HUNGARIAN GEOTECHNICAL SOCIETY
-
HUNGARIAN CHAMBER OF ENGINEERS
GEOTECHNICAL SECTION

SZÉCHY KÁROLY MEMORIAL SESSION

LECTURE
By
J.P. GIROUD
2017.02.10

JP GIROUD THE SZÉCHY LECTURE

1

DESIGN AND PERFORMANCE OF RESERVOIRS LINED WITH GEOMEMBRANES

By
J.P. GIROUD
2017.02.10

JP GIROUD THE SZÉCHY LECTURE 2

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In the past 50 years,
geomembranes have changed
the way geotechnical structures
are waterproofed.

But, some attendees
may not be familiar with geomembranes.

Therefore, I start with
a brief overview of geomembranes.

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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

Photo JP Giroud

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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THE SZÉCHY LECTURE
7

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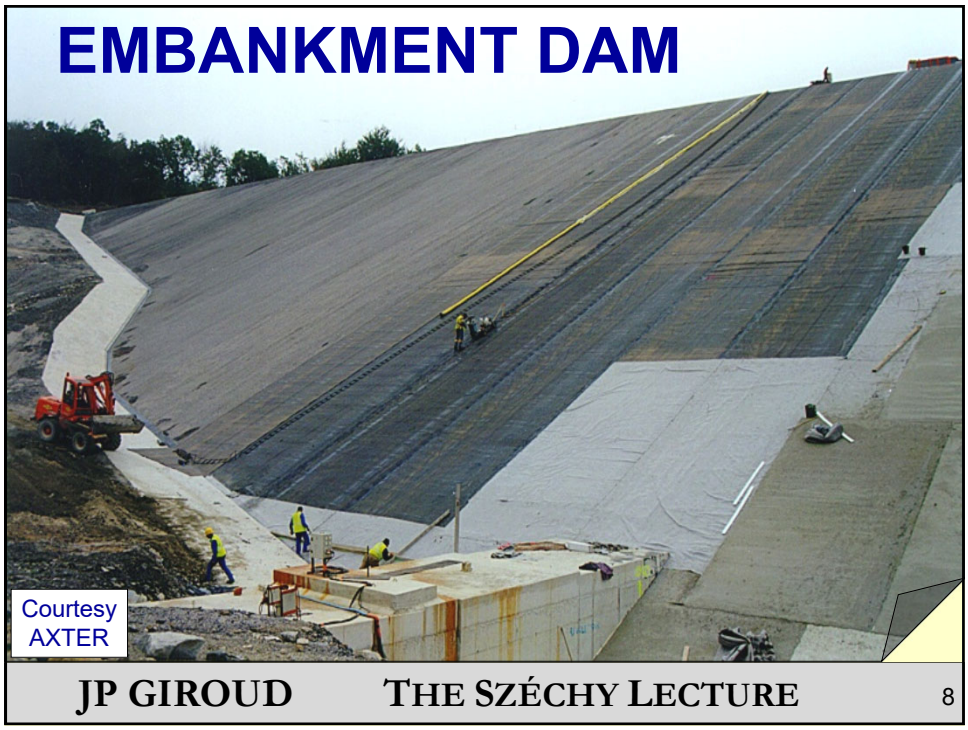
EMBANKMENT DAM
Courtesy
AXTER
JP GIROUD
THE SZÉCHY LECTURE
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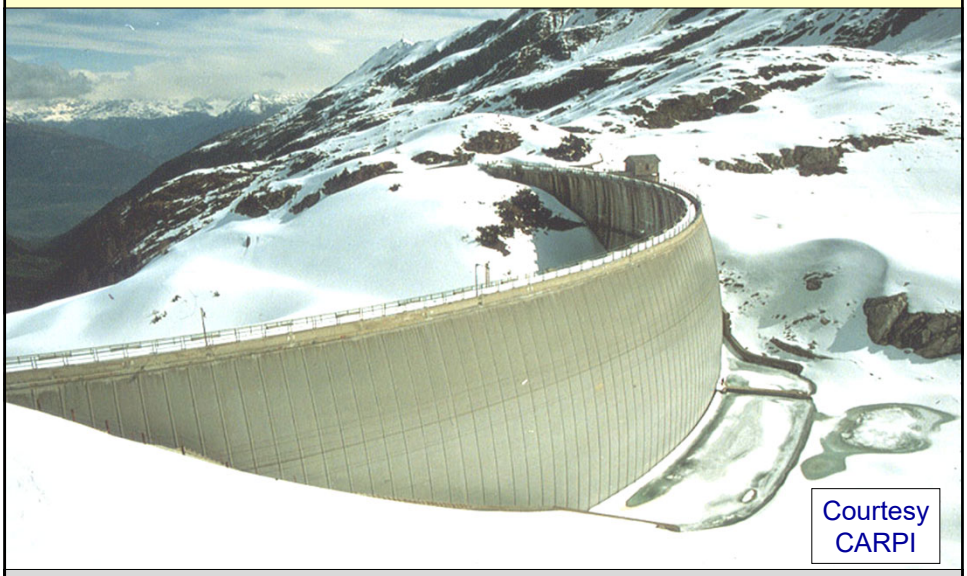
CONCRETE DAM



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CANAL

JP GIROUD THE SZÉCHY LECTURE 10

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Most geomembranes significantly **elongate** when subjected to tensile stresses, which allow them to accommodate **differential displacements**, which is essential in many applications.

However, some geomembranes are **reinforced** with yarns or fibers, which **restrict their elongation**. This is useful in some cases and may be detrimental in other cases.

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Geotextiles are often used to **protect geomembranes** from mechanical damage such as puncturing by stones.

First use of a geotextile to protect a geomembrane
Connantre, France, sugar industry pond, 1971

Geomembrane installed on sand at the bottom and on a nonwoven geotextile on side slopes

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Geonets are often used
to construct **drainage layers**
associated with geomembranes.

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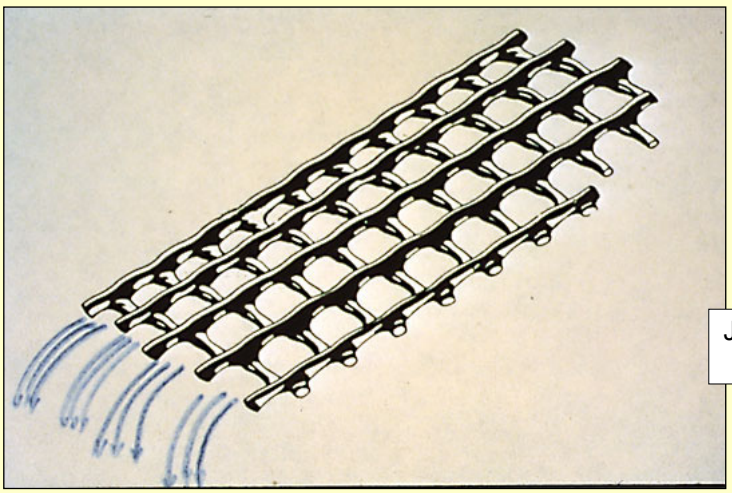
Geonets are thick structures that can convey liquid and gas within their channels.



J.P. Giroud
TENSAR

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Geonet rolls in the field

Photo
J.P. Giroud

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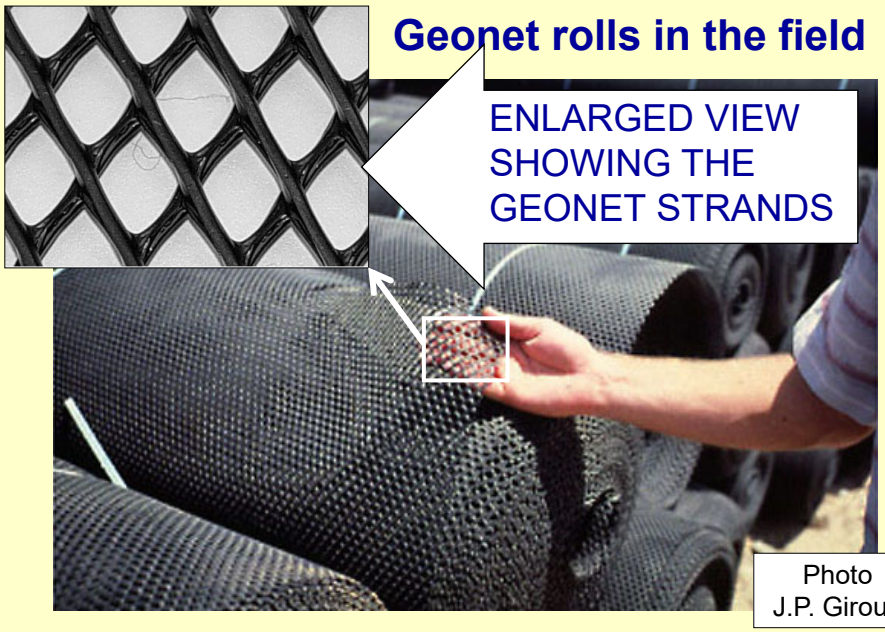
Geonet rolls in the field



Photo
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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 significantly **more permeable**.

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Based on these facts, geomembranes
can be considered **quasi impermeable**.

*Indeed, a **sample of geomembrane***
is practically impermeable.

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

But: *Impermeability on a small scale (**sample**)*
does not guarantee
*impermeability on a large scale (**liner**).*

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In the field, there is always the possibility
of defects associated with geomembranes,
in particular **holes** that cause **leakage**.

Considering that geomembrane liners
are perfectly waterproof,
thereby **ignoring the possibility of leakage**,
would be a **major mistake**
and could lead to **catastrophic failures**.

The importance
of addressing the possibility of leakage
will be illustrated by **four case histories**.

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The **FIRST CASE HISTORY** shows that

BOTH
DESIGN DETAILS
AND
CONCEPTUAL DESIGN
ARE IMPORTANT

This case history describes the
FAILURE OF A
GEOMEMBRANE-LINED RESERVOIR
BUILT ON KARSTIC GROUND

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JP GIROUD THE SZÉCHY LECTURE 21

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CASE HISTORY

- A reservoir designed to contain water was constructed on a layer of natural soil, *only a few meters thick*, overlying a **karstic formation**.
- A karstic formation is a mass of **limestone** that includes **cavities**.
- These cavities are either **empty** or **partly filled** with soil.

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The reservoir was close to
an abandoned quarry,
which provided an opportunity
to see the karstic formation.

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

Photo
J.P. Giroud

Numerous cavities could be observed.

JP GIROUD THE SZÉCHY LECTURE 24

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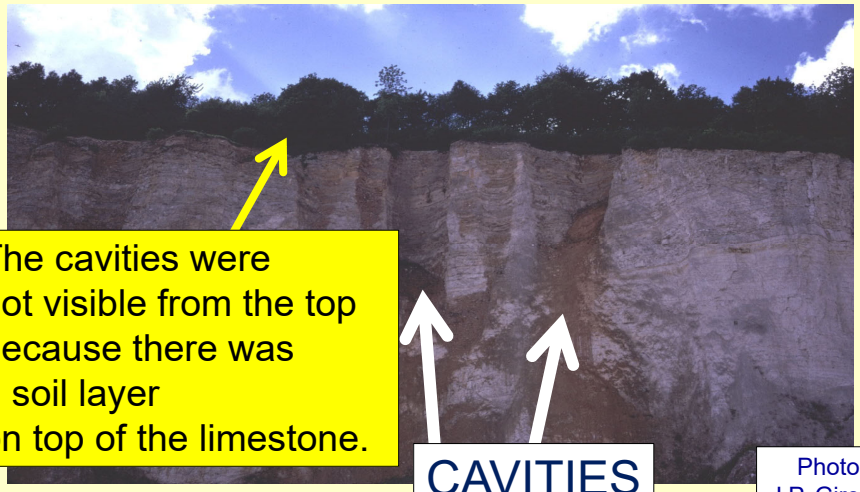
Here is the wall of the quarry,
showing a cross section of the karstic formation.



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

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Unfortunately, at the design stage,
no geological study was done
and the quarry was not observed.

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

As a result,
the designer of the reservoir ignored
the situation shown on the next slide.

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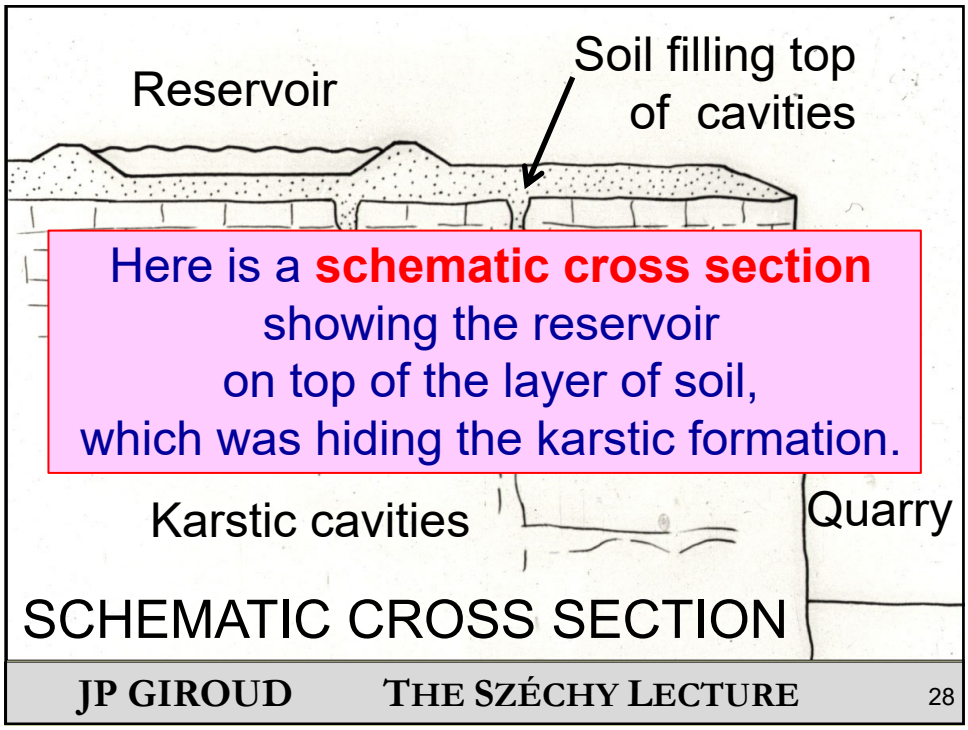

JP GIROUD THE SZÉCHY LECTURE 28

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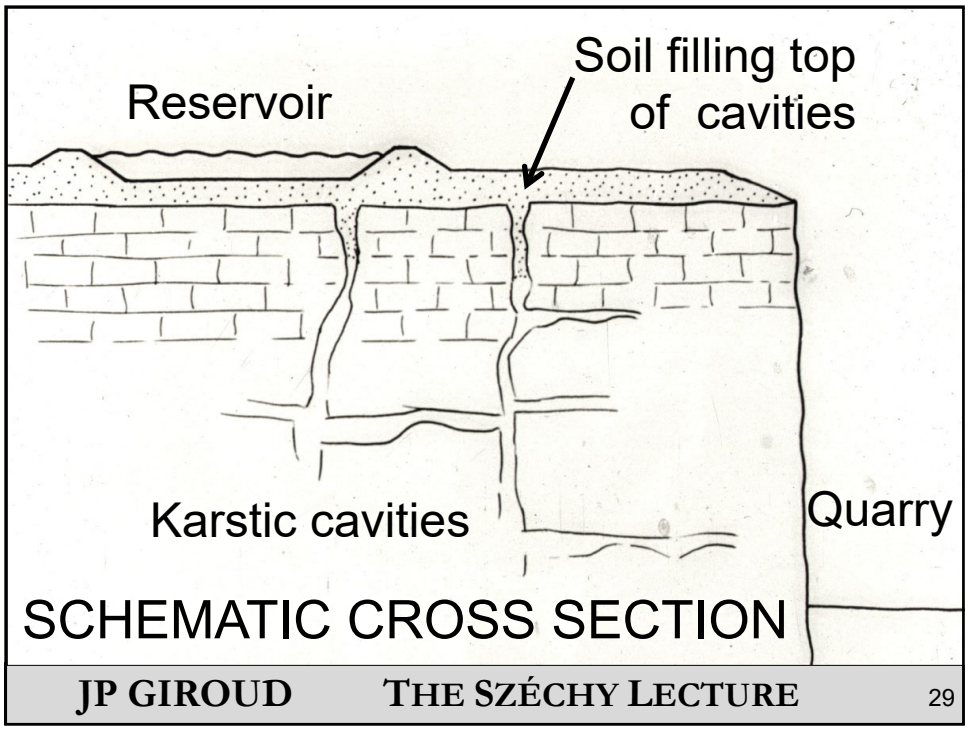

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THE RESERVOIR LINER SYSTEM

- 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.

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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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A schematic cross section
of the liner system
is shown on the next slide.

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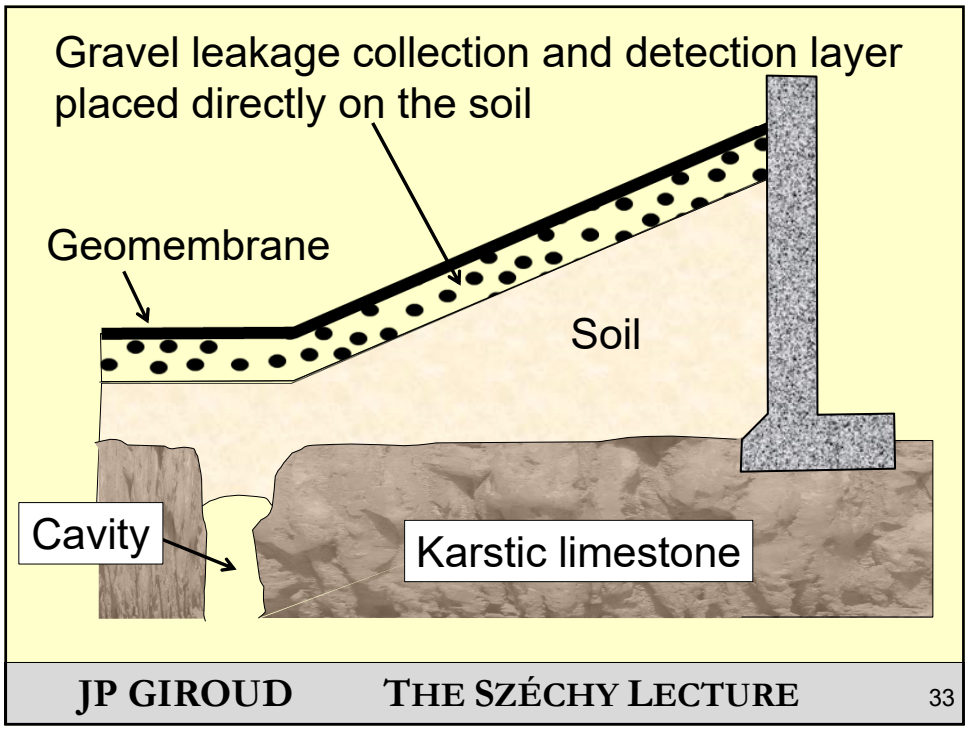
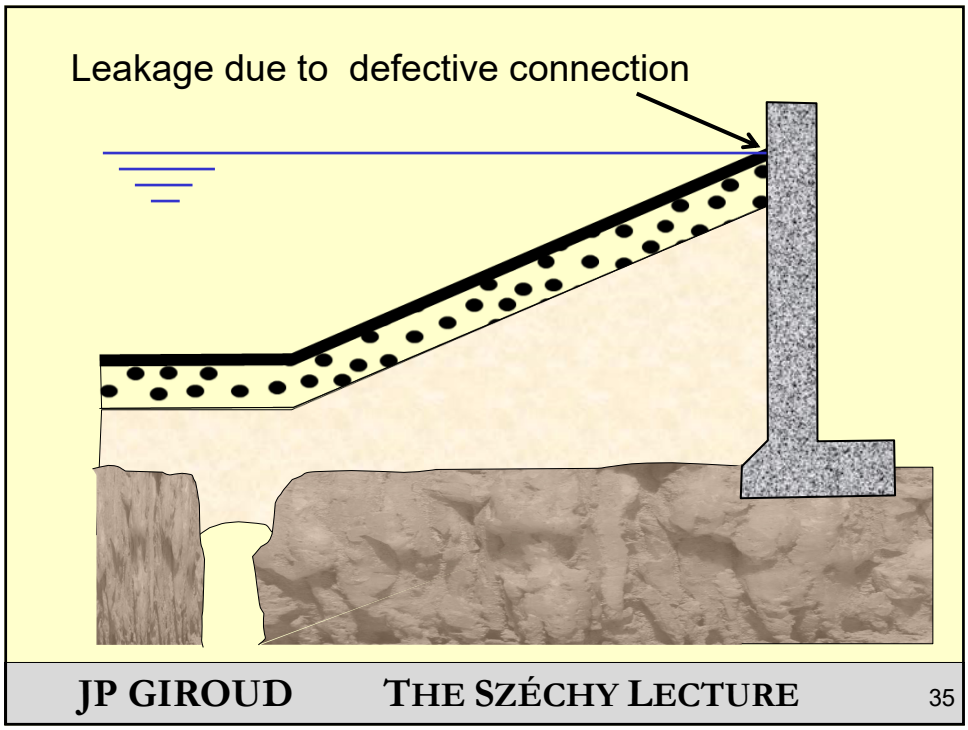


33

DESCRIPTION OF FAILURE

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

34



35

DESCRIPTION OF FAILURE

- During the first filling of the reservoir, extensive leakage occurred at the defective connection between the geomembrane and a concrete structure.
- The **leaking water flowed downslope** in the leakage collection and detection layer and reached an area where soil covered and partly filled a **cavity**.

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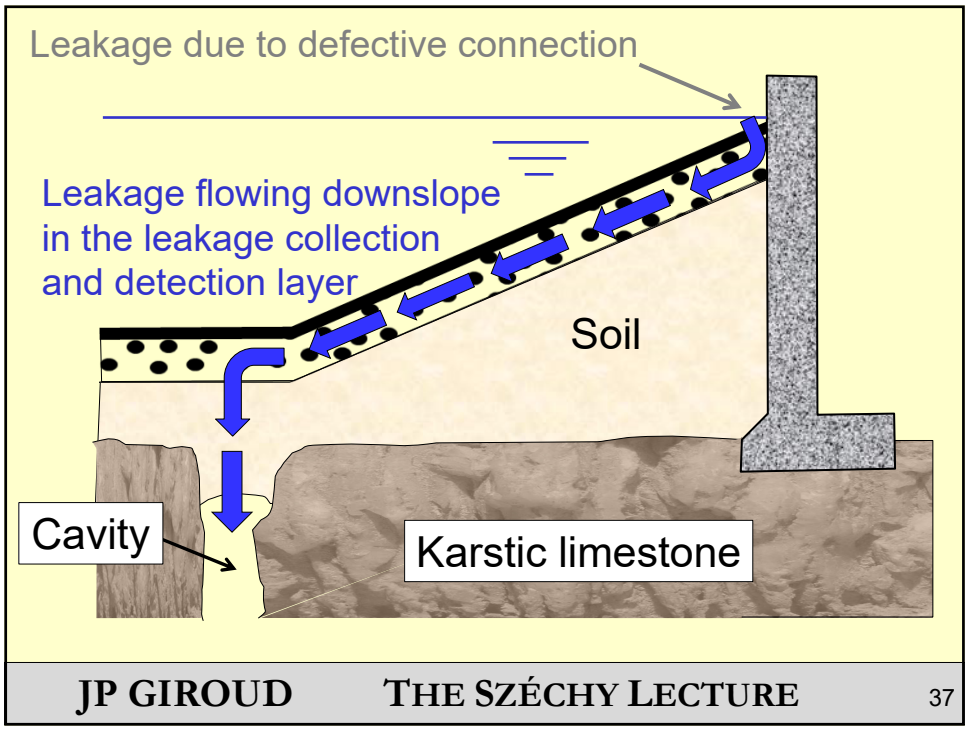
Leakage due to defective connection
Leakage flowing downslope
in the leakage collection
and detection layer
Soil
Cavity
Karstic limestone
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THE SZÉCHY LECTURE
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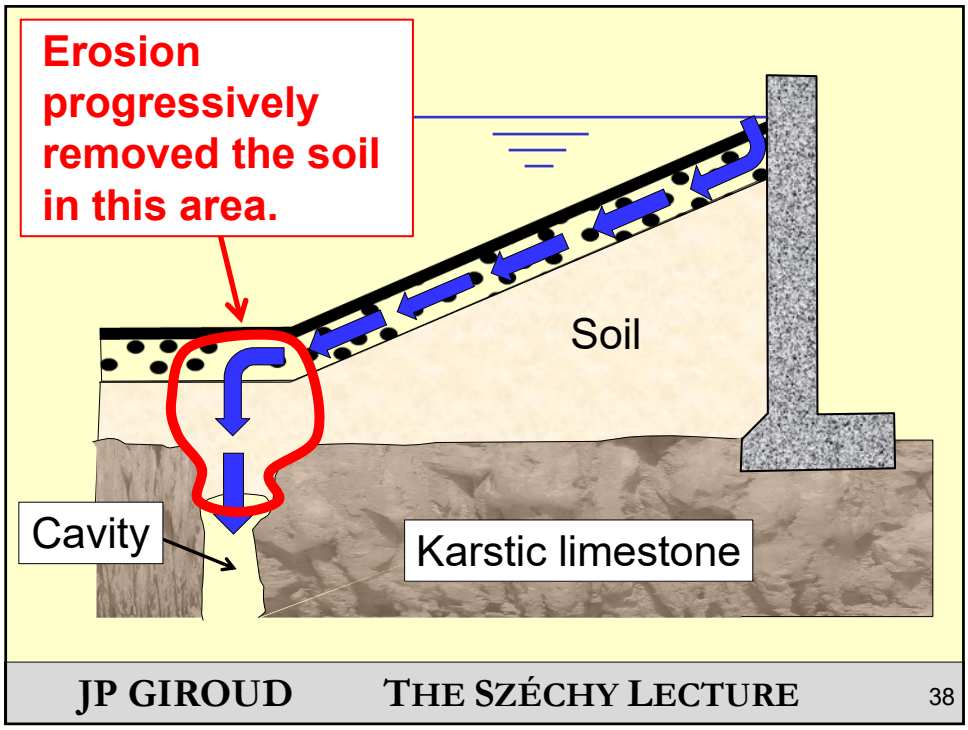
Erosion
progressively
removed the soil
in this area.
Soil
Cavity
Karstic limestone
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THE SZÉCHY LECTURE
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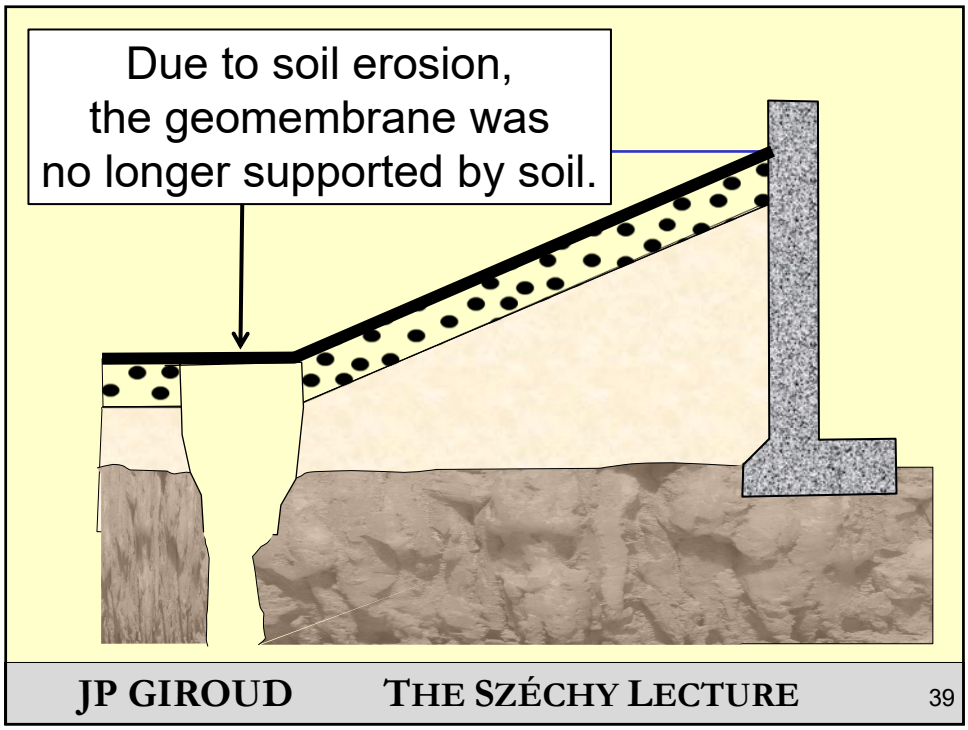
Due to soil erosion,
the geomembrane was
no longer supported by soil.
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THE SZÉCHY LECTURE
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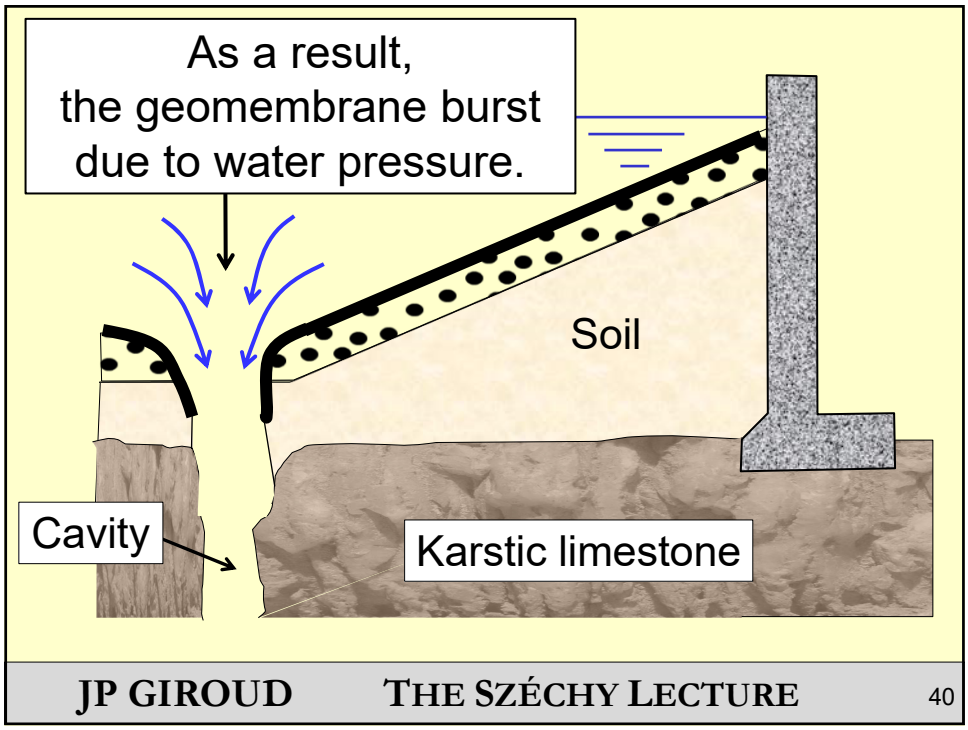
As a result,
the geomembrane burst
due to water pressure.
Soil
Cavity
Karstic limestone
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THE SZÉCHY LECTURE
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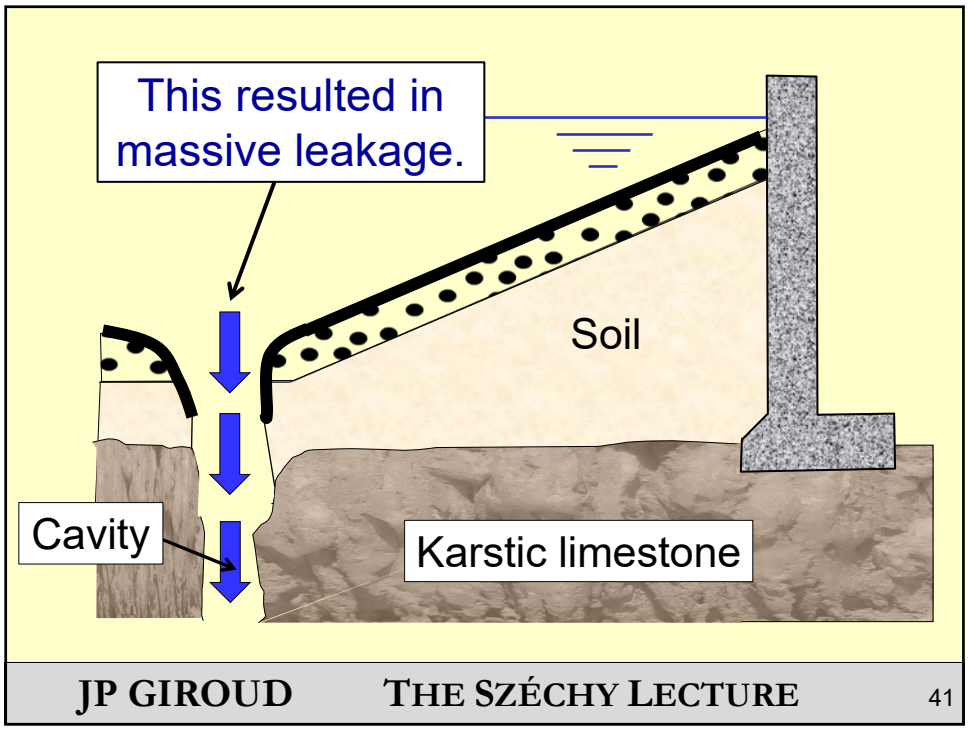
This resulted in massive leakage.
Soil
Cavity
Karstic limestone
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THE SZÉCHY LECTURE
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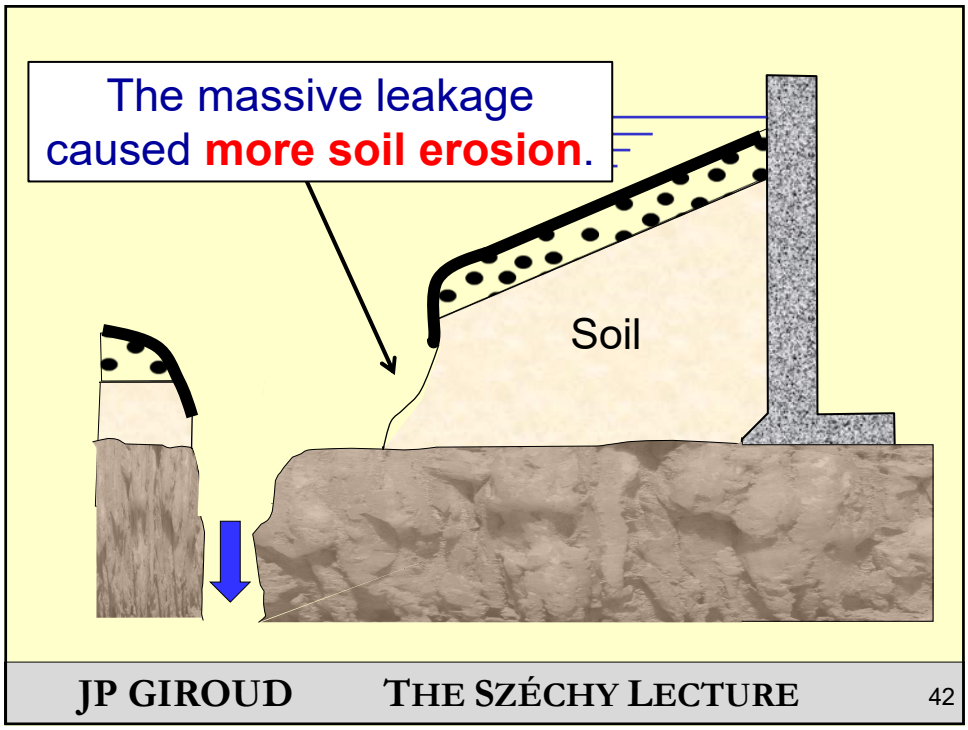
The massive leakage caused more soil erosion.
Soil
JP GIROUD
THE SZÉCHY LECTURE
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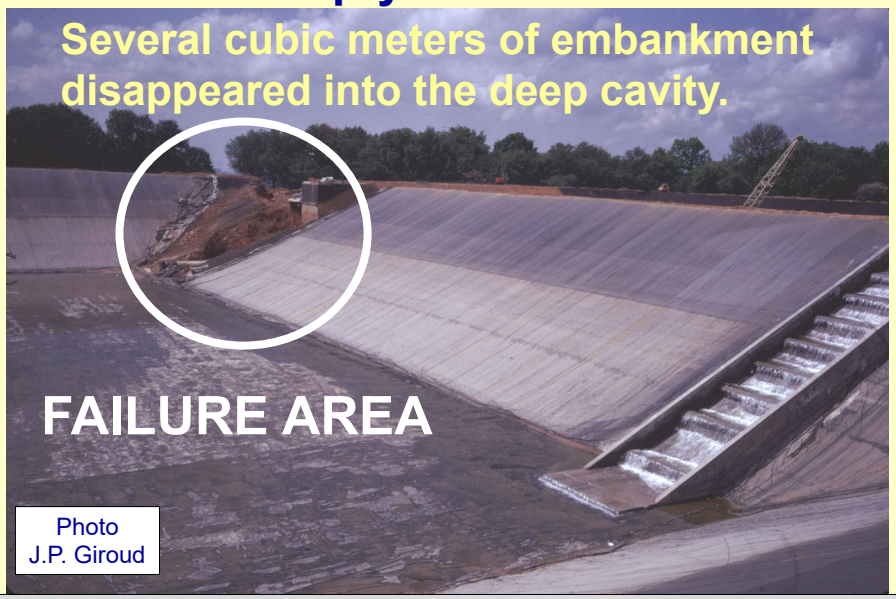
View of the empty reservoir after failure



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CLOSER VIEW OF THE FAILURE AREA

Concrete structure to which the geomembrane was attached.

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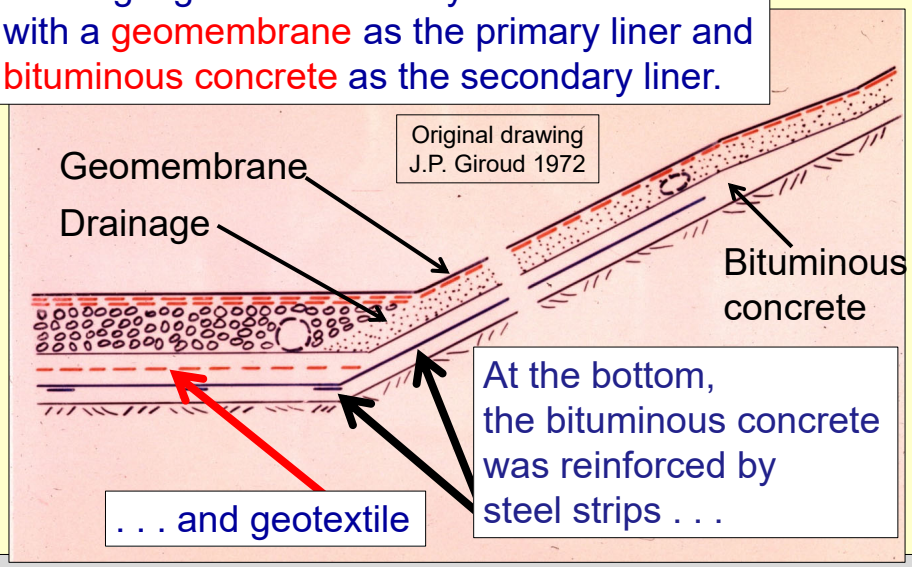
The repair consisted in replacing
the single geomembrane by a **double liner**
with a geomembrane as the primary liner and
bituminous concrete as the secondary liner.



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The function of the secondary liner
(i.e. the liner located under
the leakage collection and detection layer)
was to **prevent water**
collected by
the leakage collection and detection layer
from infiltrating into the ground.

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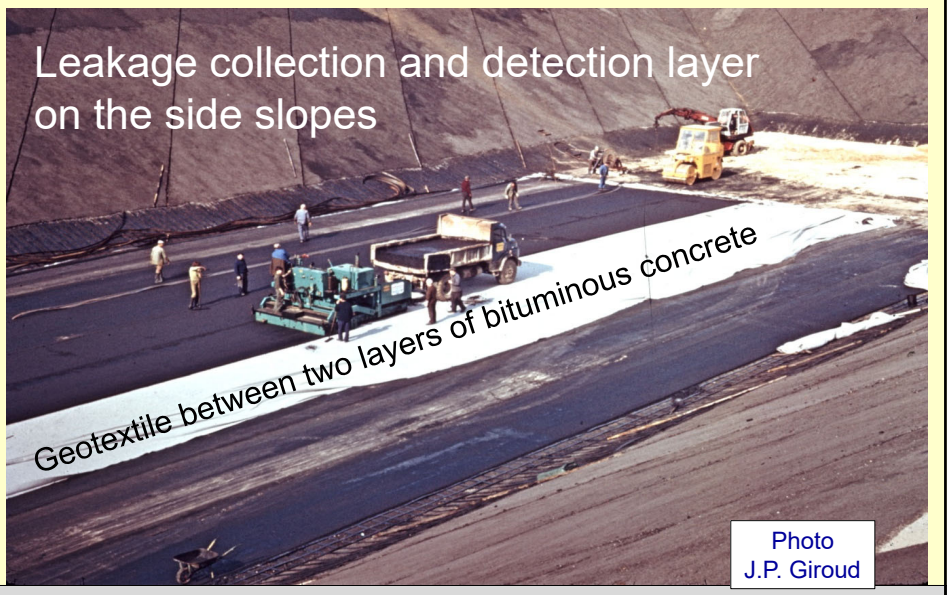
CONSTRUCTION OF THE REMEDIATION



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STEEL STRIPS USED TO REINFORCE THE BOTTOM

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COMMENT ON THE REMEDIATION

- The most important aspect of the repair was the use of a **double liner** system, because it addressed the **cause of the problem**, which was leakage into the ground.
- The use of **reinforcement** only addressed the *consequence of leakage*, which was bursting of the geomembrane.

CONCLUSION

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

In other words :

- The **main cause** was a **conceptual design flaw**: the **absence of a liner** under the leakage collection and detection layer.
- With an appropriate conceptual 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 lesson learned:

- With a geomembrane liner, **a leak is always possible** *(for example, due to a geomembrane hole, or a defective connection)*.
- Therefore, the **potential consequences of a leak** should always be analyzed.
- If the consequences are unacceptable, the **design should be improved**.

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While the first case history was about a **failure**, the second case history is not about failure.

The **SECOND CASE HISTORY** is about a **successful performance** thanks to adequate design.

This is the case history of the first double liner constructed with two geomembranes.

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Before presenting the case history, let's review some general information about **double liners**.

Remember, in the preceding case history, the remediation of the failure consisted in constructing a **double liner**.

After this successful remediation, I published in 1973 a paper presenting the double liner concept.

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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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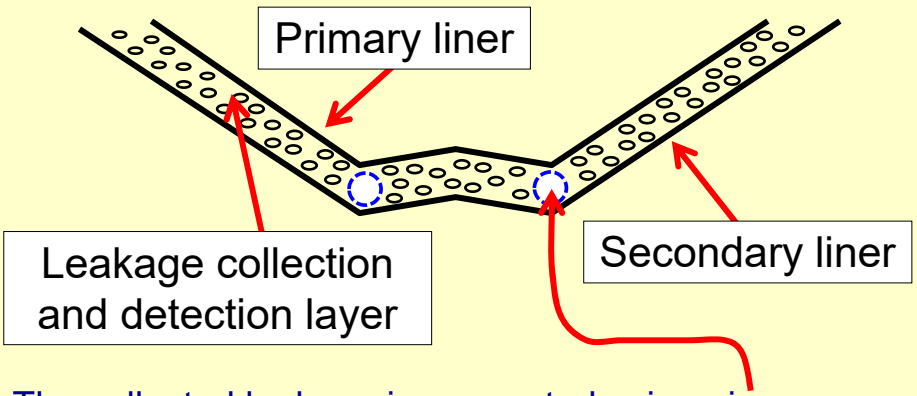
SCHEMATIC REPRESENTATION OF A DOUBLE LINER SYSTEM



The collected leakage is evacuated using pipes included in the leakage collection and detection layer.

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

And now, the case history

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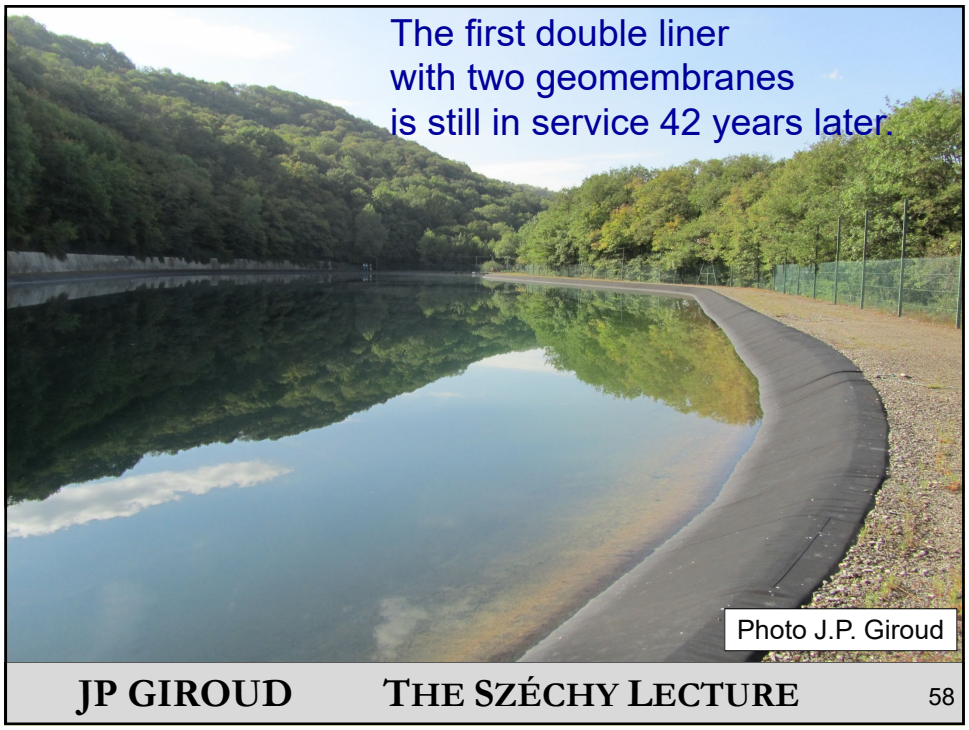

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The water **reservoir** is located on a **steep slope**.

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.

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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.

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

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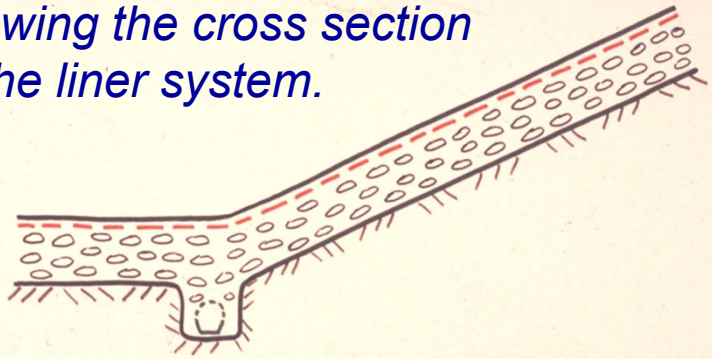
Here is the original drawing showing the cross section of the liner system.



Original drawing by J.P. Giroud

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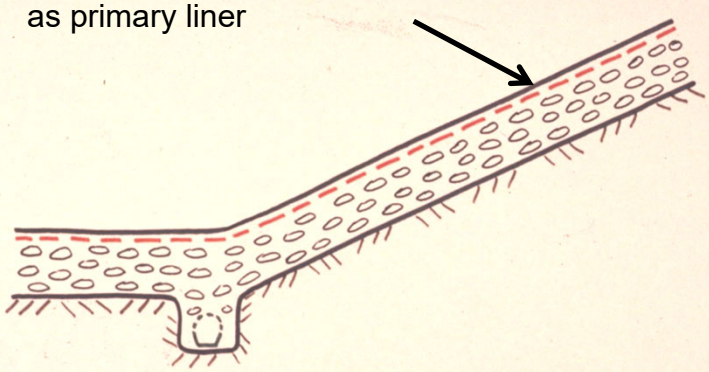
Butyl rubber geomembrane
as primary liner



Original drawing by J.P. Giroud

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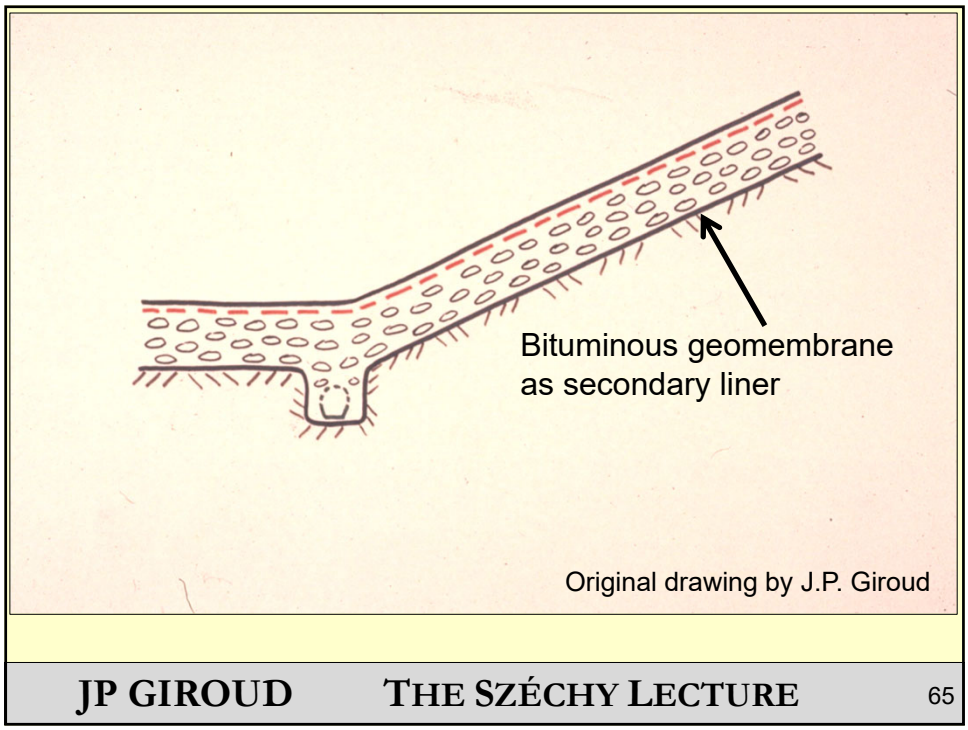
Bituminous geomembrane
as secondary liner
Original drawing by J.P. Giroud
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THE SZÉCHY LECTURE
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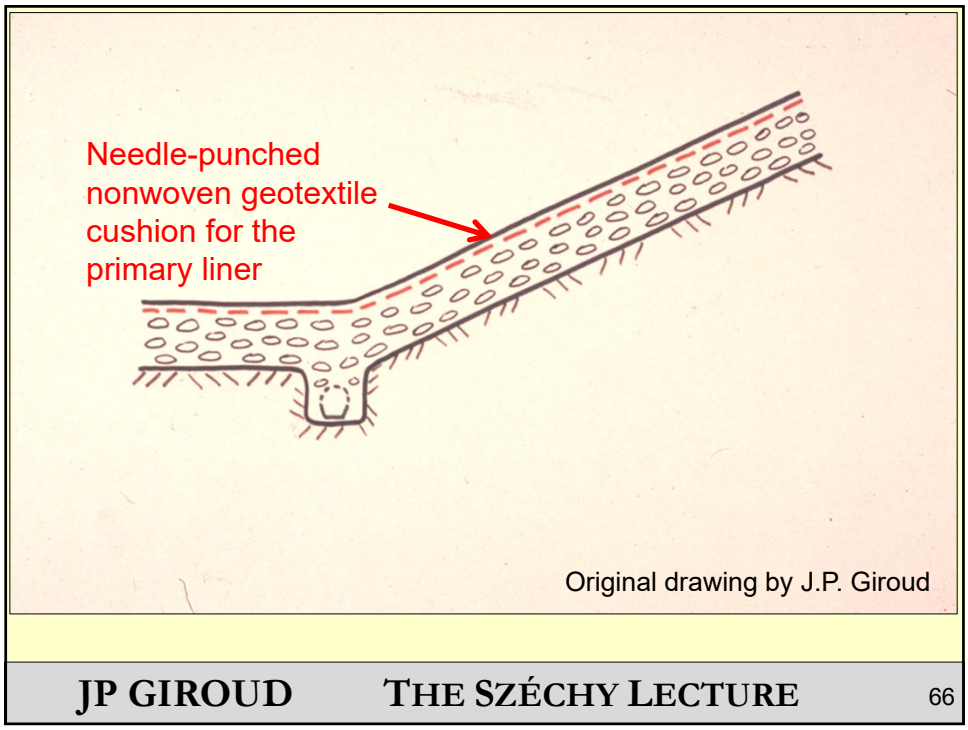
Needle-punched
nonwoven geotextile
cushion for the
primary liner
Original drawing by J.P. Giroud
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THE SZÉCHY LECTURE
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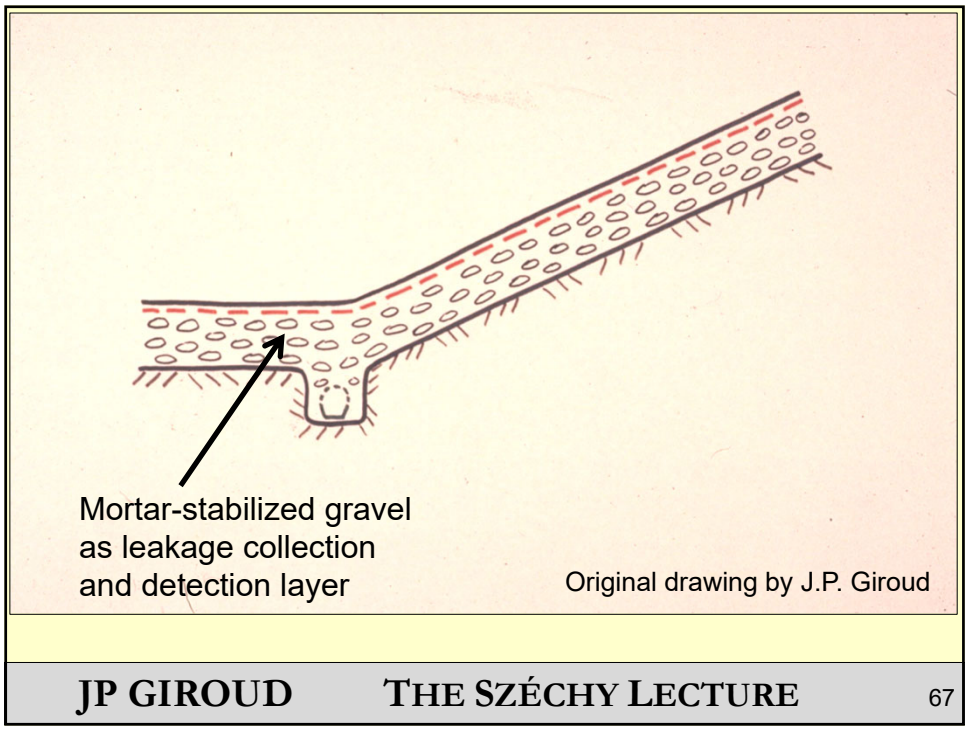
Mortar-stabilized gravel
as leakage collection
and detection layer
Original drawing by J.P. Giroud
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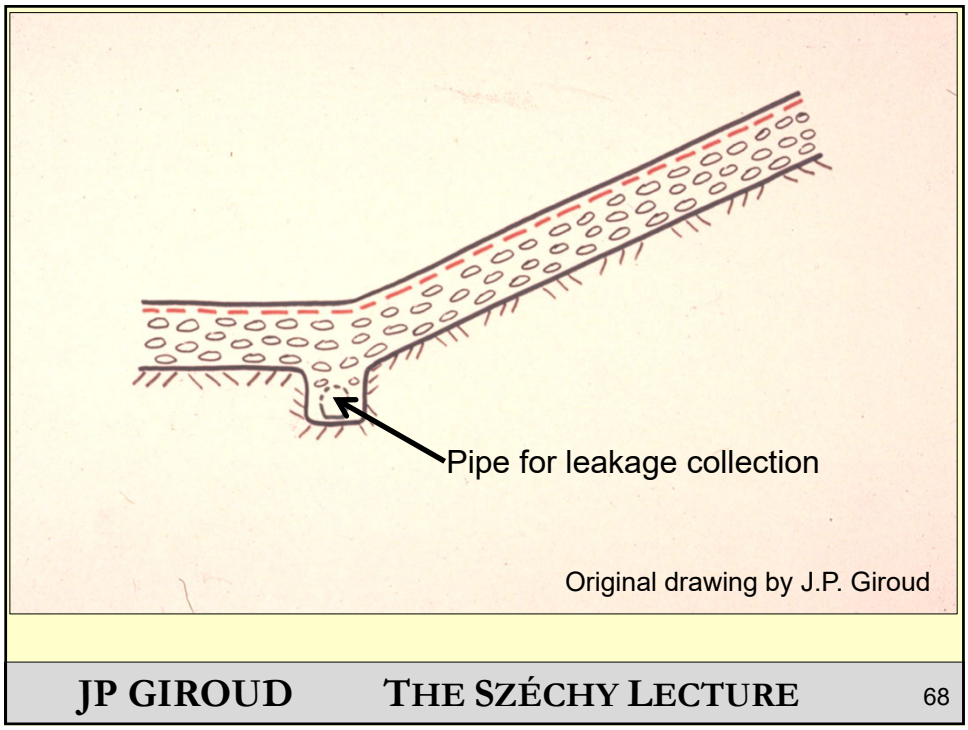
Pipe for leakage collection
Original drawing by J.P. Giroud
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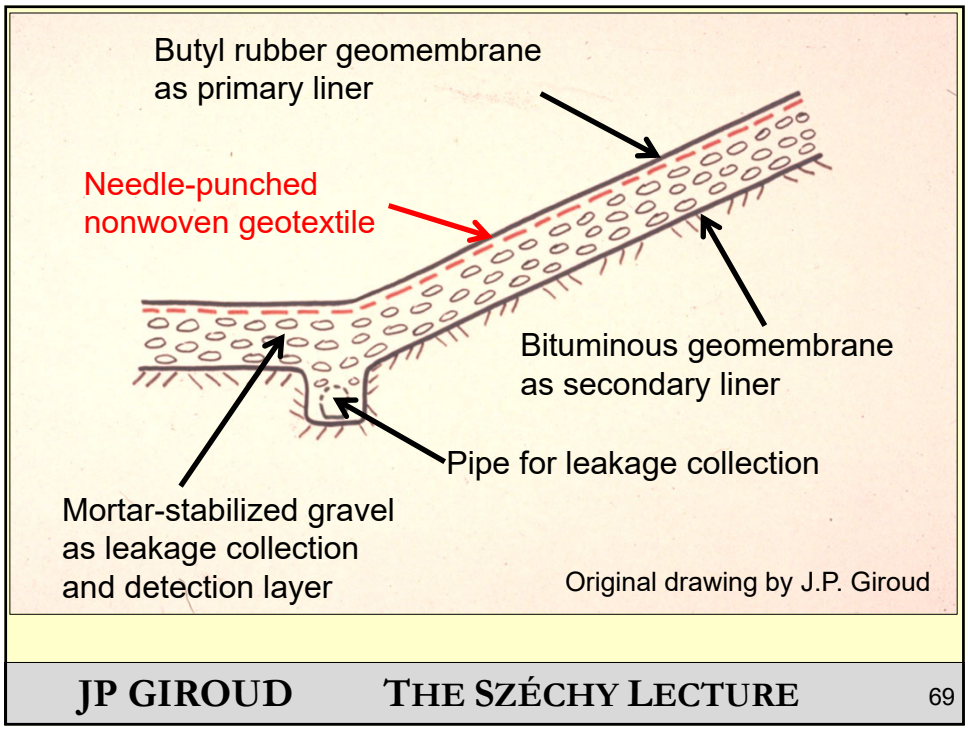

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The construction phases
are presented
on the following slides.

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THE SZÉCHY LECTURE
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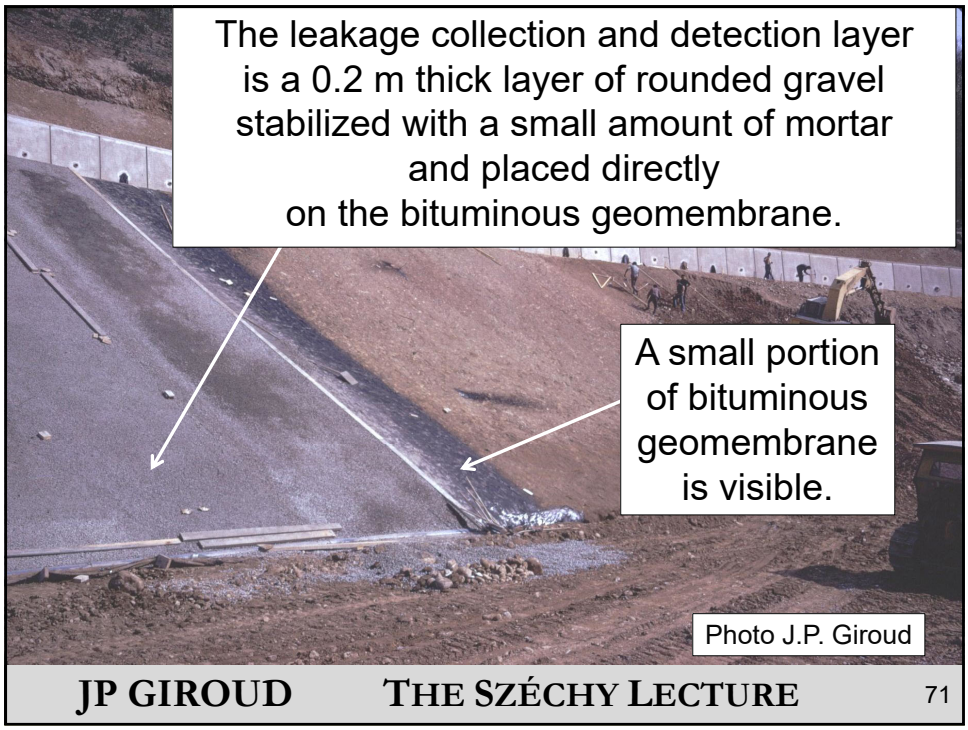
The leakage collection and detection layer is a 0.2 m thick layer of rounded gravel stabilized with a small amount of mortar and placed directly on the bituminous geomembrane.
A small portion of bituminous geomembrane is visible.
Photo J.P. Giroud
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THE SZÉCHY LECTURE
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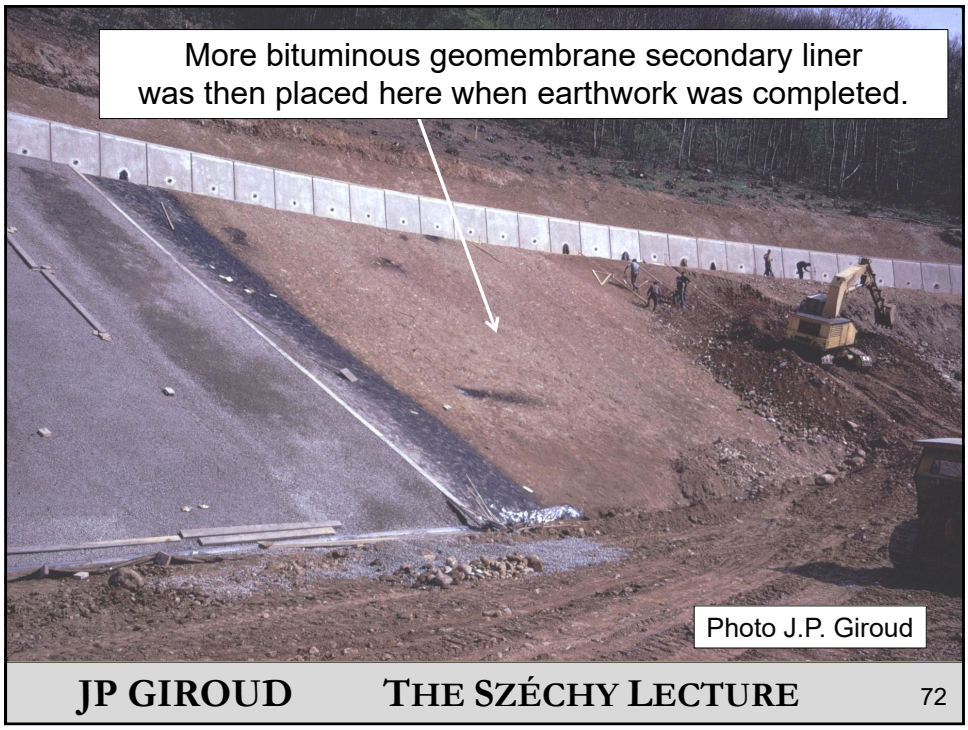
More bituminous geomembrane secondary liner was then placed here when earthwork was completed.
Photo J.P. Giroud
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THE SZÉCHY LECTURE
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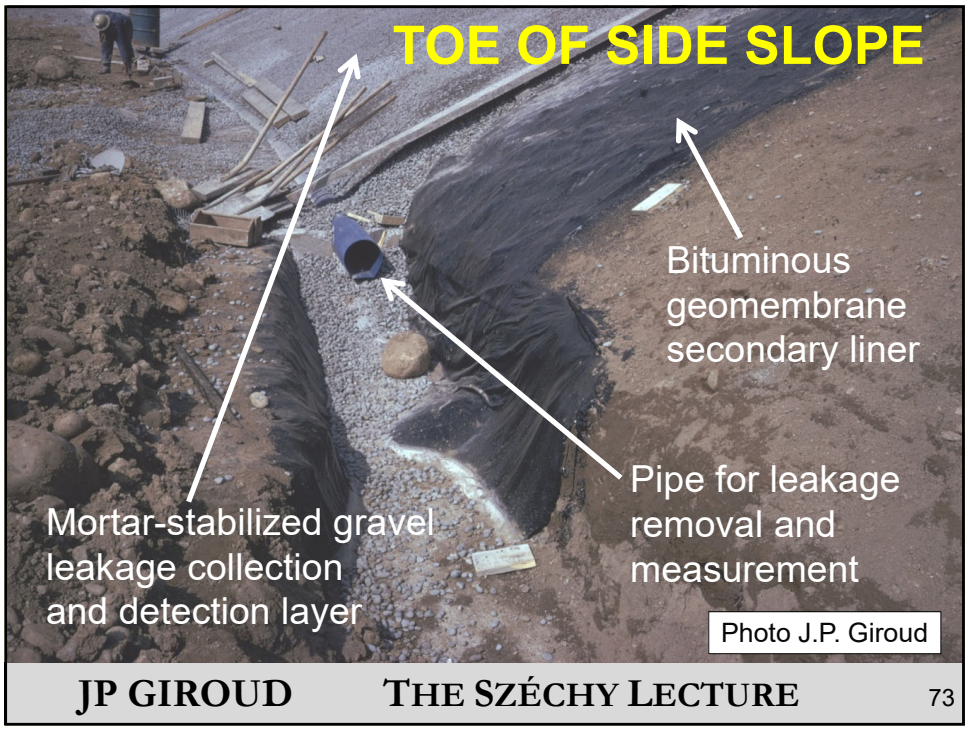
TOE OF SIDE SLOPE
Bituminous geomembrane secondary liner
Pipe for leakage removal and measurement
Mortar-stabilized gravel leakage collection and detection layer
Photo J.P. Giroud
JP GIROUD THE SZÉCHY LECTURE 73

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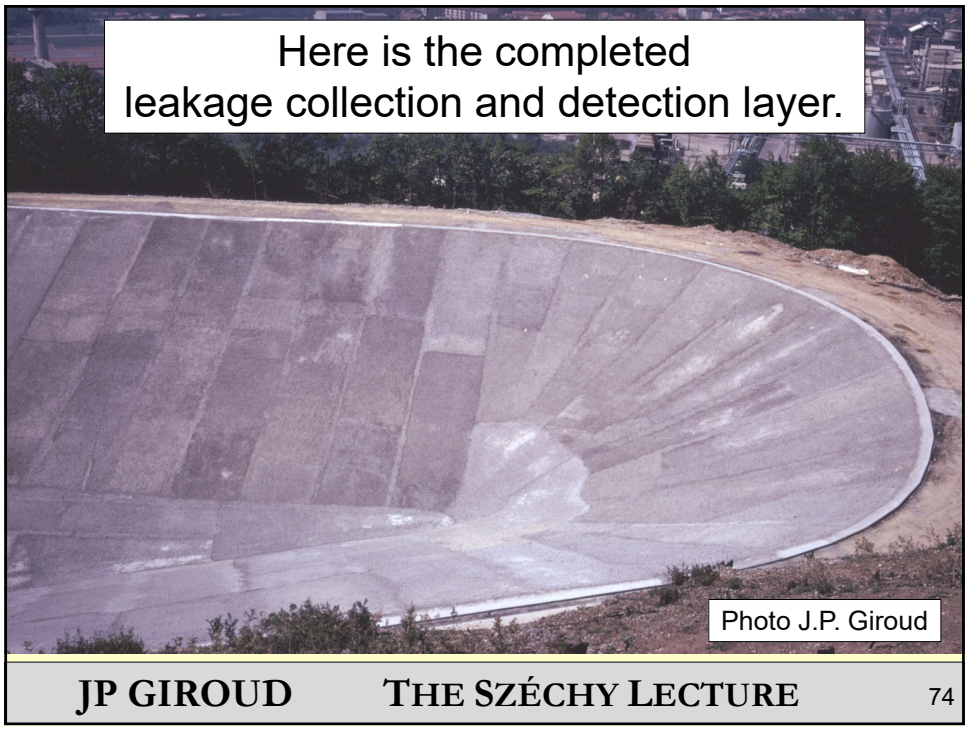
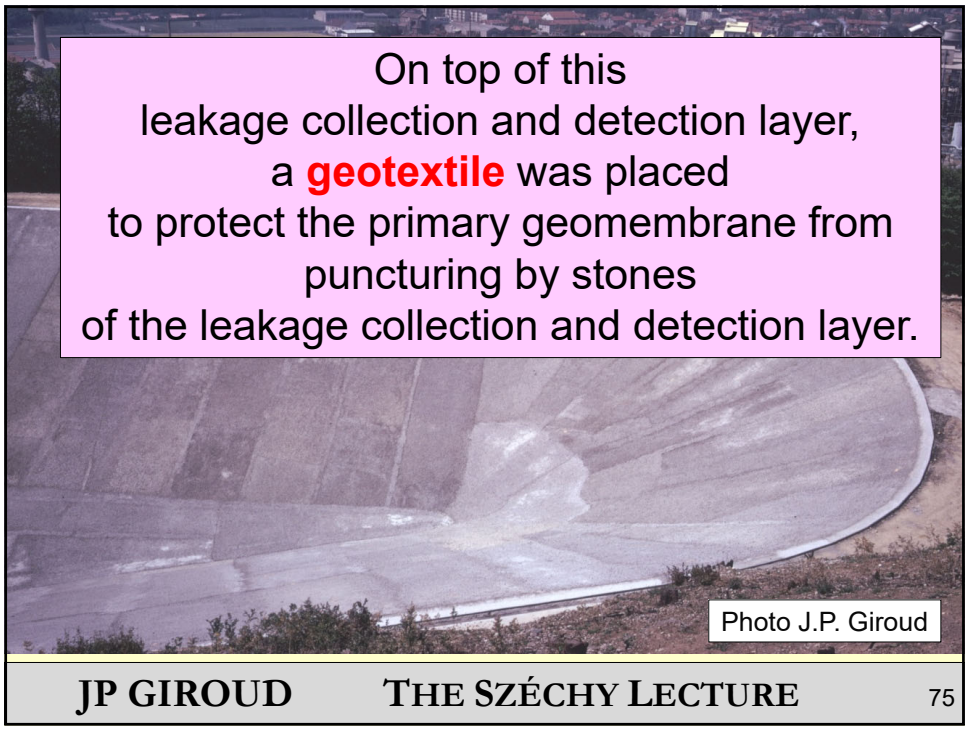
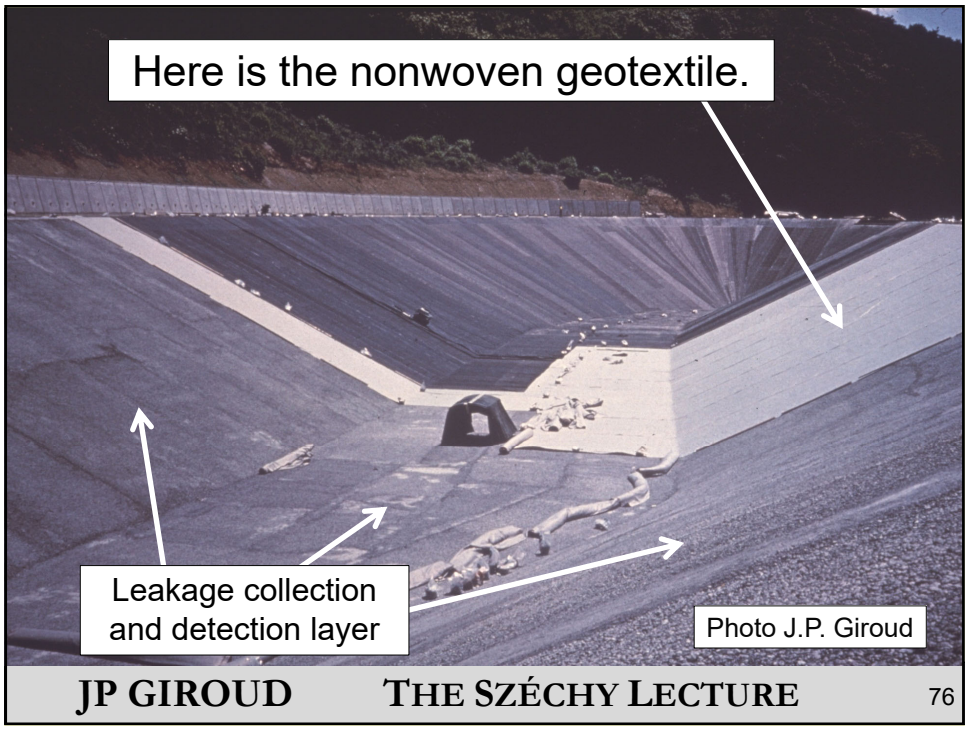

Here is the completed leakage collection and detection layer.
Photo J.P. Giroud
JP GIROUD THE SZÉCHY LECTURE 74

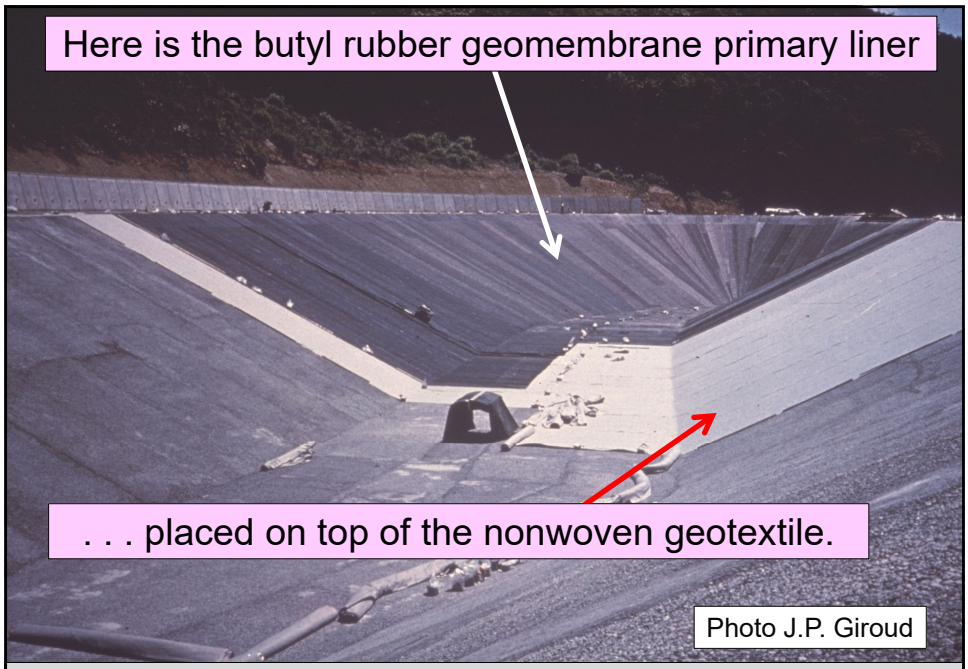
74


On top of this
leakage collection and detection layer,
a geotextile was placed
to protect the primary geomembrane from
puncturing by stones
of the leakage collection and detection layer.
Photo J.P. Giroud
JP GIROUD THE SZÉCHY LECTURE 75

75


Here is the nonwoven geotextile.
Leakage collection
and detection layer
Photo J.P. Giroud
JP GIROUD THE SZÉCHY LECTURE 76

76



77

The selection
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

78

JP GIROUD THE SZÉCHY LECTURE 79

79

PERFORMANCE DURING 42 YEARS

- Only one incident happened:
  very small **leakage** was detected
  by the leakage collection and detection system
  in 2004: **30 years after construction**.
- The exact **location of the leak**
  was found thanks to air bubbles
  moving up to the reservoir water surface.
- The **hole** in the geomembrane was small,
  as reported by divers.
- The hole was **near the water intake structure**.

JP GIROUD THE SZÉCHY LECTURE 80

80

81

The small hole in the geomembrane was repaired by divers.

82

JP GIROUD THE SZÉCHY LECTURE 83

83

The **remarkable durability** of the geomembrane can be explained as follows:

- Butyl rubber ages more rapidly when it is elongated because the **double bonds** of its molecular chains then become **more accessible to ozone atoms**, which cause aging of butyl rubber.
- As a result, **reinforced butyl rubber**, *(where elongation is restricted by the reinforcing fabric)* ages less rapidly than non-reinforced butyl rubber.
- Therefore, the geomembrane supplier recommended the use of **reinforced geomembrane** at the **top of the side slopes**.

JP GIROUD THE SZÉCHY LECTURE 84

84

Accordingly, a reinforced geomembrane
was used in the upper two meters
of the side slope,
that is the portion of geomembrane
that was to be permanently exposed
to atmosphere, therefore, to ozone.

In contrast a non-reinforced
butyl rubber geomembrane was used
in the rest of the slope and on the bottom.

JP GIROUD THE SZÉCHY LECTURE 85

85

Using a **non-reinforced** geomembrane
for the **rest of the liner** was appropriate
because a **non-reinforced geomembrane**
can elongate more
than a reinforced geomembrane,
and is, therefore, better
to **accommodate differential displacements**
between the embankment
and the concrete structure
to which the geomembrane is attached.

JP GIROUD THE SZÉCHY LECTURE 86

86

Therefore, the remarkable **durability**
of the geomembrane liner
resulted from **cooperation** between
a **geomembrane supplier**
understanding **polymer behavior**
and a **geotechnical engineer**
understanding
the **behavior of construction materials**
(in this case, differential settlement).

JP GIROUD THE SZÉCHY LECTURE 87

87

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 THE SZÉCHY LECTURE 88

88

It should be noted that the **usual reasons** for using a double liner are **economical** (*to minimize the loss of liquid*) and **environmental** (*to minimize soil contamination*).

In this case, the reason was to eliminate the risk of slope instability.

Clearly **the reason was geotechnical**.

A lesson to be remembered by geotechnical engineers.

The lessons learned from this case history are:

- Geotechnical engineers **should learn** about the behavior of **new materials** such as geomembranes.
- From this viewpoint, **cooperation** between **geotechnical engineers** and **polymer scientists** is necessary.

The **THIRD CASE HISTORY** shows that

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

FAILURE OF A RESERVOIR LINER
DUE TO INADEQUATE
CONCEPTUAL DESIGN

CASE HISTORY

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

The pond emptied after **bursting** of the geomembrane over several **large cavities**.

JP GIROUD THE SZÉCHY LECTURE 93

93

These cavities resulted from dissolution by phosphoric acid of calcium carbonate contained in the soil.

When the geomembrane was removed, many cavities were found.

JP GIROUD THE SZÉCHY LECTURE 94

94

GEOMEMBRANE REMOVAL

Photo J.P. Giroud

JP GIROUD THE SZÉCHY LECTURE 95

95

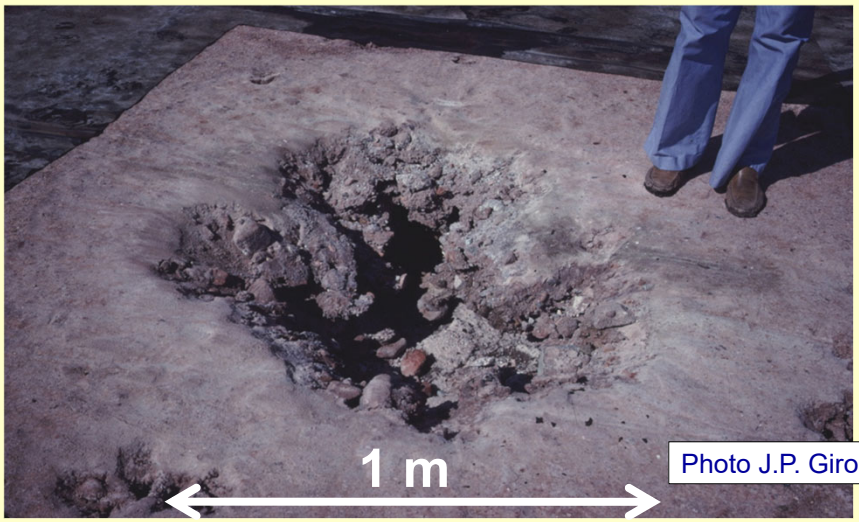
Dissolution of calcium carbonate by acid was clearly associated with leaks through the geomembrane.

Photo J.P. Giroud

JP GIROUD THE SZÉCHY LECTURE 96

96

Some cavities were large.



JP GIROUD THE SZÉCHY LECTURE 97

97

CONDITION OF THE GEOMEMBRANE

The geomembrane had many defects
(open seams, punctures, tears)
due to careless construction.

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

JP GIROUD THE SZÉCHY LECTURE 98

98

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 pond** demanded
that the contractor install
a new geomembrane "with zero leakage".

99

STRATEGY FOR REPAIR

I convinced the owner
that it is impossible
to install a geomembrane liner
over two hectares without defects,
and that the same problem
would happen again,
unless the project is redesigned.

100

From a discussion with the owner,
I understood that the large pond
had two functions:

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

I concluded that the **solution**
would consist in
separating the two functions.

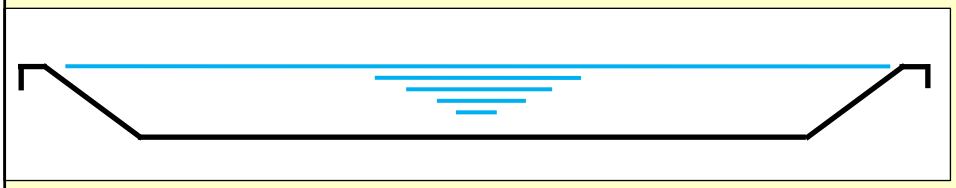
101

RECONSTRUCTION

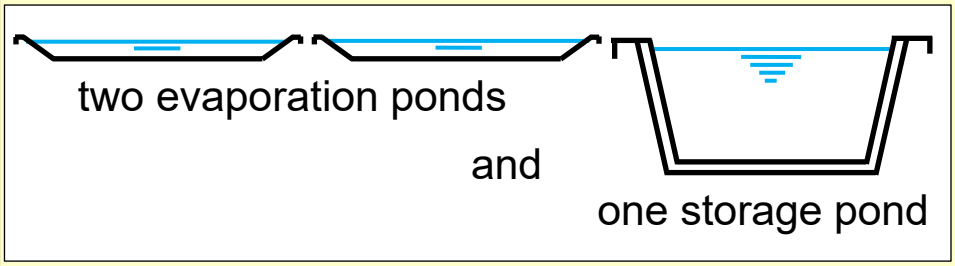
After earthwork
to eliminate the soil contaminated
and/or attacked by acid,
three smaller ponds
were constructed
to replace the large pond.

102

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



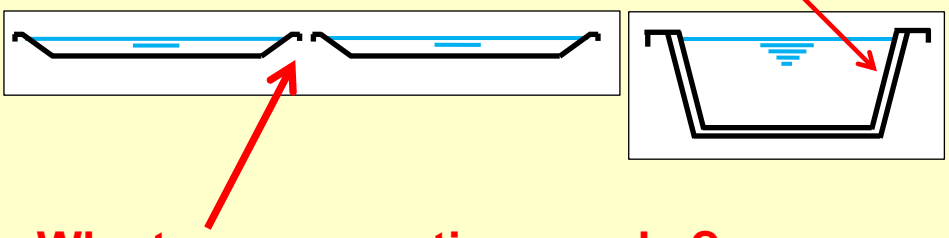
was replaced by three ponds:



JP GIROUD THE SZÉCHY LECTURE 103

103

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



Why two evaporation ponds ?

Answer on the next slide

JP GIROUD THE SZÉCHY LECTURE 104

104

Why two evaporation ponds ?

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

JP GIROUD THE SZÉCHY LECTURE 105

105

GENERAL LESSONS LEARNED

- Claims such as "**zero leakage**"
  or "**absolutely impermeable liner**"
  should not be believed.
- In reality, **all liners may leak**.
- The **consequences of leakage**
  should be evaluated.
- The design of the pond
  should be adapted to the situation.

JP GIROUD THE SZÉCHY LECTURE 106

106

GENERAL LESSONS LEARNED

Leakage control is not achieved
by believing in an ideal material.

Leakage control is achieved by **design**.

Therefore,
geotechnical engineers are essential
for the successful performance
of geomembrane liners.

107

The FOURTH CASE HISTORY
shows that

IT IS IMPORTANT TO CONVINCE OTHERS

FAILURE OF A RESERVOIR LINER
DUE TO MISUNDERSTOOD
GEOMEMBRANE BEHAVIOR

108

A large volume of water
(about 8000 m^3)
was needed
for a physics experiment
by a team
led by a Nobel prize winner
to evaluate the life span
of protons.

THE PROTON DECAY EXPERIMENT

JP GIROUD THE SZÉCHY LECTURE 109

109

To contain the water required
by the physics experiment,
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*)
600 m underground
(*because cosmic radiation does not penetrate that deep*).

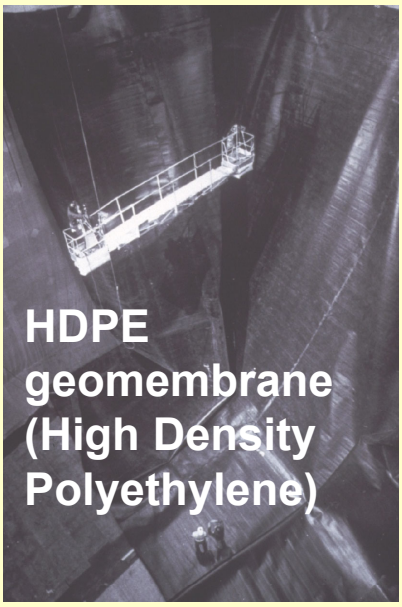
JP GIROUD THE SZÉCHY LECTURE 110

110

The reservoir was
to contain the **purest water**
ever produced
in order to detect
the faint light given off
by decaying protons.

An **HDPE** geomembrane
was selected
for its **chemical inertia**.

Other geomembranes
could have
contaminated the water.



JP GIROUD THE SZÉCHY LECTURE 111

111

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

Due to the solubility
of the salt,
I recommended
a **double liner**
(i.e. two liners
and a leakage collection
and detection layer
in between).

JP GIROUD THE SZÉCHY LECTURE 112

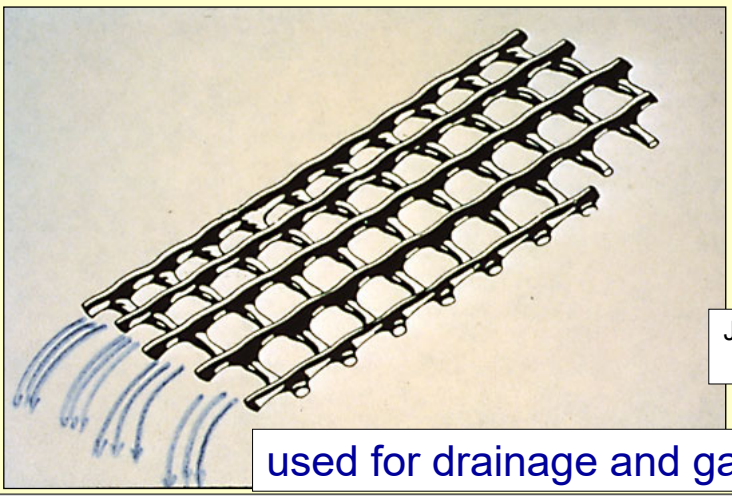
112

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
could be **installed vertically**.

JP GIROUD THE SZÉCHY LECTURE 113

113

**Geonets are thick polymeric structures
that can convey liquid and gas
within their channels.**



used for drainage and gas venting

JP GIROUD THE SZÉCHY LECTURE 114

114

Here are rolls of geonet in the field.

Photo
J.P. Giroud

JP GIROUD THE SZÉCHY LECTURE 115

115

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 SZÉCHY LECTURE 116

116

The reservoir had been excavated before designing the liner system.

The corners of the reservoir were at **right angles**.

For me this was a difficult situation, and, to design the liner, I asked for the **stress-strain curve** of the geomembrane .

JP GIROUD THE SZÉCHY LECTURE 117

117

This was an extraordinary request at that time, and it was not easy to obtain the stress-strain curve for a geomembrane !

JP GIROUD THE SZÉCHY LECTURE 118

118

Here is a **tensile test** on a geomembrane specimen.

The **elongation** is **increased** until failure occurs.

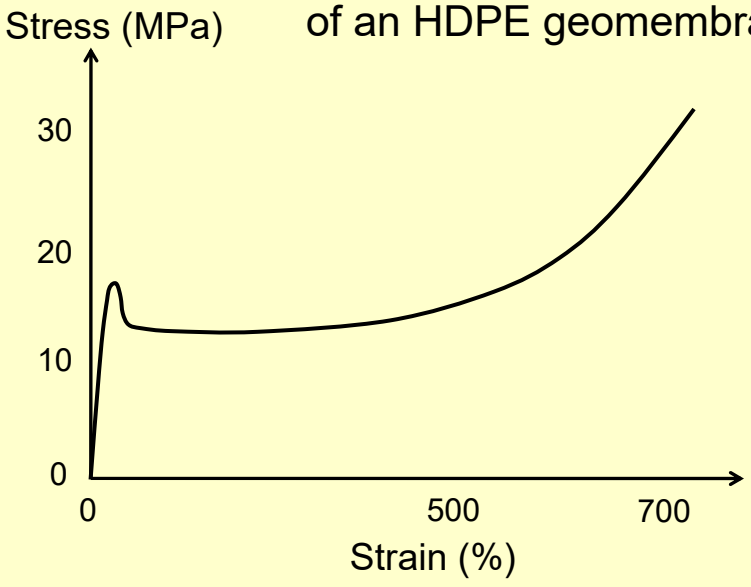
A curve of **stress** as a function of **elongation** ("strain") is obtained.

Courtesy SAGEOS

JP GIROUD THE SZÉCHY LECTURE 119

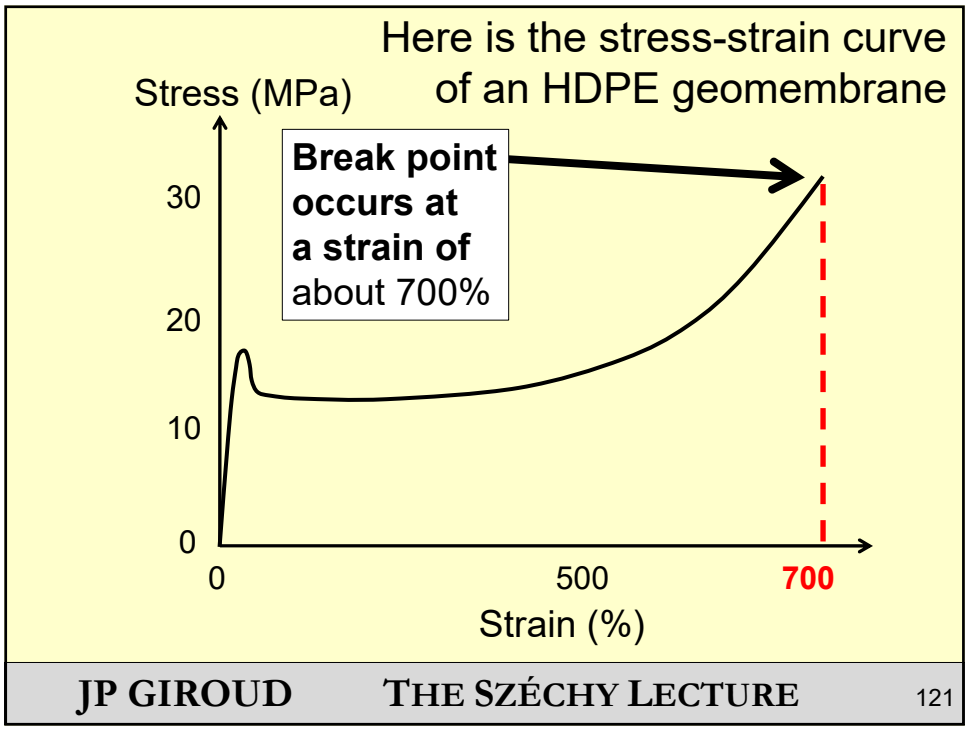
119

Here is the stress-strain curve of an HDPE geomembrane

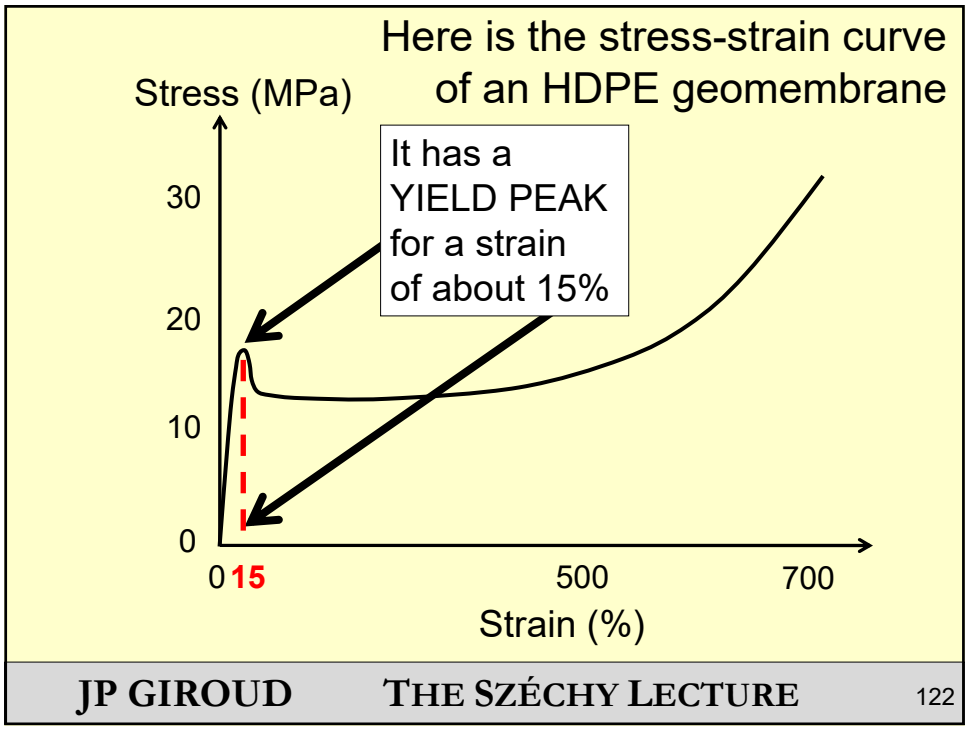


JP GIROUD THE SZÉCHY LECTURE 120

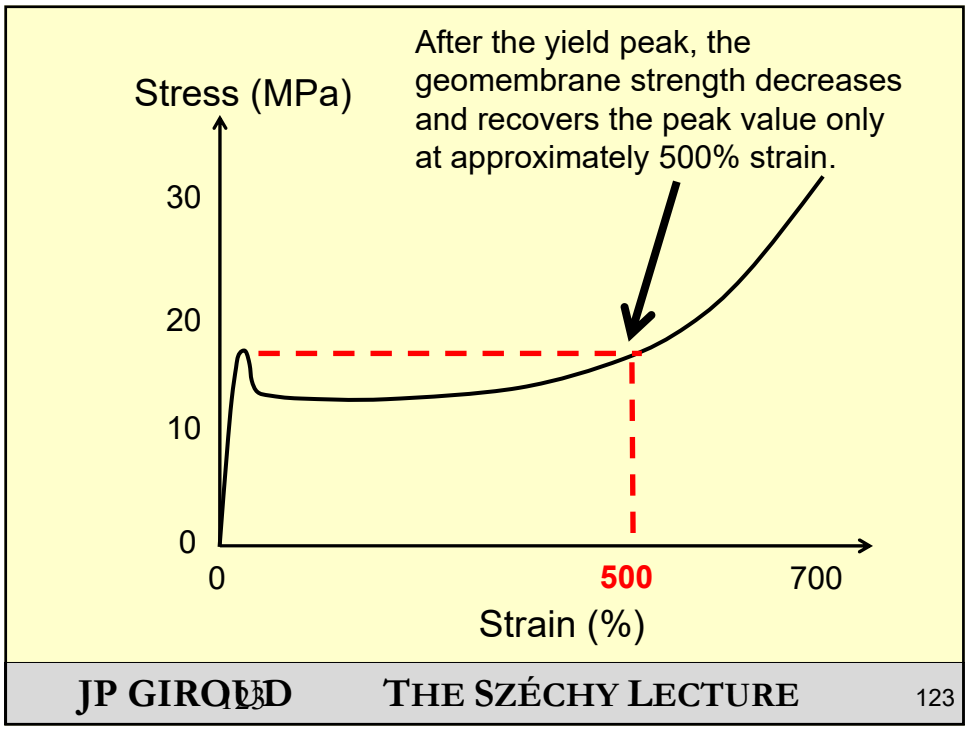
120


Here is the stress-strain curve
of an HDPE geomembrane
Stress (MPa)
Break point
occurs at
a strain of
about 700%
30
20
10
0
0
500
700
Strain (%)
JP GIROUD
THE SZÉCHY LECTURE
121

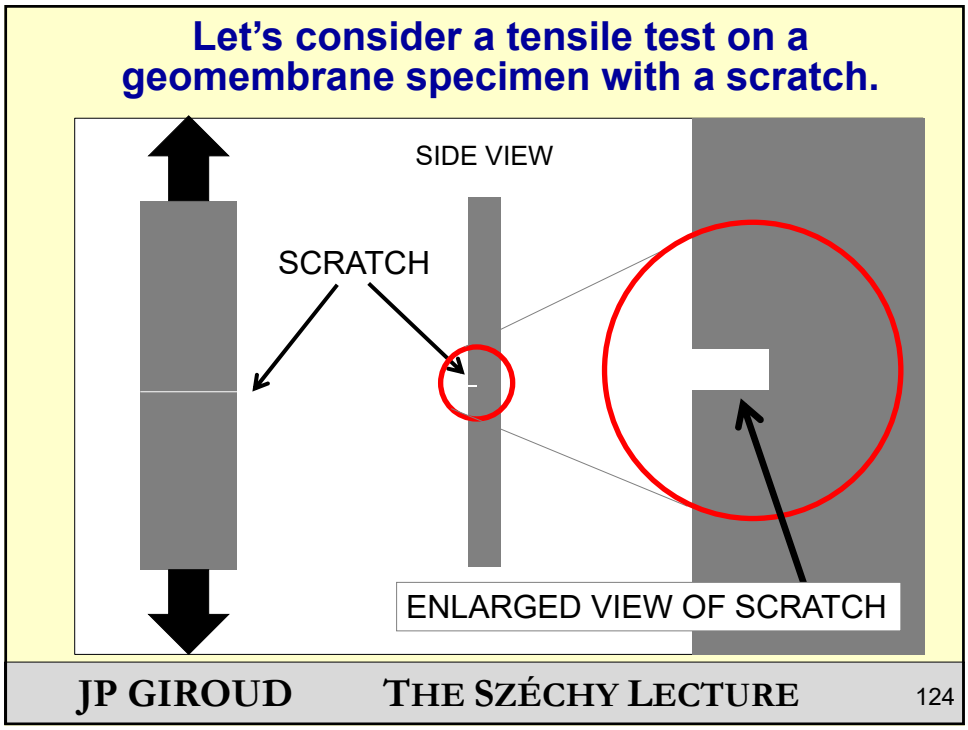
121


Here is the stress-strain curve
of an HDPE geomembrane
Stress (MPa)
It has a
YIELD PEAK
for a strain
of about 15%
30
20
10
0
0
15
500
700
Strain (%)
JP GIROUD
THE SZÉCHY LECTURE
122

122


After the yield peak, the geomembrane strength decreases and recovers the peak value only at approximately 500% strain.
Stress (MPa)
30
20
10
0
0
500
700
Strain (%)
JP GIROUD
THE SZÉCHY LECTURE
123

123


Let's consider a tensile test on a geomembrane specimen with a scratch.
SIDE VIEW
SCRATCH
ENLARGED VIEW OF SCRATCH
JP GIROUD
THE SZÉCHY LECTURE
124

124

The depth of a scratch is usually small
with respect
to the geomembrane thickness.

Nevertheless, the cross section with a scratch
is smaller than the other cross sections
of the geomembrane specimen.

STRESS = FORCE / AREA

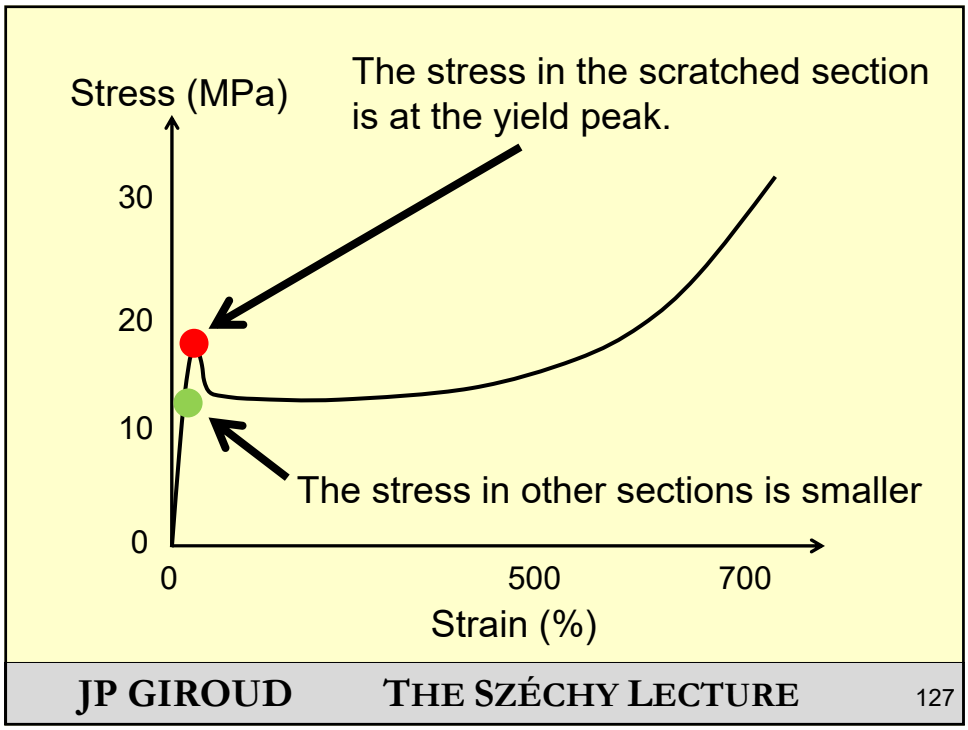
Therefore, the stress is higher
in the section with a scratch
than in other sections.

125

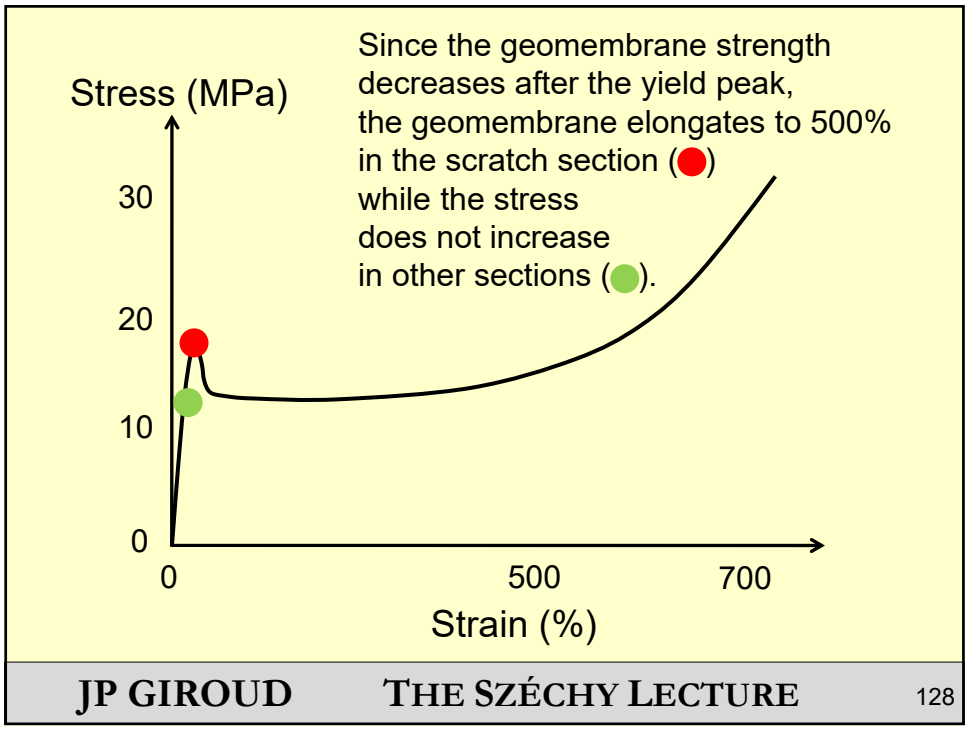
The **tensile stress**
in the section of the specimen
with a scratch
is **larger** than the stress anywhere else
in the specimen.

Therefore,
the section of the HDPE specimen
with a **scratch**
will reach the **yield stress**
before the rest of the specimen.

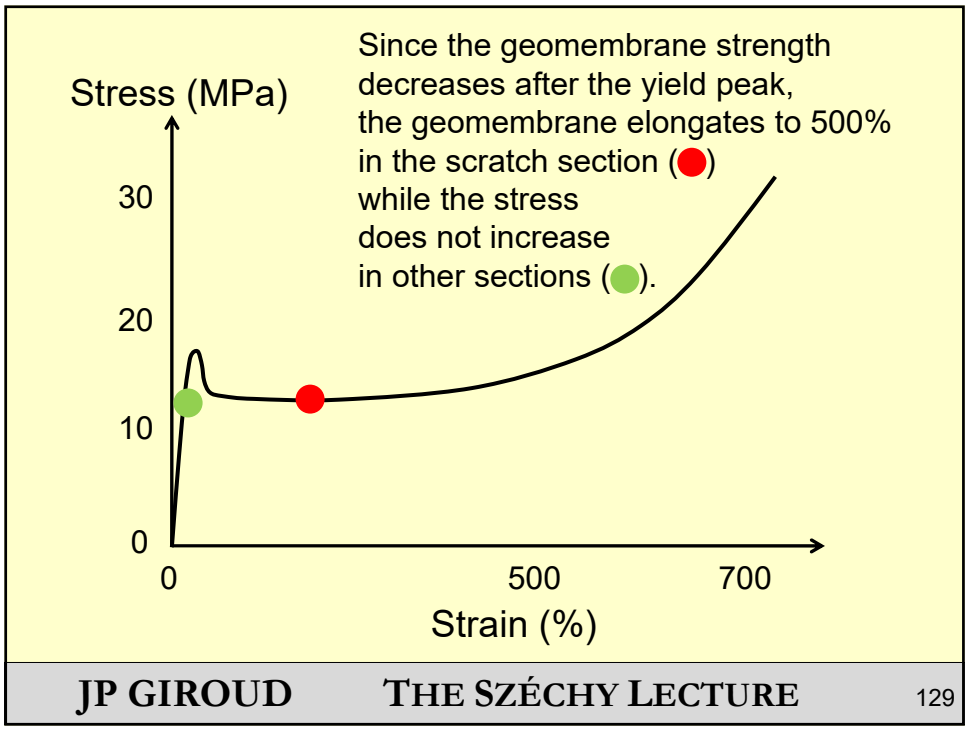
126


Stress (MPa)
The stress in the scratched section is at the yield peak.
30
20
10
0
The stress in other sections is smaller
0
500
700
Strain (%)
JP GIROUD
THE SZÉCHY LECTURE
127

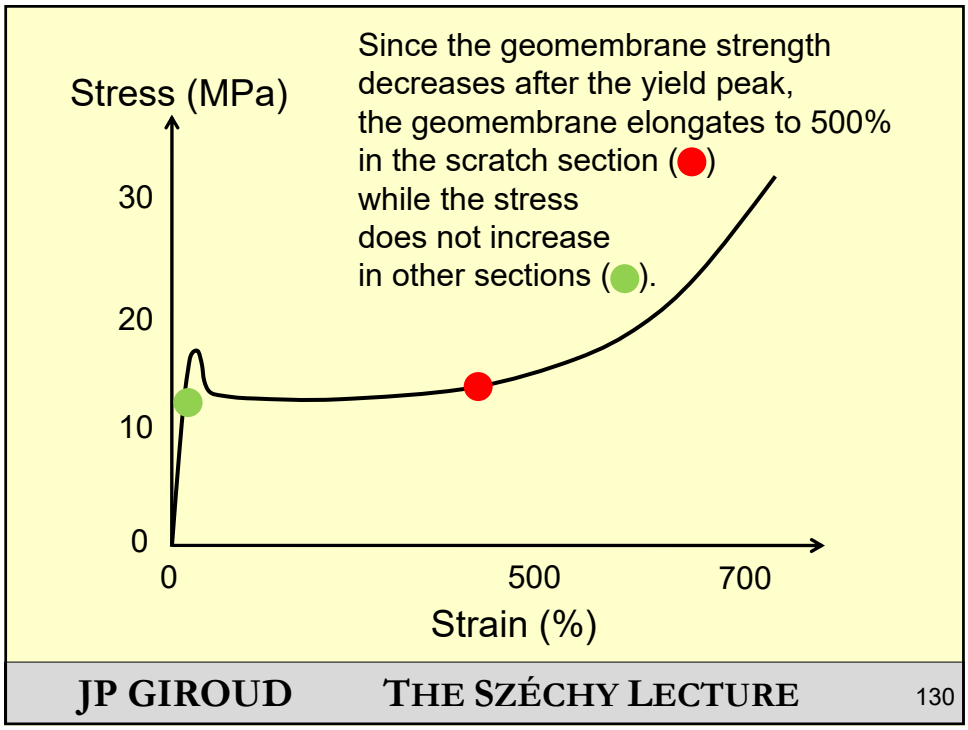
127


Since the geomembrane strength decreases after the yield peak, the geomembrane elongates to 500% in the scratch section (●) while the stress does not increase in other sections (●).
Stress (MPa)
30
20
10
0
0
500
700
Strain (%)
JP GIROUD
THE SZÉCHY LECTURE
128

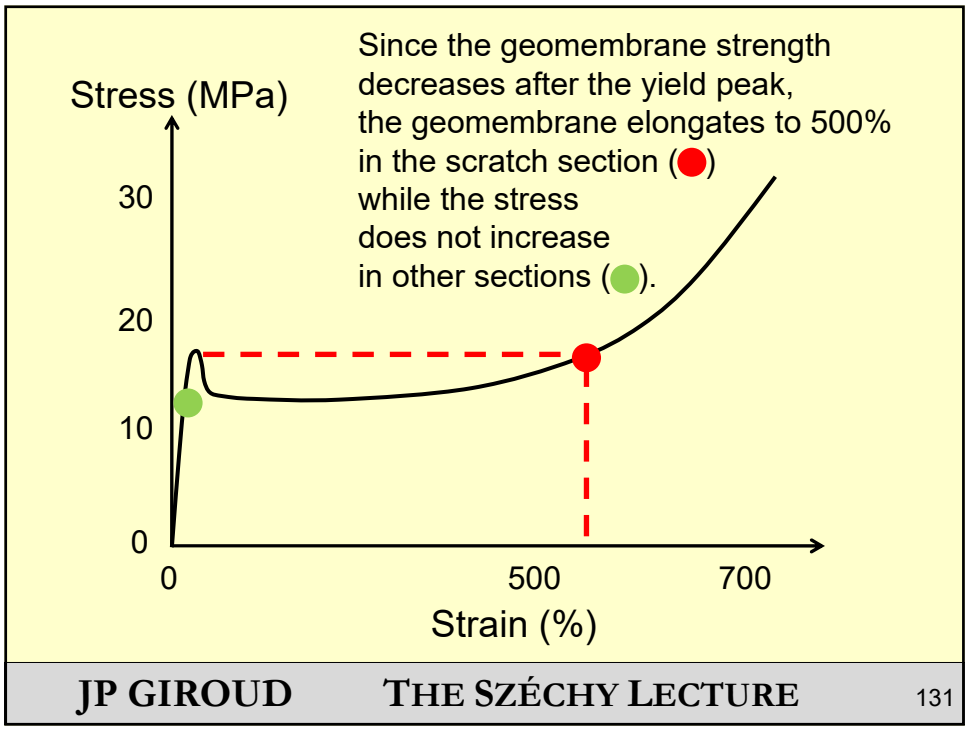
128


Since the geomembrane strength
decreases after the yield peak,
the geomembrane elongates to 500%
in the scratch section ( )
while the stress
does not increase
in other sections ( ).
Stress (MPa)
30
20
10
0
0
500
700
Strain (%)
JP GIROUD
THE SZÉCHY LECTURE
129

129


Since the geomembrane strength
decreases after the yield peak,
the geomembrane elongates to 500%
in the scratch section ( )
while the stress
does not increase
in other sections ( ).
Stress (MPa)
30
20
10
0
0
500
700
Strain (%)
JP GIROUD
THE SZÉCHY LECTURE
130

130

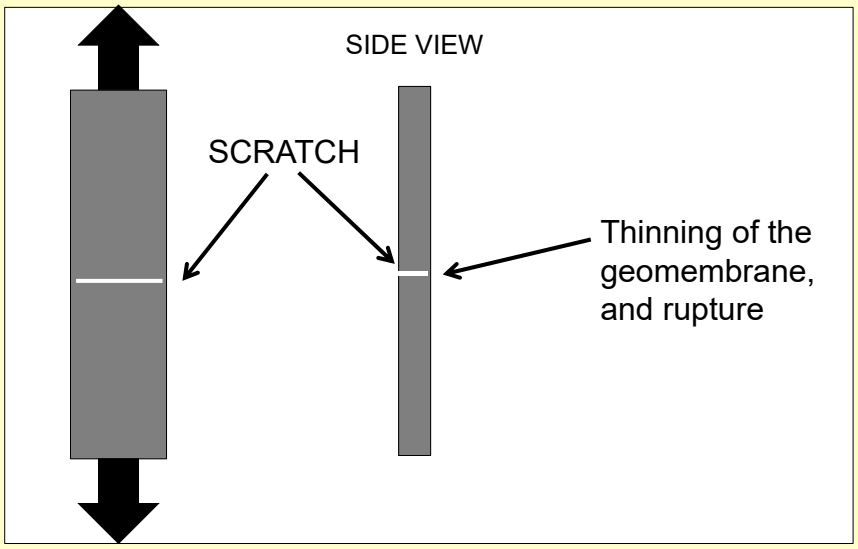


131

As it elongates from 0% to **500%**,
the geomembrane
in the scratched section
becomes **thinner** and **thinner**
until it breaks.

132

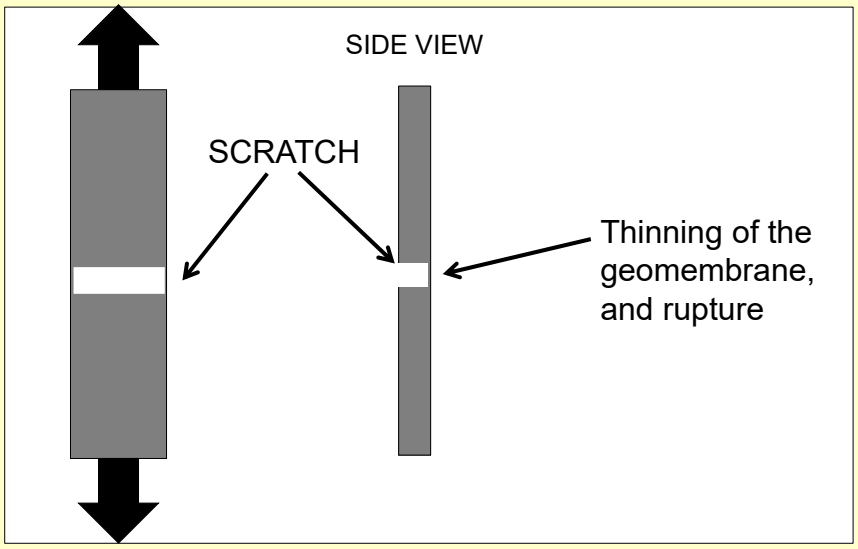
Tensile test on a geomembrane specimen with a scratch.



JP GIROUD THE SZÉCHY LECTURE 133

133

Tensile test on a geomembrane specimen with a scratch.



JP GIROUD THE SZÉCHY LECTURE 134

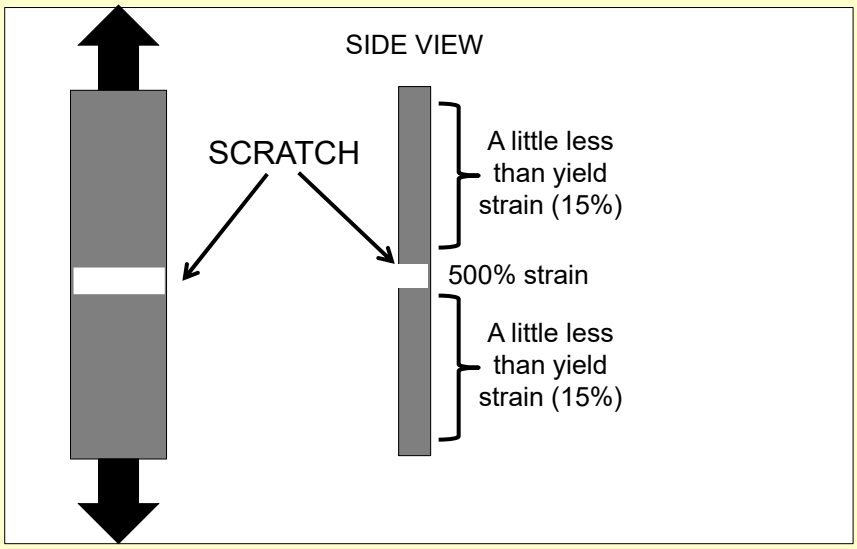
134

While the strain is 500% in the scratched section, the rest of the specimen has a strain less than the yield strain.

The length of the scratched section is short.
As a result,
the **average strain** over the entire specimen is **close to the yield strain**.

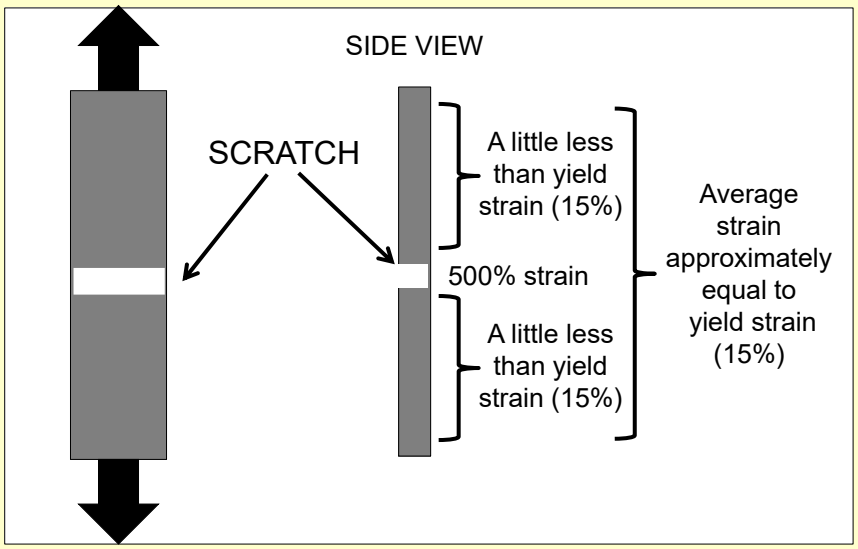
135

Average strain at end of tensile test in the specimen with a scratch



136

Average strain at end of tensile test in the specimen with a scratch



JP GIROUD THE SZÉCHY LECTURE 137

137

In the field,
a geomembrane is subjected to
numerous mechanical actions
that result in **scratches** in all directions.

Therefore, regardless of the direction
of the stresses in the field,
a **geomembrane in the field**
is in the situation
of the laboratory specimen
just discussed.

JP GIROUD THE SZÉCHY LECTURE 138

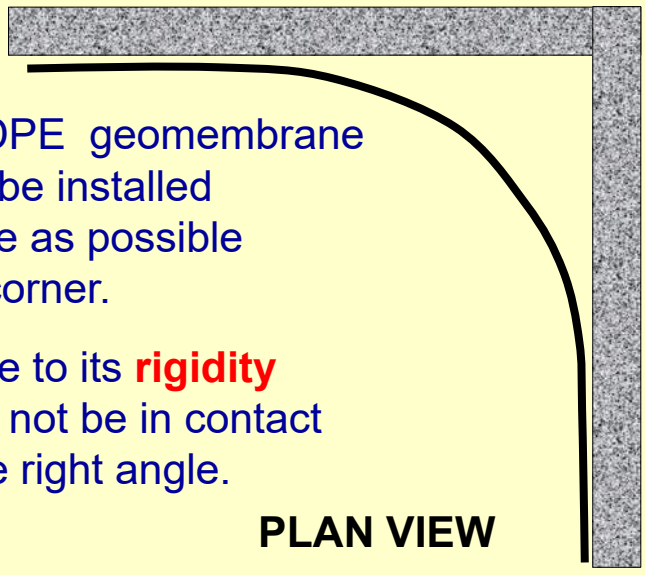
138

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

I presented this prediction
in the design report.

JP GIROUD THE SZÉCHY LECTURE 139

139



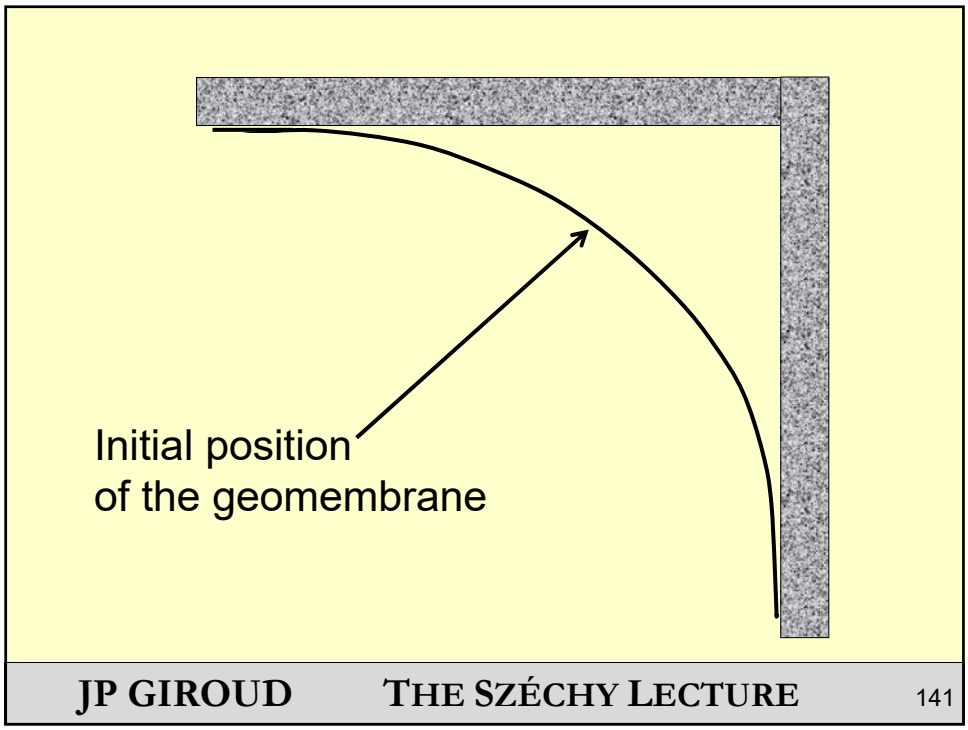
The HDPE geomembrane
was to be installed
as close as possible
to the corner.

But, due to its **rigidity**
it could not be in contact
with the right angle.

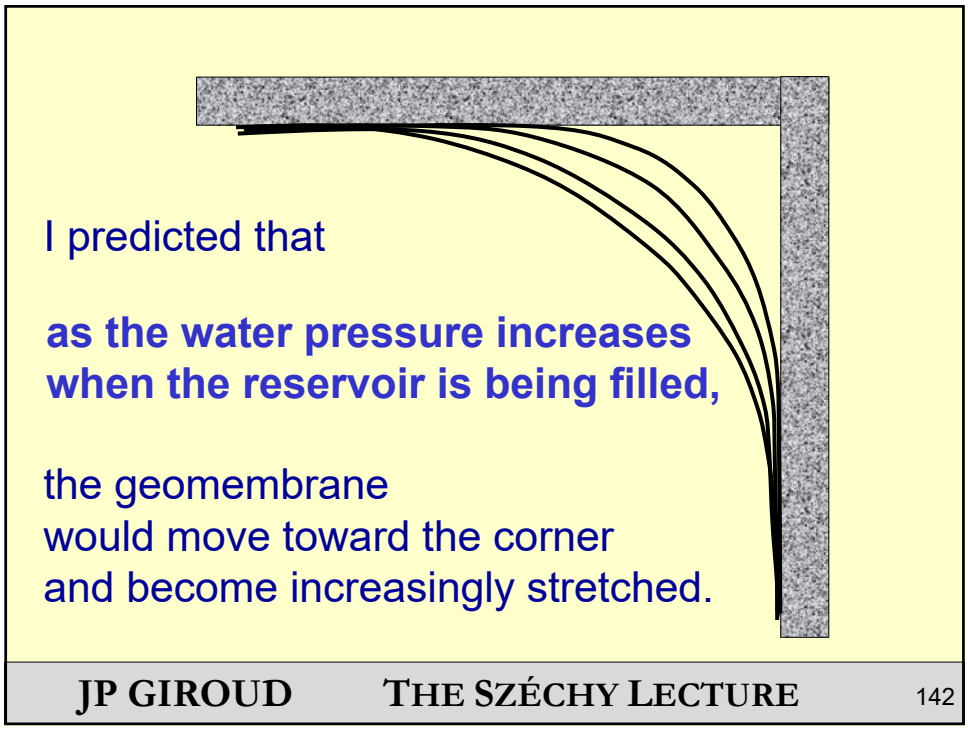
PLAN VIEW

JP GIROUD THE SZÉCHY LECTURE 140

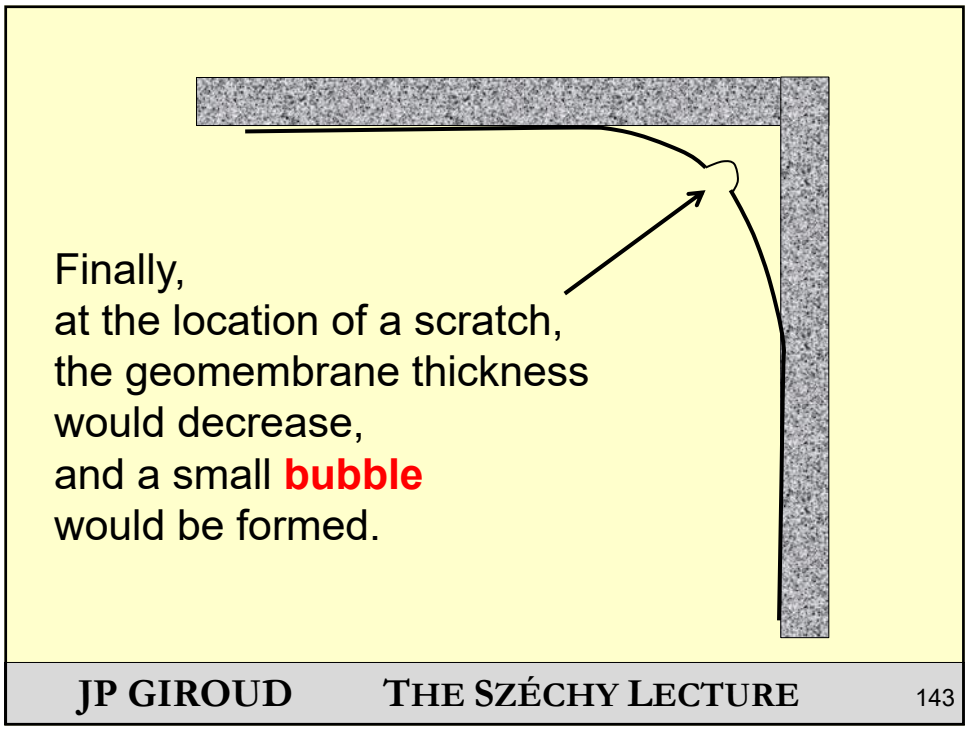
140


Initial position
of the geomembrane
JP GIROUD
THE SZÉCHY LECTURE
141

141


I predicted 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 SZÉCHY LECTURE
142

142


Finally,
at the location of a scratch,
the geomembrane thickness
would decrease,
and a small bubble
would be formed.
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THE SZÉCHY LECTURE
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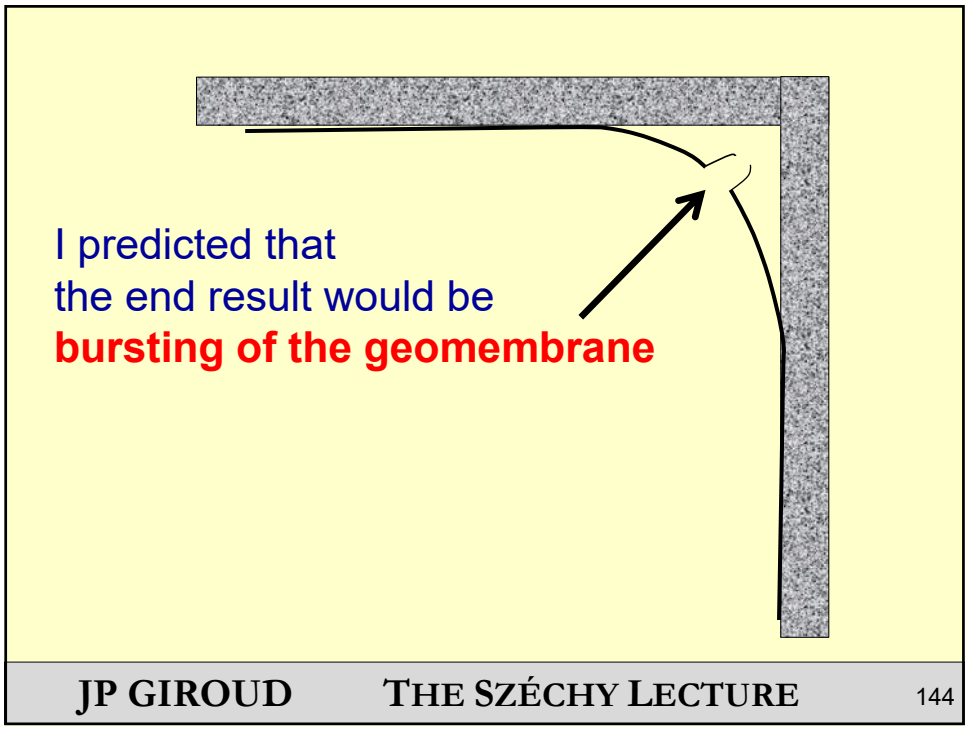
143


I predicted that
the end result would be
bursting of the geomembrane
JP GIROUD
THE SZÉCHY LECTURE
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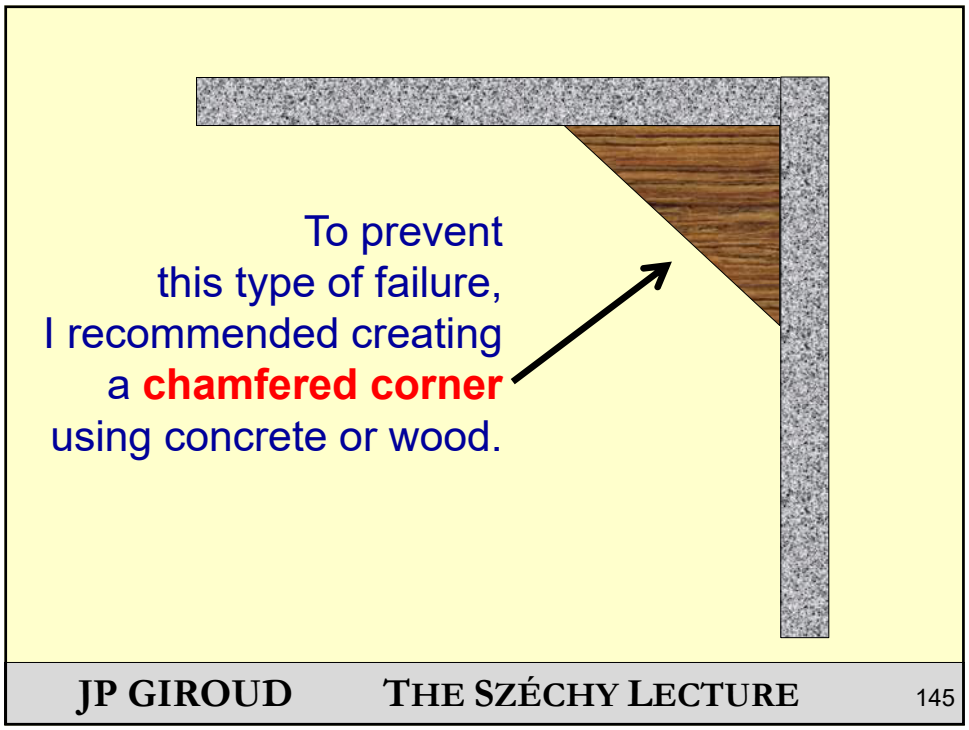
To prevent
this type of failure,
I recommended creating
a chamfered corner
using concrete or wood.
JP GIROUD
THE SZÉCHY LECTURE
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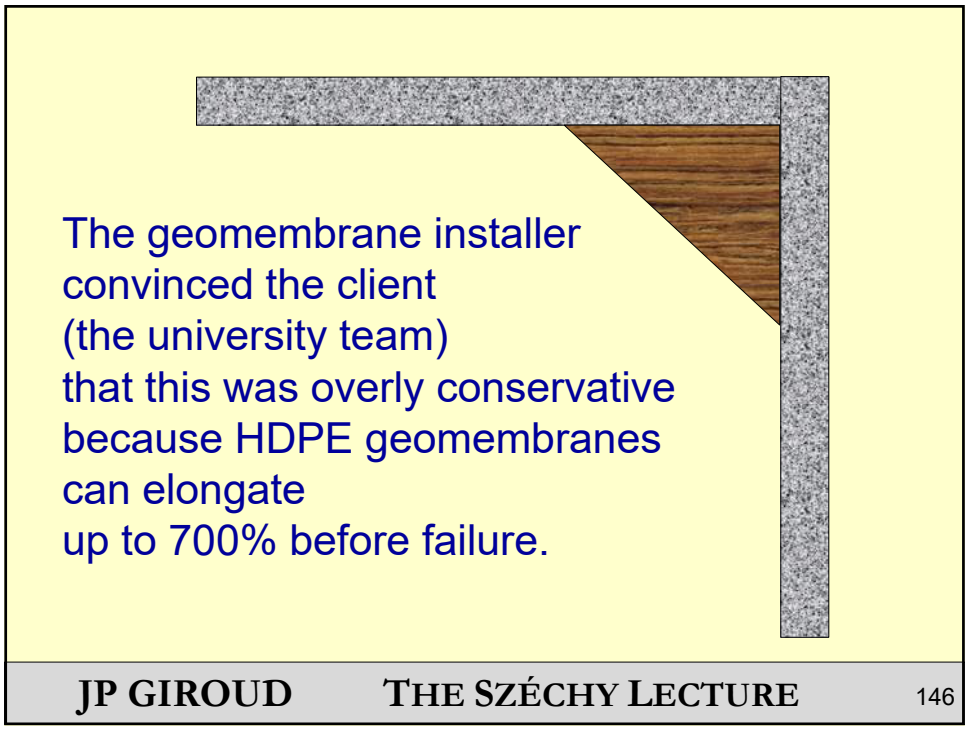
The geomembrane installer
convinced the client
(the university team)
that this was overly conservative
because HDPE geomembranes
can elongate
up to 700% before failure.
JP GIROUD
THE SZÉCHY LECTURE
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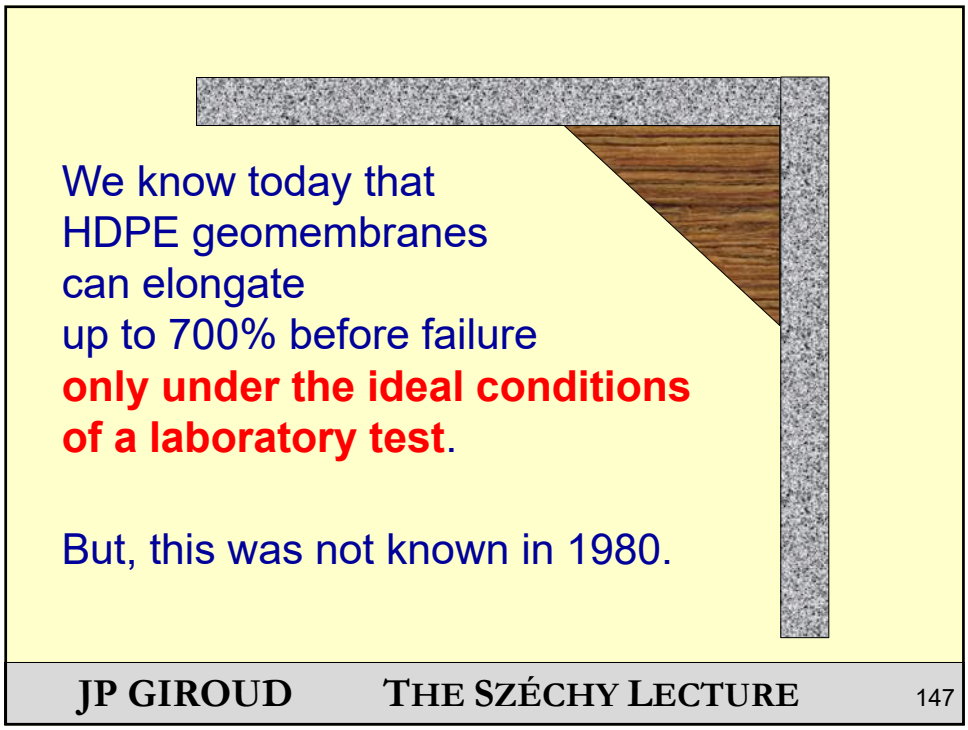
We know today that
HDPE geomembranes
can elongate
up to 700% before failure
only under the ideal conditions
of a laboratory test.
But, this was not known in 1980.
JP GIROUD
THE SZÉCHY LECTURE
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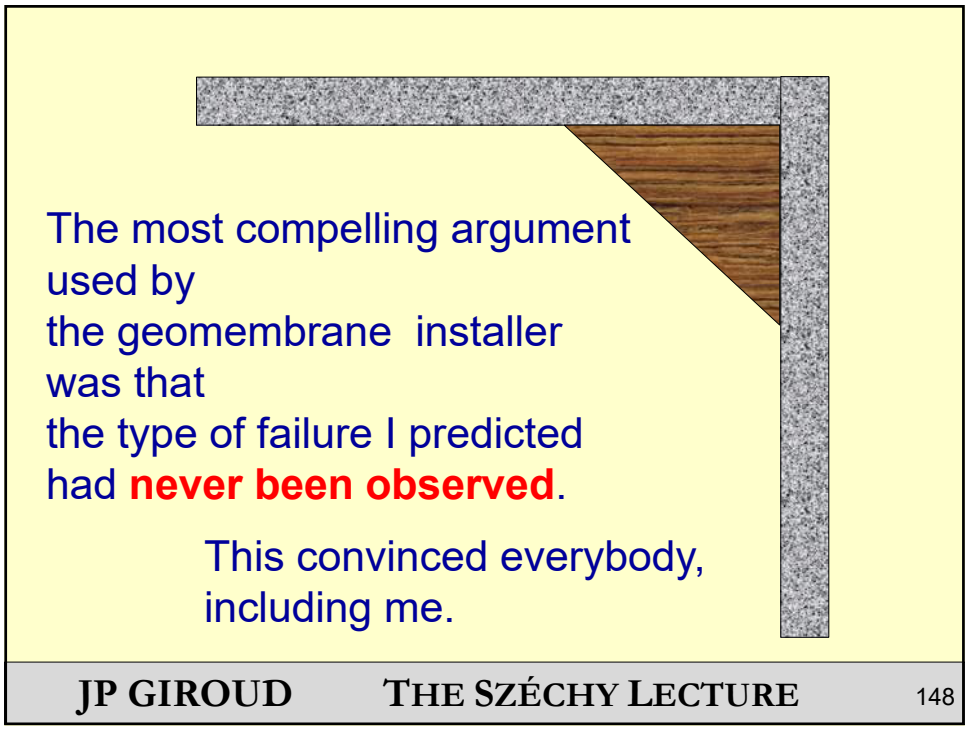
The most compelling argument
used by
the geomembrane installer
was that
the type of failure I predicted
had never been observed.
This convinced everybody,
including me.
JP GIROUD
THE SZÉCHY LECTURE
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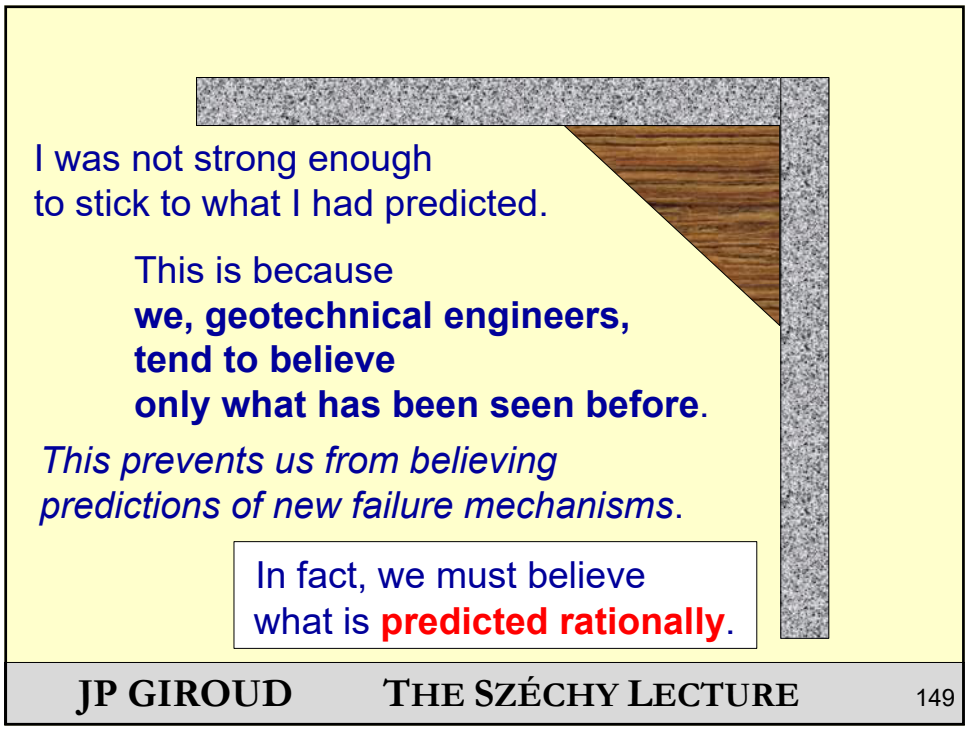
I was not strong enough
to stick to what I had predicted.
This is because
we, geotechnical engineers,
tend to believe
only what has been seen before.
This prevents us from believing
predictions of new failure mechanisms.
In fact, we must believe
what is predicted rationally.
JP GIROUD
THE SZÉCHY LECTURE
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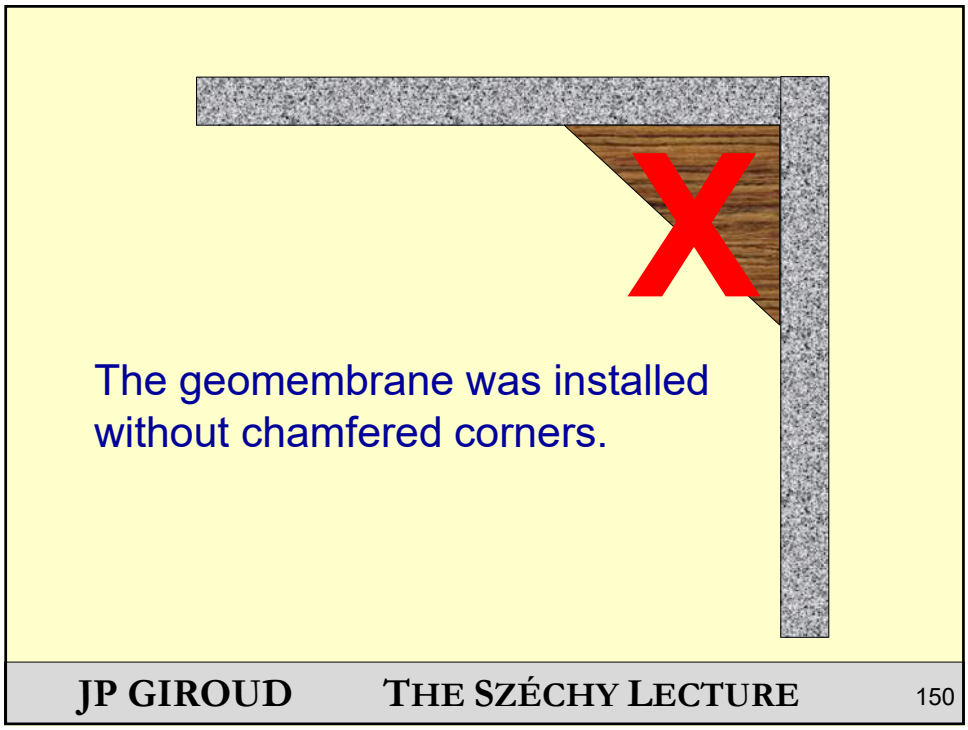
The geomembrane was installed
without chamfered corners.
JP GIROUD
THE SZÉCHY LECTURE
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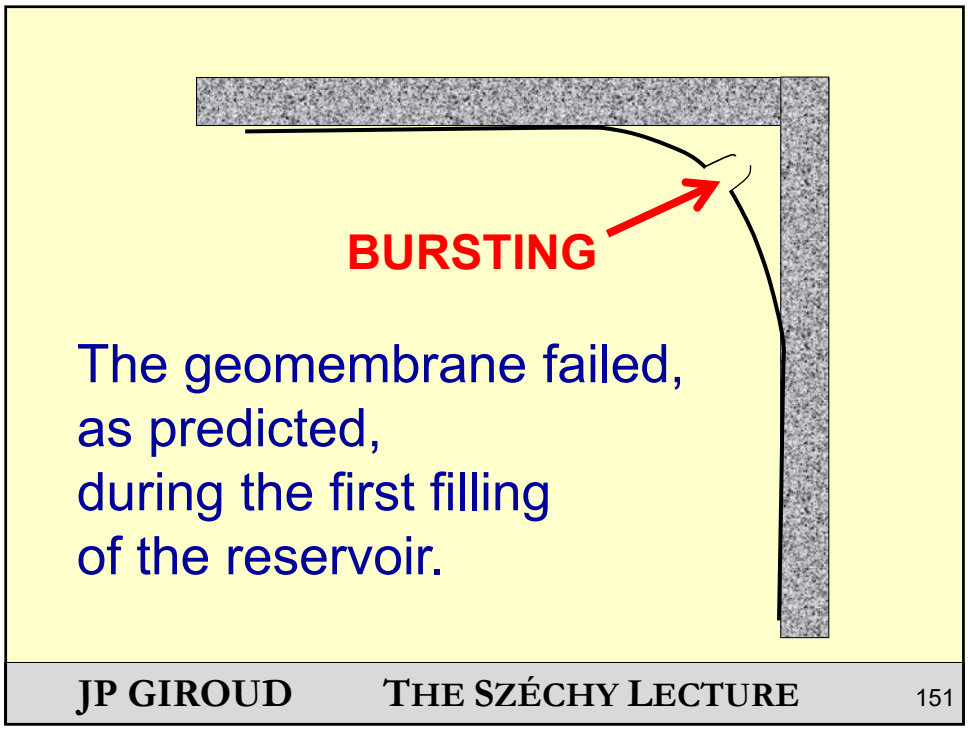
BURSTING
The geomembrane failed,
as predicted,
during the first filling
of the reservoir.
JP GIROUD
THE SZÉCHY LECTURE
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DIVERS
INSPECTED
THE
GEOMEMBRANE
JP GIROUD
THE SZÉCHY LECTURE
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PHOTO TAKEN UNDER WATER
JP GIROUD
THE SZÉCHY LECTURE
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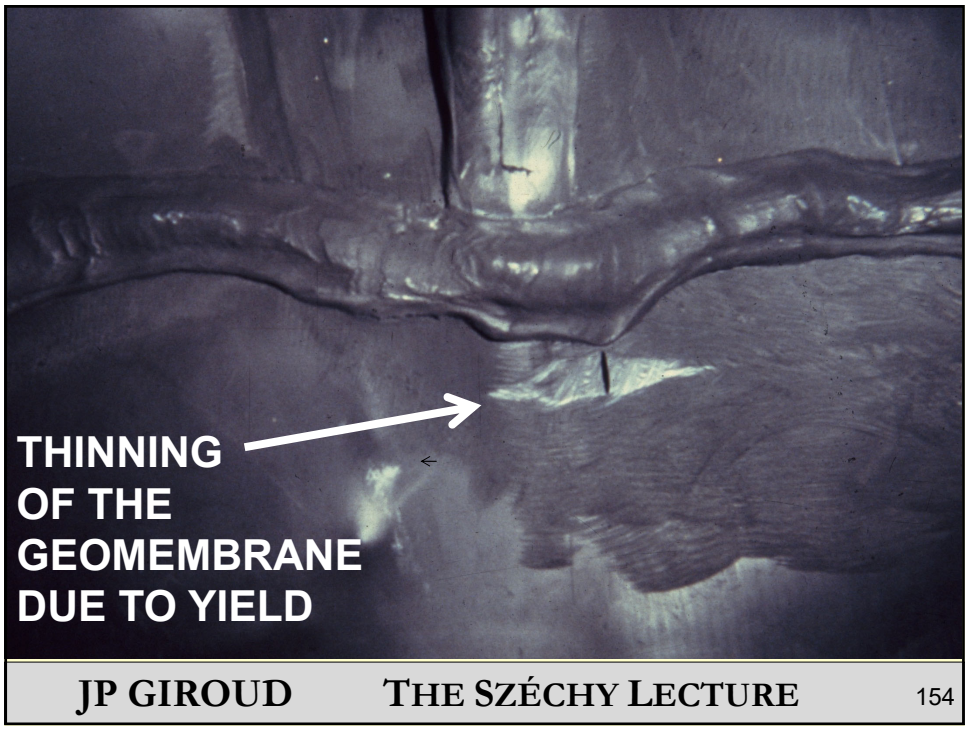
THINNING
OF THE
GEOMEMBRANE
DUE TO YIELD
JP GIROUD
THE SZÉCHY LECTURE
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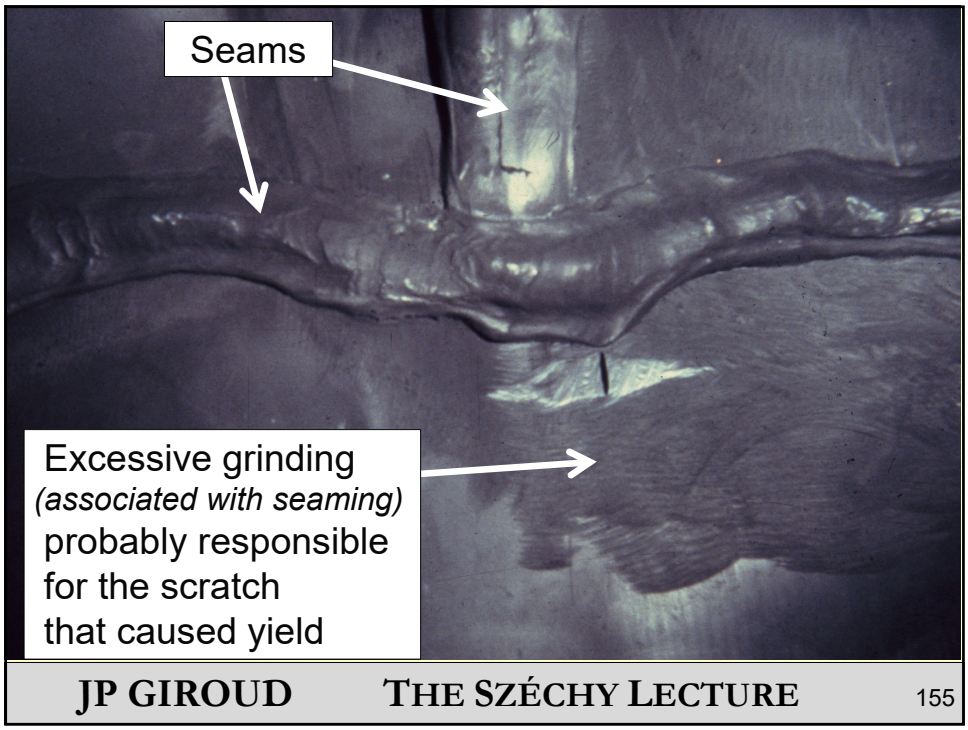
Seams
Excessive grinding
(associated with seaming)
probably responsible
for the scratch
that caused yield
JP GIROUD
THE SZÉCHY LECTURE
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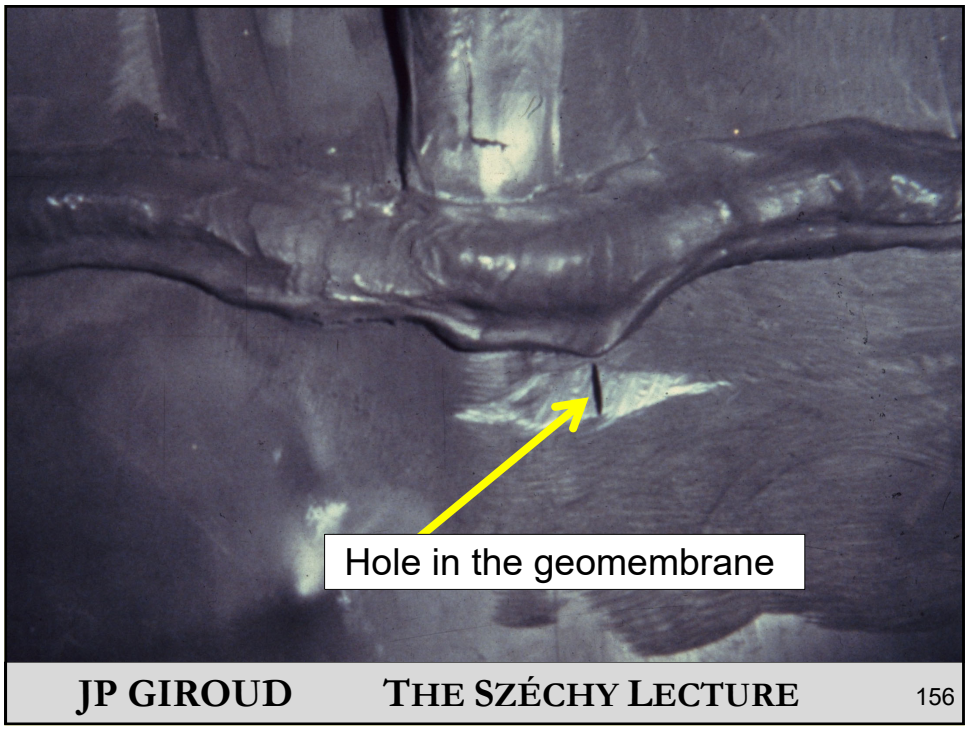
Hole in the geomembrane
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THE SZÉCHY LECTURE
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REMEDIATION

- Lightweight **concrete** was slowly cast **in the corners** using the geomembrane as a form **as water was progressively added** in the reservoir to balance the concrete pressure.
- The reservoir was thus successfully filled.

JP GIROUD THE SZÉCHY LECTURE 157

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Lesson learned from the failure of the Proton Decay Experiment liner

- I believed in the theoretical analysis.
- But I did not convince others.
- I was not strong enough (why ?).
- Because, in geotechnical engineering, we tend to only believe events that have happened before.
- In other words, we rely on experience.

JP GIROUD THE SZÉCHY LECTURE 158

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Of course, experience is important.

But, with new materials
and new technologies,
rational analyses are more important
than experience.

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In conclusion:

- We **must believe** our theoretical analyses because the theories we use in geotechnical engineering are generally correct.
- But this is not sufficient: we **must convince** other participants in the project.

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LESSONS FROM THE FOUR CASE HISTORIES

- Pay attention to **details**.
- Adapt the **conceptual design** to the needs of the project.
- Treat **geosynthetics like all materials**, with adequate testing and analyses. (*Geosynthetics are not special materials.*)
- Believe in **theoretical analyses**.
- **Learn from failures**, preferably the failures caused by others.

JP GIROUD THE SZÉCHY LECTURE 161

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This review of four case histories, shows that the proper use of geosynthetics requires **wise decisions**.

But wise decisions cannot be improvised.

Wise decisions are possible if they are **supported by research work**.

Here are two examples of research related to the preceding case histories.

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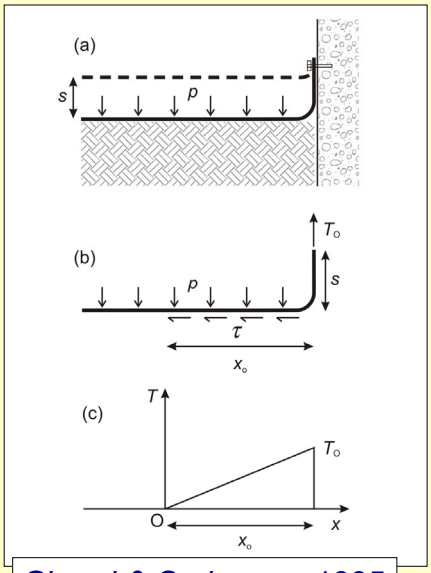
Research on the behavior of **geomembranes next to rigid structures** has shown that the geomembrane safety in case of differential settlement is proportional to the **co-energy**, which is the area between the tension-strain curve of the geomembrane and the vertical axis (the tension axis).



Giroud & Soderman 1995

JP GIROUD THE SZÉCHY LECTURE 163

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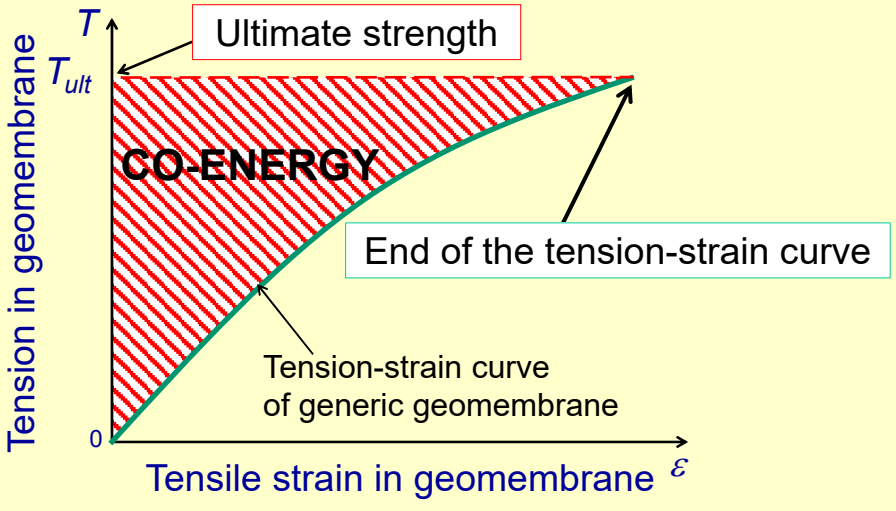
The co-energy is the red area



JP GIROUD THE SZÉCHY LECTURE 164

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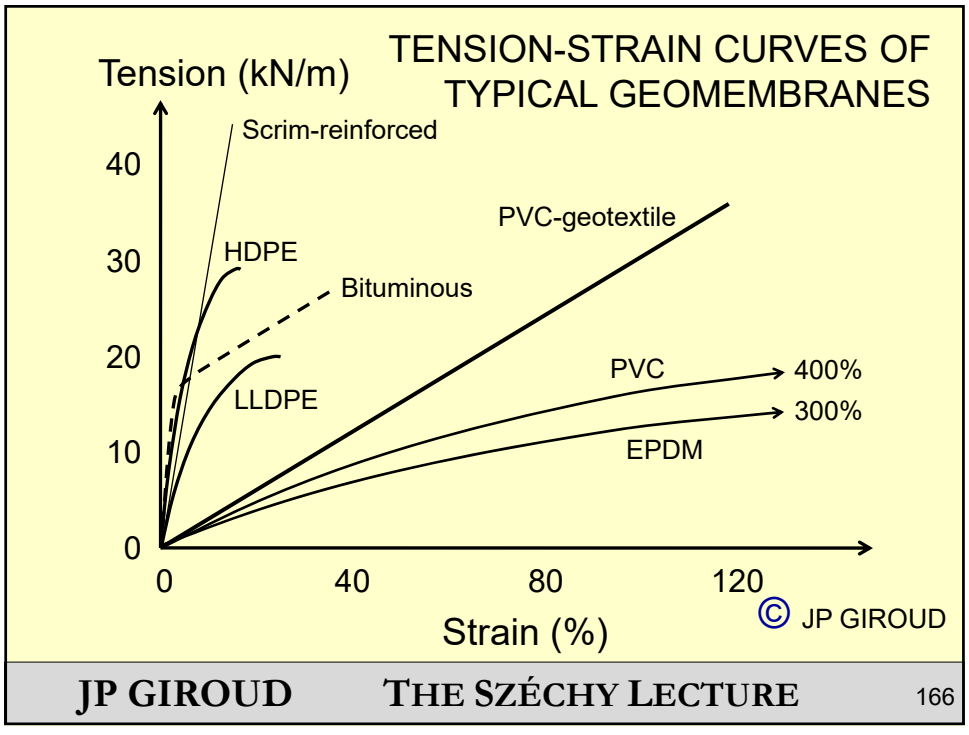
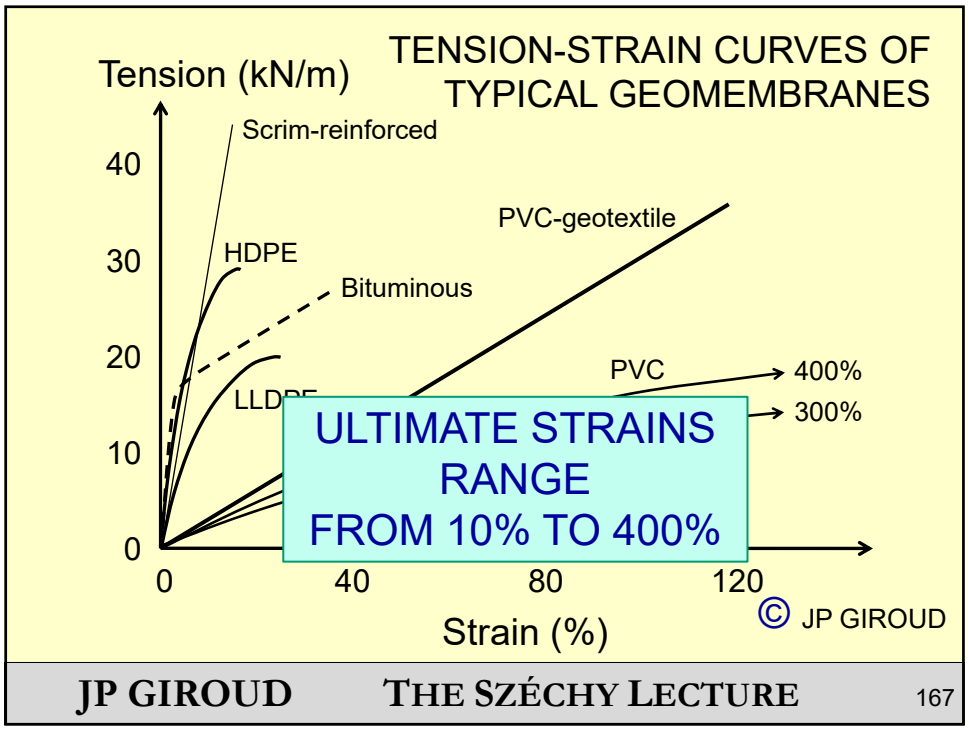
While the various available geomembranes
are **all quasi-impermeable**
and, therefore, quasi-equivalent
from the viewpoint of impermeability,
they are **very different**
from the viewpoint of **mechanical properties**.

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

165



166


TENSION-STRAIN CURVES OF TYPICAL GEOMEMBRANES
Tension (kN/m)
Scrim-reinforced
HDPE
Bituminous
PVC-geotextile
PVC
400%
300%
LLDPE
ULTIMATE STRAINS RANGE FROM 10% TO 400%
40
30
20
10
0
0
40
80
120
Strain (%)
© JP GIROUD
JP GIROUD
THE SZÉCHY LECTURE
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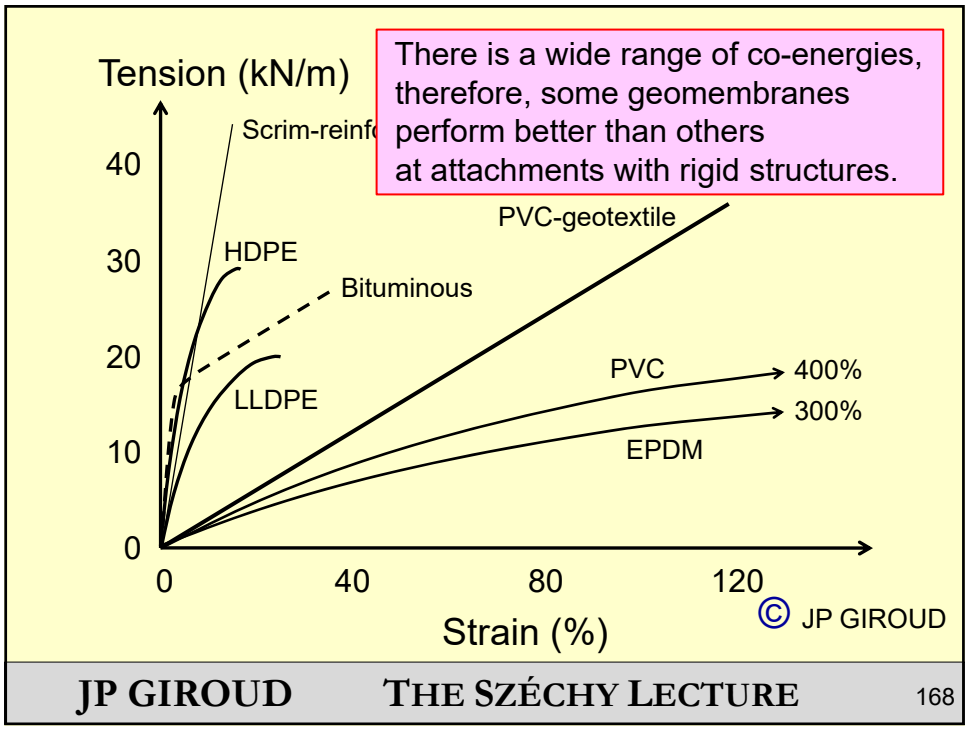
There is a wide range of co-energies, therefore, some geomembranes perform better than others at attachments with rigid structures.
Tension (kN/m)
HDPE
Bituminous
PVC-geotextile
PVC
400%
300%
LLDPE
EPDM
40
30
20
10
0
0
40
80
120
Strain (%)
© JP GIROUD
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THE SZÉCHY LECTURE
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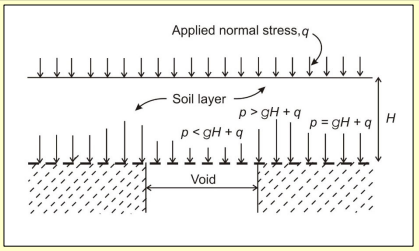
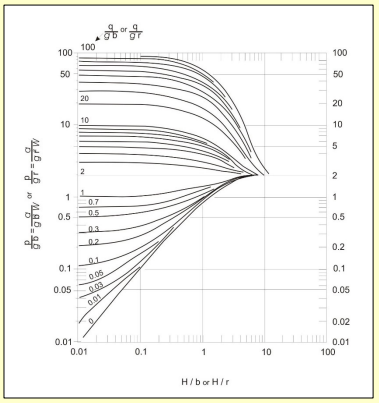
Another example is
the research about
geomembrane bridging voids
by combining
arching theory
and
tensioned membrane theory,
which led to this chart.





Note: I have used and cited work by Jaky and Kezdi in that study.

JP GIROUD THE SZÉCHY LECTURE 169

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Thanks to the kind of **research**
illustrated by these two examples
and **lessons learned**
from some failures
and from many successful projects,
geomembranes
have been used successfully
in numerous large projects.

For example . . .

JP GIROUD THE SZÉCHY LECTURE 170

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Large reservoirs: Panama Canal water basins for the locks
Courtesy Carpi
JP GIROUD
THE SZÉCHY LECTURE
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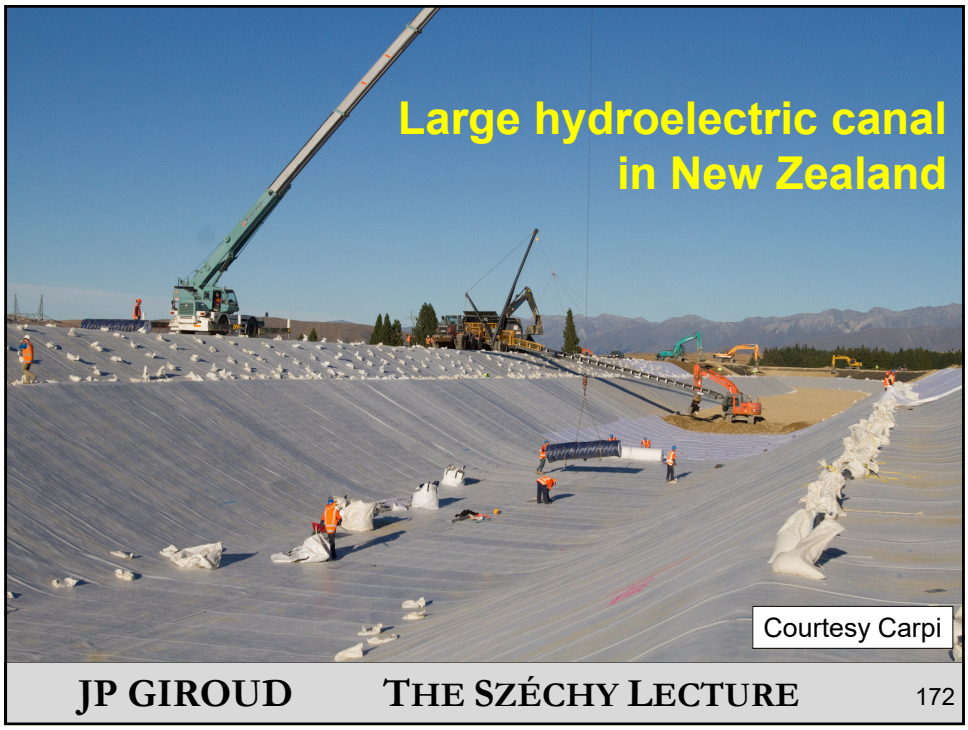
Large hydroelectric canal in New Zealand
Courtesy Carpi
JP GIROUD
THE SZÉCHY LECTURE
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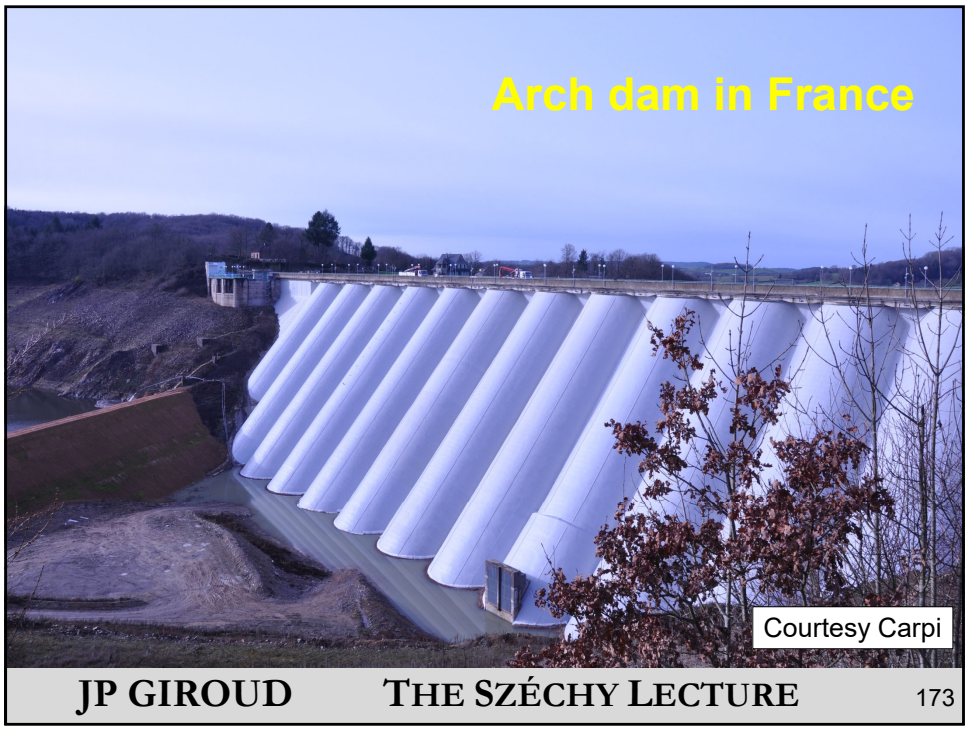
Arch dam in France
Courtesy Carpi
JP GIROUD
THE SZÉCHY LECTURE
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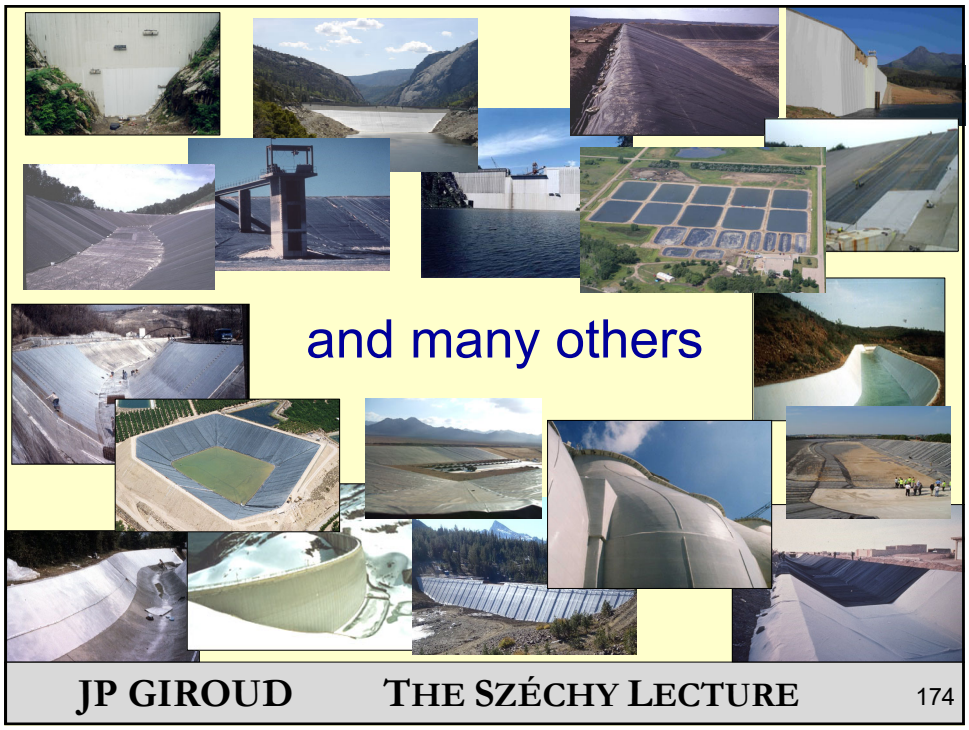
and many others
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