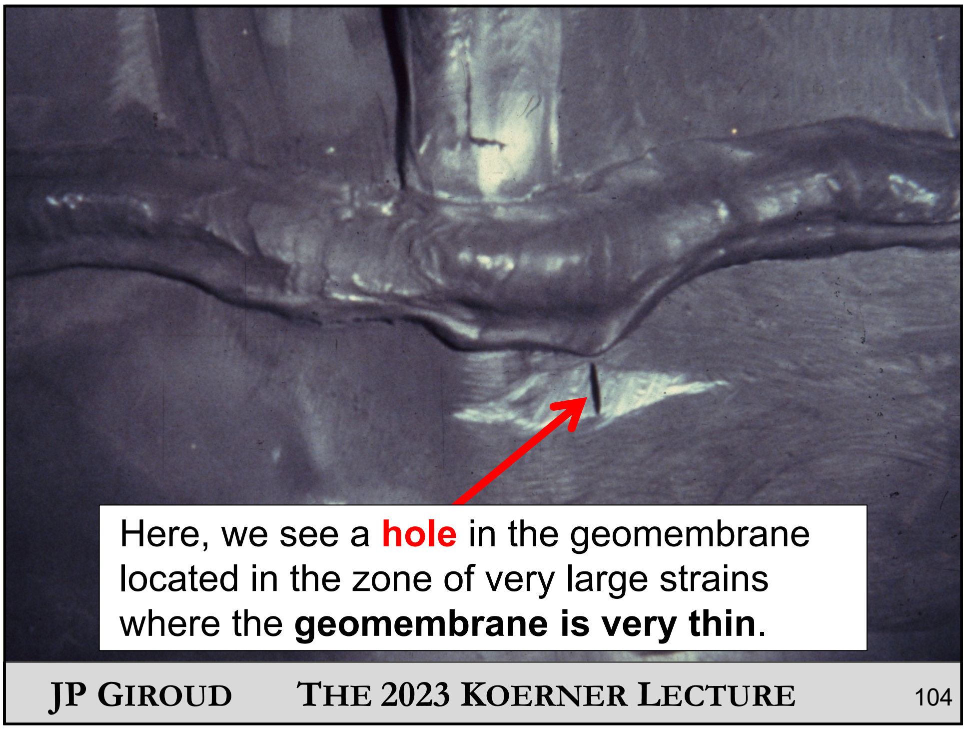
101


Here, we see a discoloration of the geomembrane
due to carbon black dispersion caused by very large strain.
This indicates that the yield strain has been exceeded.
JP GIROUD
THE 2023 KOERNER LECTURE
102

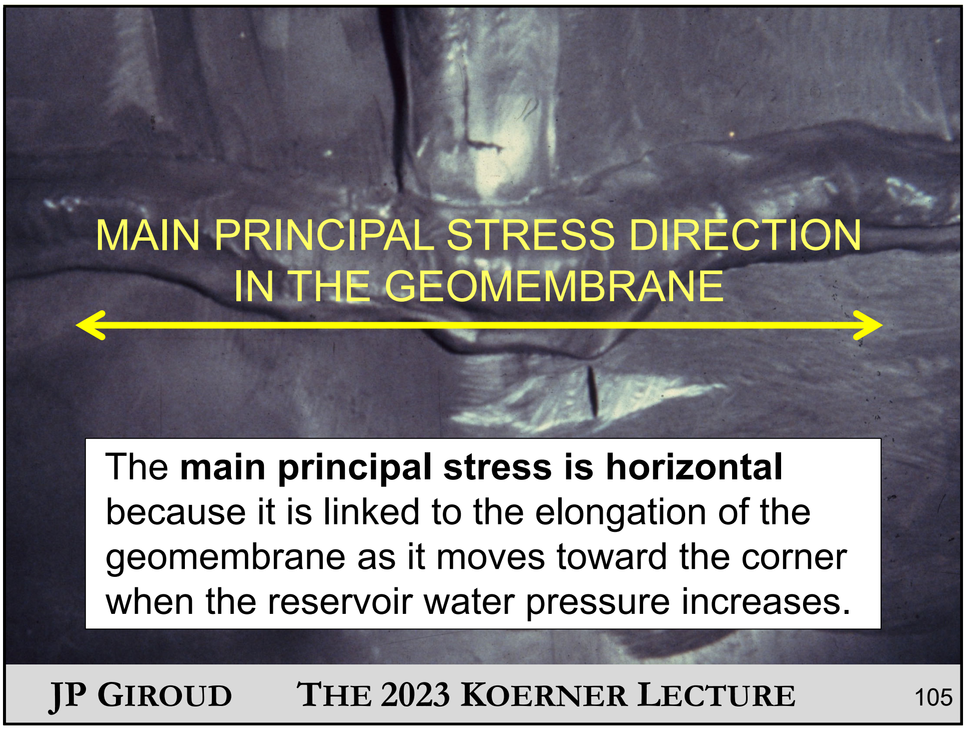
102


Seams
Here we see excessive grinding *(associated with seaming)* probably responsible for the scratch that caused the yield.
JP GIROUD THE 2023 KOERNER LECTURE 103

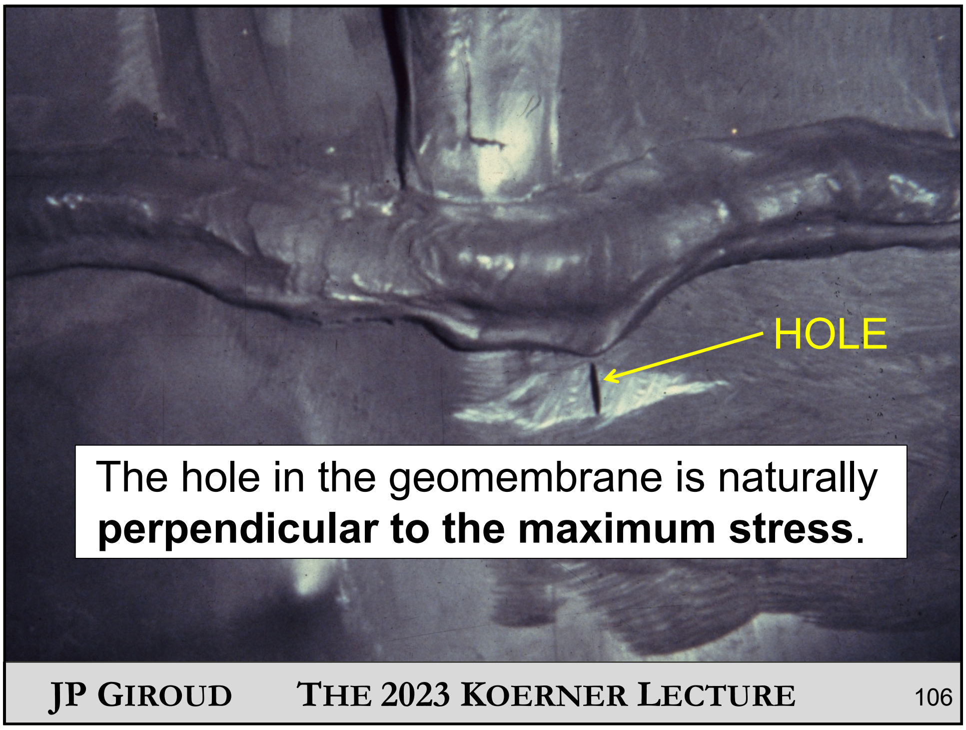
103


Here, we see a **hole** in the geomembrane located in the zone of very large strains where the **geomembrane is very thin**.
JP GIROUD THE 2023 KOERNER LECTURE 104

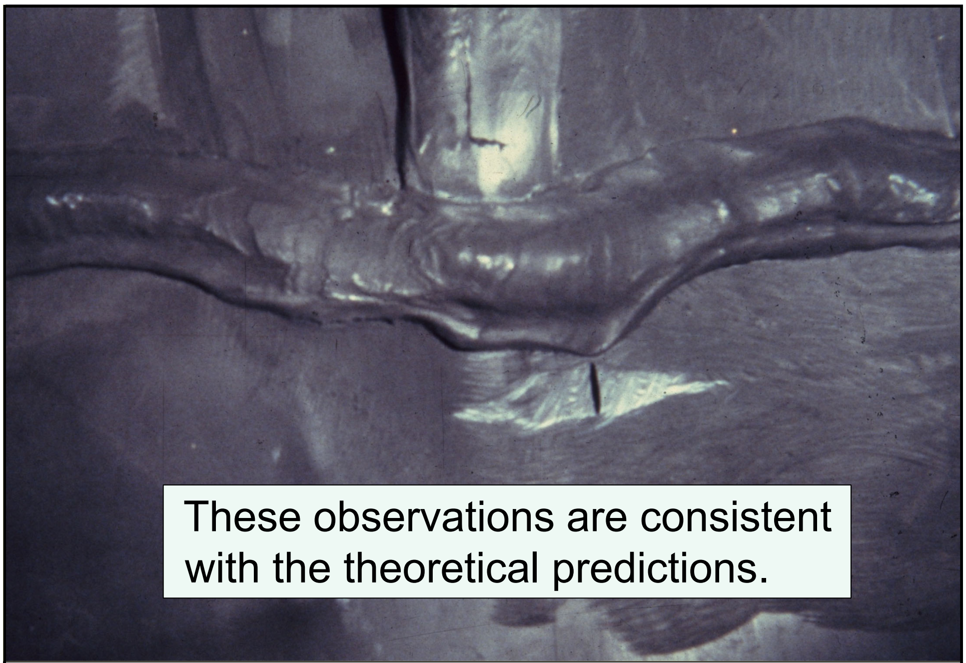
104


MAIN PRINCIPAL STRESS DIRECTION
IN THE GEOMEMBRANE
The main principal stress is horizontal because it is linked to the elongation of the geomembrane as it moves toward the corner when the reservoir water pressure increases.
JP GIROUD
THE 2023 KOERNER LECTURE
105

105


HOLE
The hole in the geomembrane is naturally perpendicular to the maximum stress.
JP GIROUD
THE 2023 KOERNER LECTURE
106

106



JP GIROUD THE 2023 KOERNER LECTURE 107

107

REMEDIATION

The **remediation** consisted in
constructing the **chamfer**
that had been initially recommended.

The physicists had an excellent idea
for **constructing the chamfers**
in the corners of the reservoir
without removing the liners.

JP GIROUD THE 2023 KOERNER LECTURE 108

108

REMEDIATION

- Lightweight **concrete** was slowly poured **in the corners** between the rock-salt wall and the secondary geomembrane, thereby *using the geomembrane as a form*, **while water was progressively added** in the reservoir, as needed to balance the fresh concrete pressure.
- The reservoir was thus successfully repaired and filled with water at the same time.

JP GIROUD THE 2023 KOERNER LECTURE 109

109

The following lesson was learned:

We **must believe** our theoretical analyses because the **theories** we use in geotechnical engineering and in geosynthetics engineering are **generally correct**.

JP GIROUD THE 2023 KOERNER LECTURE 110

110

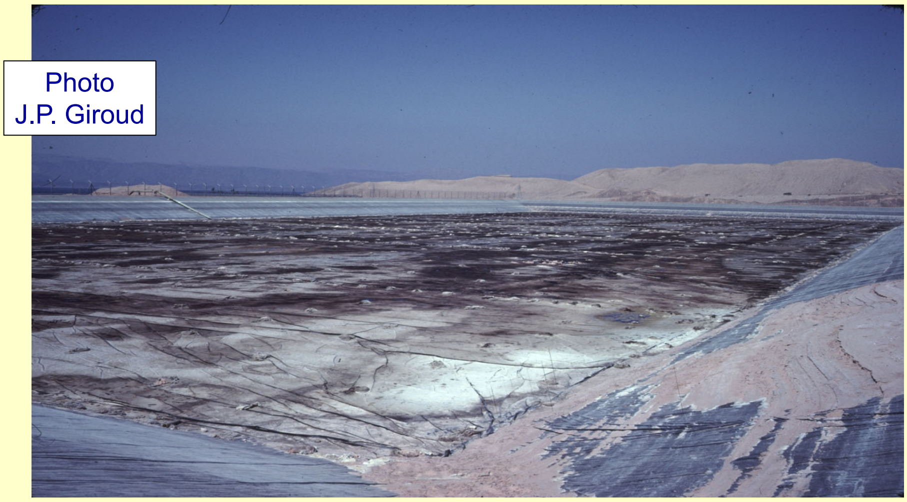
The next **CASE HISTORY** shows that

**IT IS IMPORTANT
TO UNDERSTAND THE FUNCTION
OF THE RESERVOIR.**

CASE HISTORY

- A large reservoir containing **acid** was constructed on a soil with a high **calcium carbonate** content.
- It was lined with a geomembrane installed **without construction quality assurance**.
- **Acid leaked** through the **many holes** in the geomembrane and attacked the calcium carbonate, thereby creating **cavities**.

The reservoir emptied after the geomembrane **burst** over several **large cavities**.



JP GIROUD THE 2023 KOERNER LECTURE 113

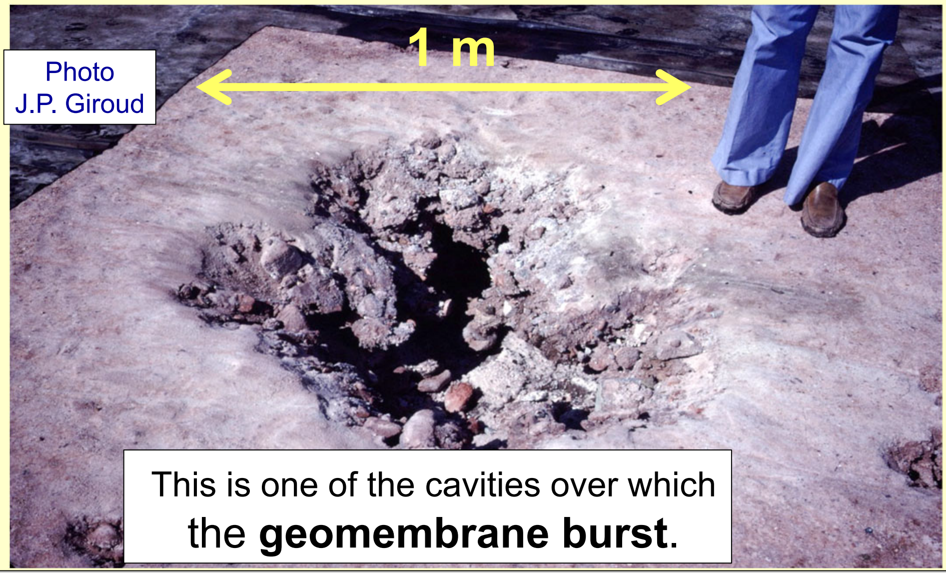
113

Removing the geomembrane unveiled many cavities.

JP GIROUD THE 2023 KOERNER LECTURE 114

114

Some cavities were large.



This is one of the cavities over which the **geomembrane burst**.

JP GIROUD THE 2023 KOERNER LECTURE 115

115

CONDITION OF THE GEOMEMBRANE

The geomembrane had **many holes** (open seams, punctures, tears) due to **careless installation**.

It was clear that the geomembrane had to be **discarded** and that **a new geomembrane had to be installed**.

JP GIROUD THE 2023 KOERNER LECTURE 116

116

STRATEGY FOR REPAIR

The **installer** of the original geomembrane
had **guaranteed in writing**
that the geomembrane
was "**absolutely impermeable**"
and that there would be "**zero leakage**".

Accordingly,
the **owner of the reservoir** demanded
a *new geomembrane* "**with zero leakage**".

JP GIROUD THE 2023 KOERNER LECTURE 117

117

STRATEGY FOR REPAIR

After a long discussion,
I convinced the owner
that it is impossible
to install a geomembrane liner
without holes,
and that the **same problem**
would happen again,
unless the project is redesigned.

JP GIROUD THE 2023 KOERNER LECTURE 118

118

From the **discussion with the owner**,
I understood that the reservoir
had **two functions**:

- **Evaporation pond**; and
- **Storage reservoir**.

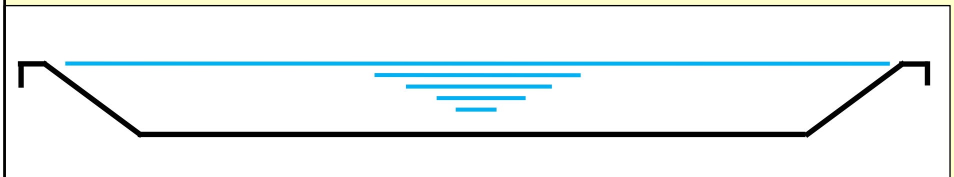
I concluded that the **solution** was to
separate the two functions.

I recommended replacing the reservoir
by **three smaller reservoirs**.

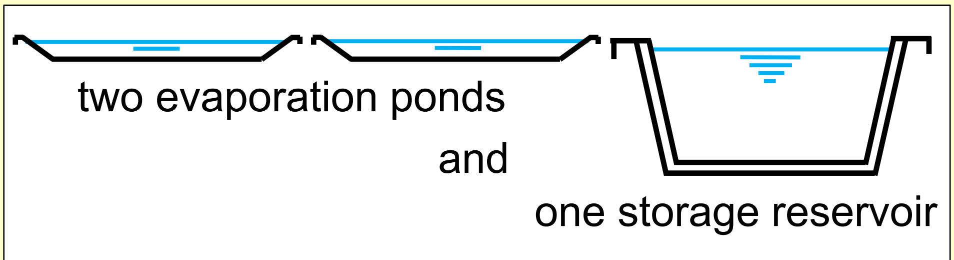
JP GIROUD THE 2023 KOERNER LECTURE 119

119

The large and deep reservoir
with two functions (evaporation and storage)



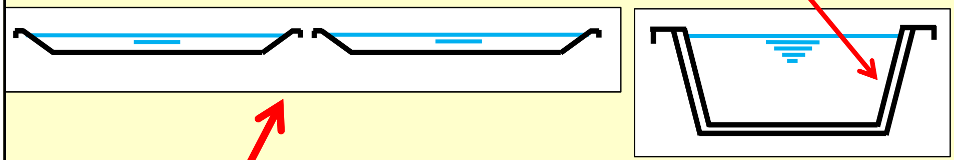
was **replaced by three reservoirs**:



JP GIROUD THE 2023 KOERNER LECTURE 120

120

The **storage reservoir** had a **double liner** to prevent leakage of acid into the ground.



But why two evaporation ponds ?

Why two evaporation ponds ?

- To promote evaporation, these two ponds were **shallow** (0.5 m of acid).
- As a result, the **risk of leakage was limited** and a single liner was appropriate.
- However, **leakage could still happen** and would attack the soil.
- But leakage would unlikely happen in the **two** evaporating ponds at the **same time**.
- If leakage happens in **one** evaporation pond, **repair can be done** **without interrupting the operation** of the facility.

The lessons learned from this case are:

- Claims such as "**zero leakage**" or "**absolutely impermeable liner**" should not be believed.
- **Demanding zero leakage is pointless**.
- The **consequences of leakage** should be evaluated.
- The design engineer should meet with the owner to **understand the needs** of the project.
- The conceptual design should be **adapted to the needs**.

JP GIROUD THE 2023 KOERNER LECTURE 123

123

The next **CASE HISTORY** is also related to deterioration of the supporting soil.

JP GIROUD THE 2023 KOERNER LECTURE 124

124

CASE HISTORY

- A large reservoir (30 ha), containing **sea water**, was constructed on a **soil** containing **gypsum**.
- It was lined with an exposed geomembrane (2 mm thick HDPE) installed **directly on the soil**.
- During the **first filling** of the reservoir, when the water depth reached 7 m, the water level suddenly decreased.

The rate of **leakage** was **huge**:
of the order of 120 m^3 per minute
(30,000 gallons per minute).

Flooding of a residential area was avoided by the site manager and his team who breached a dike during the night to redirect the flood toward an empty area.

The failure mechanism is discussed on the next slide.

A **large cavity**, 20 m^3,
had developed **under the geomembrane**,
at the bottom of the reservoir.

Photo
Archive
J.P. Giroud

The cavity developed because
the soil was **highly soluble**
in water, especially salt water.

The
high solubility
and **erodability**
of the soil
was evidenced
by deep gullies
seen at the site.

Photo
J.P. Giroud

The geomembrane **burst over the cavity**.

Here is a photo of the geomembrane ruptured **over the cavity**.

Photo I.D. Peggs

JP GIROUD THE 2023 KOERNER LECTURE 129

129

The geomembrane burst into the cavity **35 days** after the reservoir filling started.

These 35 days are **consistent** with leakage rate **calculations**, and with the **calculated time** required for the leaking water to dissolve 20 m^3 of that soil.

Also, **calculations** showed that the **bursting** of the geomembrane under 7 m of water was **consistent** with the **geomembrane strength**.

It is important in forensic analyses to present quantitative explanations.

JP GIROUD THE 2023 KOERNER LECTURE 130

130

The soil had a **low permeability**,
and the **design engineer** expected
that the geomembrane on this soil
would form a **composite liner**.

However, this "composite liner" **could not work**
for two reasons:

- **Intimate contact** is required in a composite liner between the geomembrane and the underlying low-permeability material, but there was **no load** to keep the geomembrane and the soil in contact.
- Furthermore, a leak would **dissolve** this soil.

JP GIROUD THE 2023 KOERNER LECTURE 131

131

The high **solubility** of the soil
was **known**
and, at the time of the design (2004),
it was well **known**
that the possible presence of **holes**
in geomembrane liners
should always be considered at the design stage.

Therefore, the possible **consequences of leakage should have been identified** and **evaluated.**

This was not done, and, therefore,
the **failure** was **inevitable**.

JP GIROUD THE 2023 KOERNER LECTURE 132

132

Against my recommendation,
the **repair** in 2011 was done with the **same design**.

In 2013, I wrote in a court document:

"*The reservoir, with a single geomembrane liner,
on a material highly sensitive to water,
is a **failure-prone reservoir**
where it is logical to **expect** that
the mode of failure observed in June 2011
will happen again.*"

As predicted, **the liner failed again** in 2021.

This time, **300 homes were evacuated**
by order of the authorities.

JP GIROUD THE 2023 KOERNER LECTURE 133

133

An important **lesson learned**
from this case history is that
site-specific data should not be ignored,
for example,
the solubility of the soil.

JP GIROUD THE 2023 KOERNER LECTURE 134

134

The last CASE HISTORY
shows that

**PLACING A LINER
DIRECTLY ON TOP OF
ANOTHER LINER
IS RISKY
IN A LIQUID RESERVOIR.**

JP GIROUD THE 2023 KOERNER LECTURE 135

135

Two almost identical reservoirs
were constructed on the same site,
at the same time.

This case is remarkable
because the **two reservoirs**
experienced the **same problems**.

Only the problems
of **one of the two** reservoirs
will be described.

JP GIROUD THE 2023 KOERNER LECTURE 136

136

A reservoir of **brine** for a **pumping station** was lined with an **old bituminous roofing membrane**.

This old membrane was in **relatively good condition**, but there was **some leakage**, which contaminated groundwater.

The environmental agency required that the leakage be fixed.

JP GIROUD THE 2023 KOERNER LECTURE 137

137

The owner asked an **installer** to place a geomembrane **directly on top of the old membrane** to solve the leakage problem.

The environmental agency liked this solution.

No design engineer was involved, *but I was informed of this project* by the installer.

JP GIROUD THE 2023 KOERNER LECTURE 138

138

I told the installer that
installing a **liner on a liner** was **risky**
because liquid may accumulate
between the two liners and uplift the top liner.

Both the installer and the owner ignored my warning.

I sent a letter to the installer
to make sure it was clear
that I did not support the adopted solution.

Then, I did not hear about this project for a year.

I eventually learned that the owner and the installer
had ignored my warning
because they considered that
I was driven by **theoretical considerations**
(*and, I agree, they were right*)
and they had concluded that
I lack **common sense**
(*and, I agree, they were right*).

Indeed, it was obvious to them that
common sense dictates that
two liners are better than one
(which, I know, can be wrong).

As decided by the owner,
a 1 mm thick PVC geomembrane
was installed on a geotextile **cushion**
placed on
the old bituminous roofing membrane.

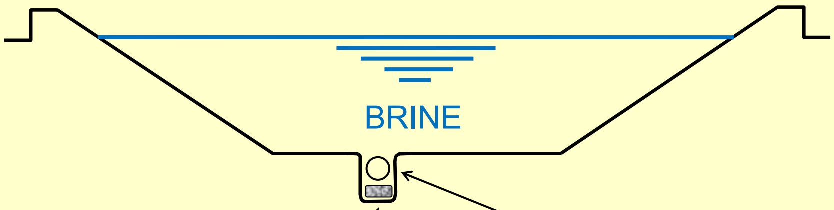
The **pumping station** reservoir
was used for more than six months
with the **brine level fluctuating daily**
between full and half full.

It was not easy to see the geomembrane
through the brine,
but the operator of the pumping station knew
that the **geomembrane liner was moving**.

And, I was asked to visit the site
to investigate problems with the liner.

To understand the problems,
a cross section is needed.

A long ditch was used as a sump to pump the brine.



A pipe at end of the ditch was connected to the pump.

The geomembrane was ballasted at the bottom of the ditch.

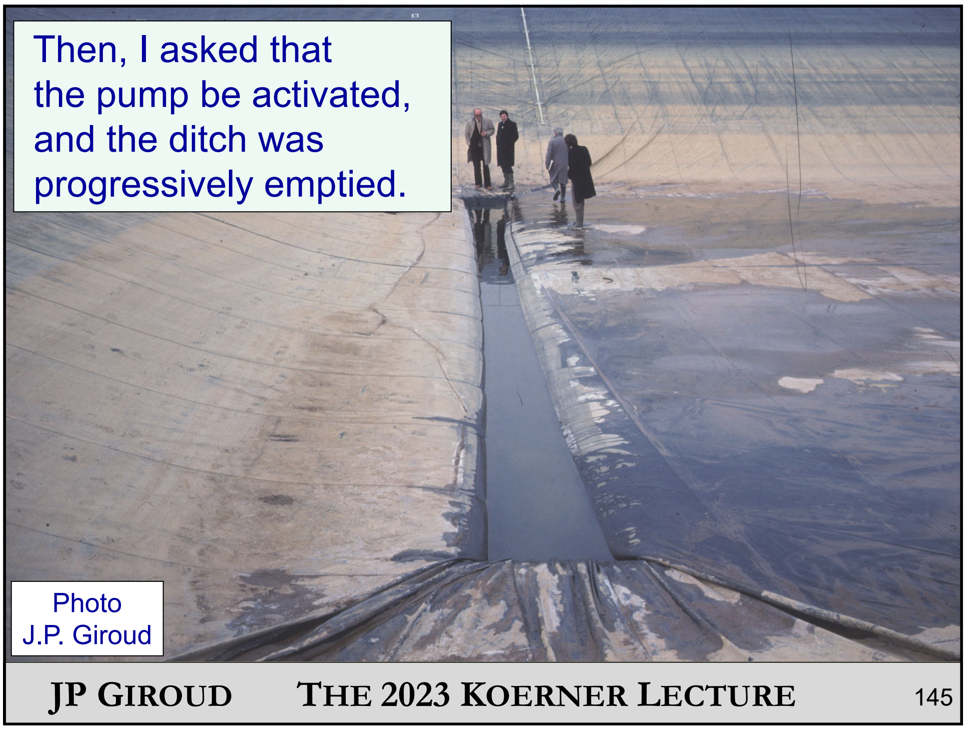
Therefore, the geomembrane could not move at the bottom of the ditch, but could move elsewhere since it was not covered.

JP GIROUD THE 2023 KOERNER LECTURE 143

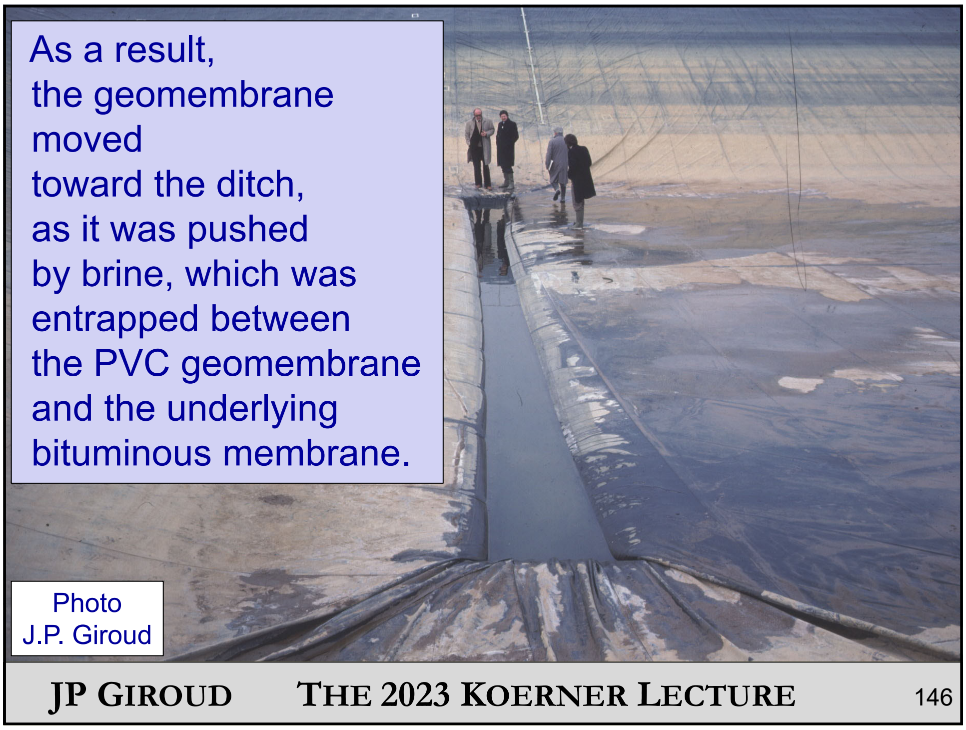
143

JP GIROUD THE 2023 KOERNER LECTURE 144

144


Then, I asked that
the pump be activated,
and the ditch was
progressively emptied.
Photo
J.P. Giroud
JP GIROUD
THE 2023 KOERNER LECTURE
145

145


As a result,
the geomembrane
moved
toward the ditch,
as it was pushed
by brine, which was
entrapped between
the PVC geomembrane
and the underlying
bituminous membrane.
Photo
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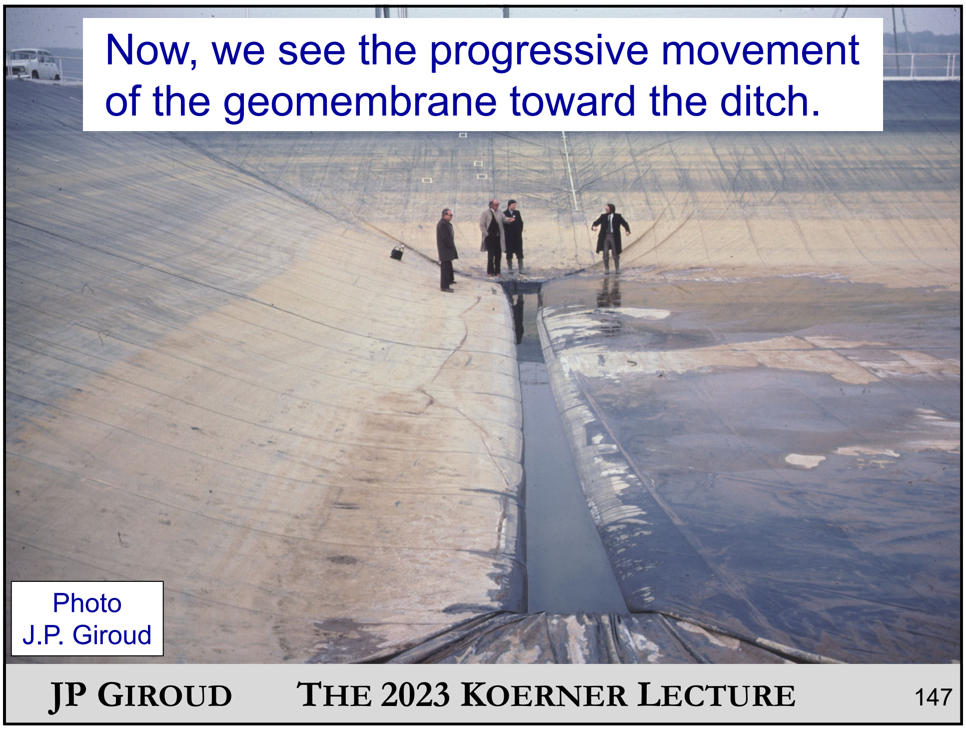
Now, we see the progressive movement of the geomembrane toward the ditch.
Photo
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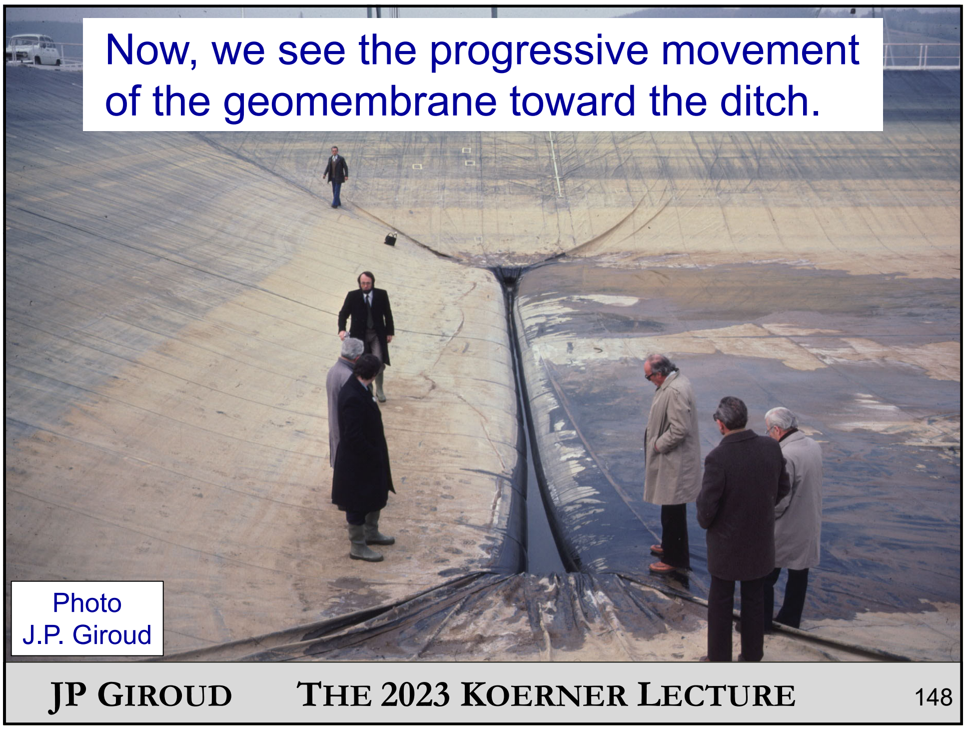
Now, we see the progressive movement of the geomembrane toward the ditch.
Photo
J.P. Giroud
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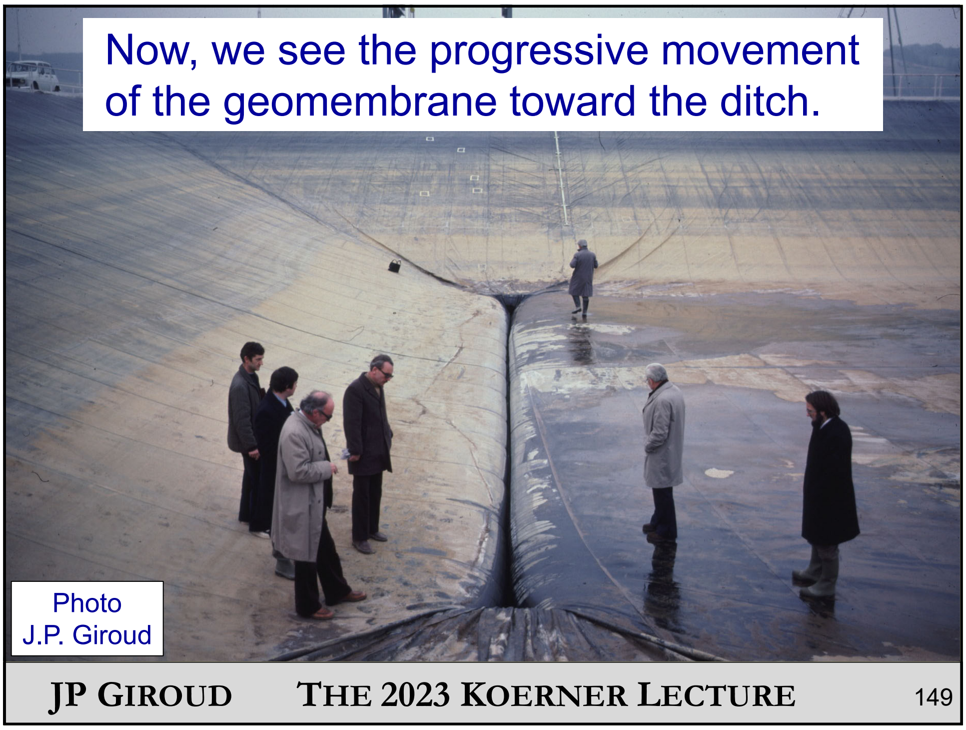
Now, we see the progressive movement of the geomembrane toward the ditch.
Photo
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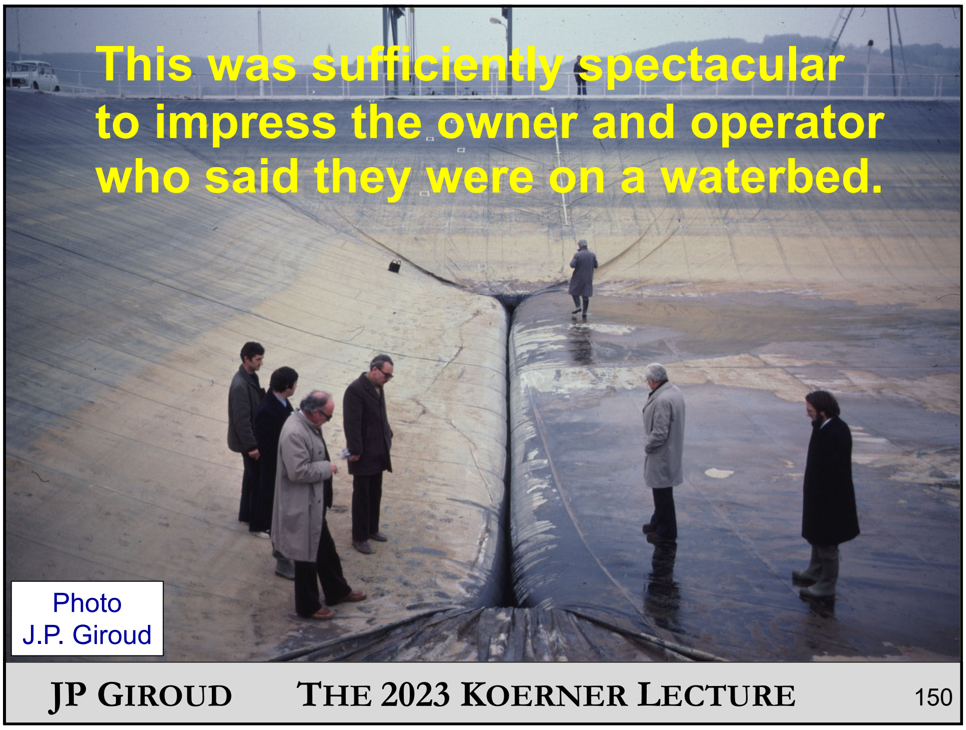
This was sufficiently spectacular to impress the owner and operator who said they were on a waterbed.
Photo
J.P. Giroud
JP GIROUD
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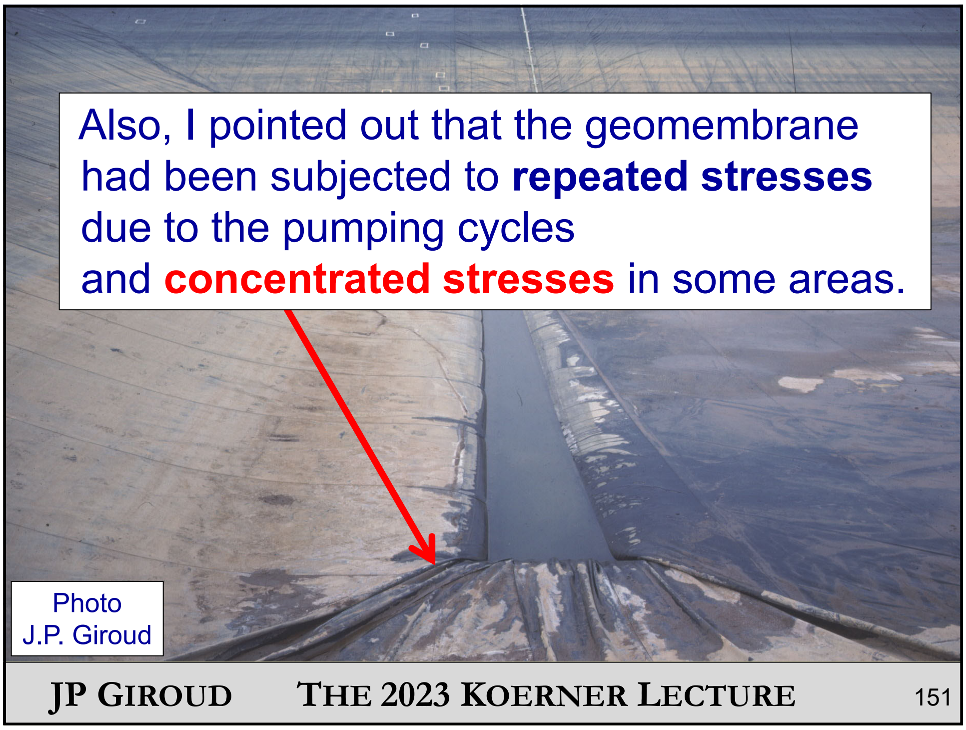
Also, I pointed out that the geomembrane had been subjected to **repeated stresses** due to the pumping cycles and **concentrated stresses** in some areas.
Photo
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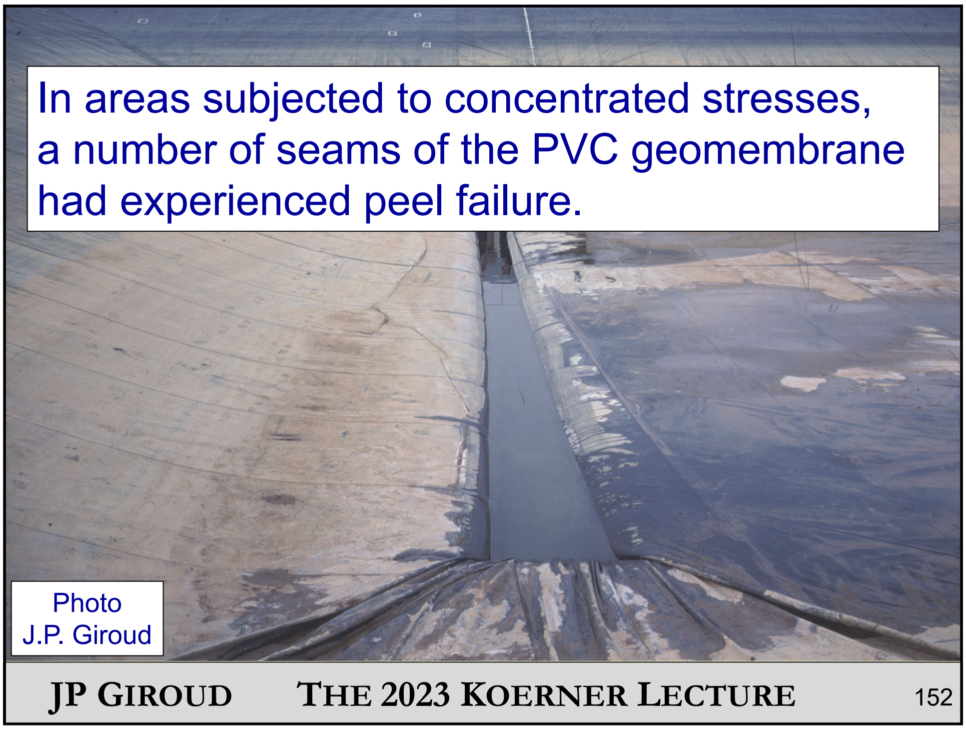
In areas subjected to concentrated stresses, a number of seams of the PVC geomembrane had experienced peel failure.
Photo
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Also, during my visit, I learned **interesting facts**.

During six months in service,
the reservoir had been **emptied twice**.

Each time, the geomembrane was **displaced** toward the ditch by **liquid entrapped under the geomembrane**.

Each time, the geomembrane was *intentionally* cut to discharge the entrapped liquid in the ditch, and *salinity measurements* indicated that the **entrapped liquid was brine**.

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I also learned that, **shortly after installation**, and *before any brine was stored in the reservoir*, the geomembrane had moved toward the ditch, pushed by **liquid under the geomembrane**.

Based on the bulging, the volume of liquid entrapped was estimated to be between 2 and 4 m^3.

The geomembrane was *intentionally* cut, and **fresh water** was discharged into the ditch.

This water was attributed to **intensive rainfall** during geotextile and geomembrane installation.

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I checked this assumption as follows.

During geotextile and geomembrane **installation**,
the 50 m^3 ditch was filled with rainwater;
therefore, more than 50 m^3 of rain fell on the reservoir.

I calculated that the 300 g/m^2 **geotextile**
could **contain** approximately **6 m^3 of water**,
and that it would take **only several days**
for this water flowing downslope **to reach the ditch**.

These numbers, *volume and time*, indicate that,
indeed, **rainwater** explained the 2 to 4 m^3 bulging,
which occurred shortly after installation.

Again, it is important in forensic analyses
to present quantitative explanations.

After this investigation, it was clear to me that
a **new design was needed**
because of the following facts:

- The fact that geomembrane displacement by entrapped liquid had happened **every time** the reservoir was empty.
- The fact that the **same problems** happened at the **other reservoir** *at the same site* constructed with the **same design**.
- The fact that the geomembrane displacement was **rationally explained** and **predicted**.

The repair consisted in creating a **double liner**:

- The damaged PVC geomembrane was discarded.
- The old bituminous roofing membrane was kept as a **secondary liner**.
- A thick geotextile (600 g/m^2) was placed on top of the existing geotextile (300 g/m^2) to serve as **leakage detection layer** (*today a geonet would be used*).
- The ditch was *filled with gravel* to become a sump for the leakage detection layer.
- The **primary liner** was a new PVC geomembrane.

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Many lessons were learned from this case history:

- **Installers** who agree to install a geomembrane **without a design engineer** should be careful, because a failure is possible.
- **Common sense** is wrong as often as it is right. It is a *random process*, not a design guide.
- **Theoretical analyses** are a reliable guide.
- Two liners are better than one **only** if **engineering principles** are respected, for example, by *ballasting* or by creating a *double liner* by draining between the two liners.

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This case history provides an opportunity
to repeat that **composite liners** are effective
only if there is **intimate contact**
between the two components
of the composite liner,
the geomembrane
and the underlying low-permeability material.

To that end, the geomembrane must be **flat**
(that is with no wrinkles)
and must be subjected to a **load**
over its entire surface.

The load has two beneficial effects:

- The load maintains the geomembrane and the underlying low-permeability material in **intimate contact**, which is its primary function.
- The load **prevents liquid accumulation** between the geomembrane and the underlying low-permeability material, thereby *preventing uplifting of the geomembrane*.

Liquid pressure *is not an adequate load*
because it uplifts the geomembrane
if it leaks through the geomembrane.

Many **geotechnical engineers**
have learned about composite liners
while designing **landfills**.

They should not use, for liquid containment,
what they have used for landfills
without recognizing
fundamental differences
between the use of composite liners
in landfills and in reservoirs.

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In the case of **landfills**,
the conditions are **ideal** for a composite liner.

The **primary reason** is that
the waste applies a **high load**,
which ensures **intimate contact** between
the two components of a composite liner,
hence a **small leakage rate**.

In addition, there is a **low liquid pressure**
on the geomembrane, hence a **small leakage rate**.

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In the case of **reservoirs**,
a composite liner **may not be appropriate**
because:

- there may not be enough **load**
  to ensure **intimate contact** between
  the **two components** of the composite liner;
  and
- there may not be enough **load**
  to prevent liquid from **accumulating between**
  the *geomembrane* and
  the underlying *low-permeability material*.

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Finally, a related **recommendation**:

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

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

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

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CONCLUSION

I could present more cases,
but it is time to conclude.

First, I want to reassure you.

Most geomembrane projects are **successful** thanks to designers, manufacturers, installers, laboratories, and providers of **essential services**, *construction quality assurance* and *electrical leak location surveys*.

In most cases, **leakage is controlled** *(but, generally, it is not zero).*

However, there are still too many failures, and **we must learn from failures**.

If we do not learn from failures caused by others, **we will learn form our own failures**.

In this presentation, we have seen that failures are often caused by **design mistakes**.

The first design mistake is to have no design.

Indeed, in some projects,
there may be significant risks
if the **owner relies** only
on the geomembrane installer.

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Also, *design problems are evident*
is the case of reservoirs designed
by **structural engineers** who ignore
the requirements of geomembrane **installation**.

Designs that ignore the requirements
of geomembrane installation
result in *geomembrane liners with defects*,
thereby missing the goal of **zero leak**
at end of installation.

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And design mistakes are also made by engineers who are **knowledgeable** about geomembranes.
Examples are:

- A design engineer who *repeats a past design* even though the conditions are different.
- A design engineer who made unjustified claims and does the *design in accordance with the claims*.
- A design engineer who takes risks thinking that *failures only happen to others*.
- A design engineer who wants to *please the owner*.

An example, which includes all of the above, is in the next slide.

A design engineer wrote in a paper at an International Conference on Geosynthetics:

> "*pinholes, seam or joint imperfections, tears and other defects are generally assumed to be present in a geomembrane installation even when a thorough quality control plan is implemented to minimize the presence of such defects.*"

This is correct.

Nevertheless, **designing a reservoir**,
after the publication of his paper,
this engineer made **very different statements**.

The design engineer **assured the owner** that **leakage was unlikely**.

Here are **citations** from the design documents, and even from a risk analysis report:

- "*unexpected (unlikely) liner leak*"
- "*a liner tear is unlikely to develop*"
- the liner is "*designed to completely isolate water placed in the reservoir from the underlying*" material.

This liner failed causing significant **leakage**.

Clearly, the **zero-leak** and **zero-leakage goals** cannot be achieved if the liner **design is flawed**.

The **zero-leak goal** cannot be achieved **at end of geomembrane installation** if the design of the containment facility *ignores the properties* of geomembranes and the *requirements of geomembrane installation*.

The **zero-leakage goal** cannot be achieved **in service** if the design of the containment facility *ignores the mechanisms* that may cause leakage.

In conclusion,
quasi-zero leakage in service could be envisioned only under ideal conditions, including :

- perfect design for installation and performance;
- reservoir with no appurtenances;
- double geomembrane liner;
- perfect earthwork and ground preparation;
- geomembrane installation under ideal conditions;
- first-class installing crew;
- strict construction quality assurance;
- electrical leak location survey of both liners;
- **zero-leak at end of installation**;
- well-planed and careful operation and maintenance;
- no filling-emptying cycles; etc.

Considering that these ideal conditions are rarely met, and considering that **specifying zero leakage** or an *excessively small leakage rate*, may lead to extensive investigations and repairs that could cause defects generating **more leakage**, the rational approach consists in specifying an **acceptable leakage rate** based on:

- an *evaluation of the consequences* of leakage that is specific to the project being designed; and
- *published guidelines, studies and recommendations* on acceptable leakage rates.

I hope that this lecture will promote progress in the design of liquid containment reservoirs.

Controlling leakage is **essential**
for the **protection of the environment**
not only
by **preventing migration of contaminants**
into the ground
but, also, by **reducing waste of water**.

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Saving water will be a major
economic and environmental **challenge**
for the coming decades.

Geomembranes
and other geosynthetics
will be at the forefront of the efforts
to meet this **challenge**,

and, therefore,
our industry should play a **major role**
in the 21st century.

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CLOSURE

I want to close this lecture
by sharing with Bob Koerner
the thoughts I presented today
on engineering, on geosynthetics,
on our discipline, on our industry.

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And thank you, Bob, for being together once again.

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And thank you all for attending.

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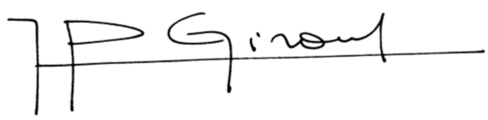
ACKNOWLEDGEMENTS

I am grateful to
Eric Blond, Richard Thiel and Robert Wallace
who reviewed this presentation
and provided valuable comments.

I also want to thank Fred Chuck and the
Geosynthetic Materials Association (GMA)
for their invitation to present the Koerner Lecture,
as well as Barbara Connett and Rick Collins
for their assistance.



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References of papers on acceptable leakage rate (see Slide 174)

Peggs, I.D. & Giroud, J.P., 2014, "Action leakage rate for reservoir geomembrane liners", *Proceedings of the 10th International Conference on Geosynthetics*, Berlin, 10 p.

Giroud, J.P., 2016, "Leakage Control using Geomembrane Liners", The Victor de Mello Lecture, Soils and Rocks, São Paulo, Brazil, Vol. 39, No. 3 September-December 2016, pp. 213-235.

These two papers can be downloaded from
https://geosyntheticsconference.com/proceedings-archive/

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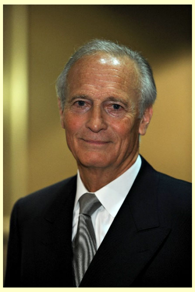
ABOUT THE LECTURER



Dr. J.P. Giroud, civil engineer Ecole Centrale Paris and PhD University of Grenoble, is: a consulting engineer; a former professor of geotechnical engineering; co-founder and Chairman Emeritus of Geosyntec Consultants; past president of the International Geosynthetics Society (IGS); co-founder and former chairman of the Editorial Board of the IGS journals, *Geotextiles and Geomembranes* and *Geosynthetics International*; and a member of the U.S. National Academy of Engineering.

Dr. Giroud coined the terms "geotextile" and "geomembranes". He has developed numerous design methods used in geosynthetics engineering, for example, methods for leakage evaluation, liner stability on slopes and voids, filters, unpaved roads.

Dr. Giroud originated several geosynthetics applications: first use of a geotextile filter in a dam, first use of geotextiles to protect geomembranes, first double geomembrane liner, first use of a geonet between two geomembranes to form an entirely geosynthetic double liner, and his design method for geomembrane wind uplift made it possible to construct landfills with exposed geomembrane cover. Also, he co-pioneered construction quality assurance of geomembrane liner installation.

Dr. Giroud is author of more than 450 publications, and he has presented several prestigious lectures, such as: the Vienna Terzaghi Lecture, the ASCE Terzaghi Lecture, the Victor de Mello Lecture, the Széchy Lecture, the Mercer Lecture, the Jack Hilf Lecture, the Raoul Dutron Lecture, and now the Koerner Lecture.

Dr. Giroud has been appointed Honorary Member of the IGS with the mention "Dr. Giroud is truly the father of the International Geosynthetics Society and the geosynthetics discipline." The IGS has named his highest award "The Giroud Lecture" with the mention "in recognition of the invaluable contributions of Dr. J.P. Giroud to the technical advancement of the geosynthetics discipline".

Dr. Giroud is Doctor *Honoris Causa* of the Technical University of Bucharest, he has been named Hero of the Geo-Institute of the American Society of Civil Engineers, he received the Felix Leader Award of Ecole Centrale Paris for 2013, and he is Chevalier in the Order of the Legion d'Honneur.

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