International Geosynthetics Society

Improving the performance of canals with geosynthetics

GEOSYNTHETICS IN CANALS APPLICATIONS AND PERFORMANCE

J.P. GIROUD

Updated 2021.11.22
after the presentation made on 2021.11.15

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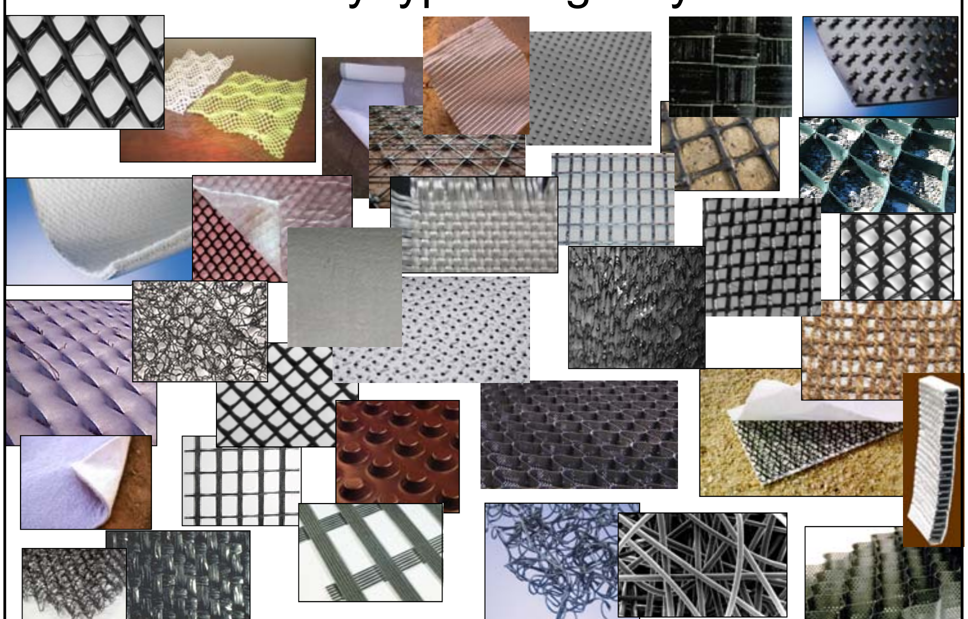
There are many types of geosynthetics.



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And more types of geosynthetics !

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First,
let's focus on **geomembranes**
because they are
watertight geosynthetics.

Indeed, **seepage**/**leakage control**
is an **essential goal**
in canal design.

By the way,
should we say **seepage** or **leakage**?

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Seepage or leakage: which term is correct?

Both terms are correct.

Seepage refers to flow through a **porous medium**, such as soil.
It is, therefore, the appropriate term for unlined canals.

Leakage refers to flow through a passageway, such as a **crack** in concrete or a **hole** in a geomembrane.

> It should be noted that **leakage** through a lining is followed by **seepage** into the ground.

Geomembranes are **flexible** sheets of **watertight** material, generally polymeric (sometimes bituminous).

POLYMERIC GEOMEMBRANES	BITUMINOUS GEOMEMBRANES

Courtesy Firestone

Courtesy Coletanche

The **flexibility** of geomembranes is evident on these photos.

POLYMERIC GEOMEMBRANES	BITUMINOUS GEOMEMBRANES

Courtesy Firestone

Courtesy Coletanche

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Geomembranes are produced in rolls.

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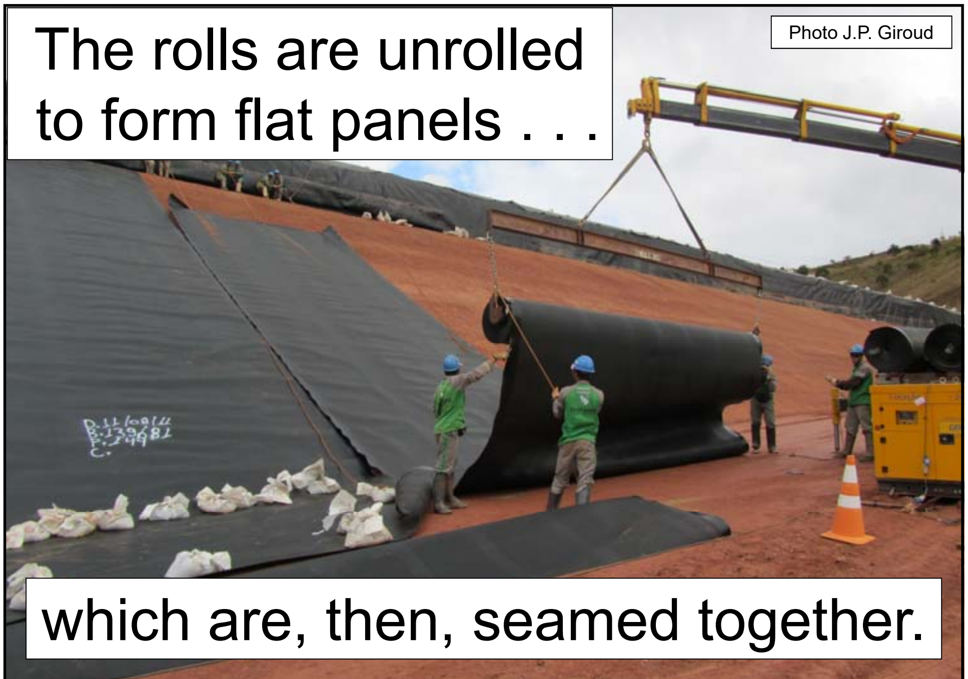
The rolls are unrolled to form flat panels . . .



which are, then, seamed together.

Geomembrane panels
are seamed
together
in the field
to form
large liners.

Rolls can also be seamed together in a factory

Courtesy F. Rohe
Environmental Protection, Inc.

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to form large panels that are packed

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and delivered at the construction site,

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where they are deployed.

Courtesy FIRESTONE

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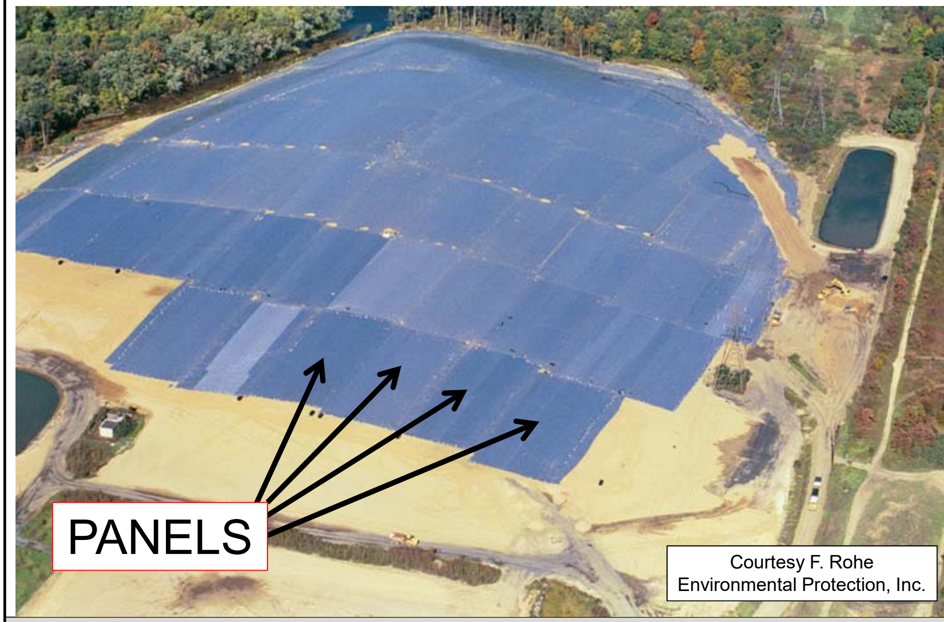
Panels are then seamed together in the field.



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In many applications, **geomembranes** are associated with **geotextiles**.

Generally the geotextile is used to protect the geomembrane.

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GEOTEXTILE
ON TOP
OF A
GEOMEMBRANE
Courtesy
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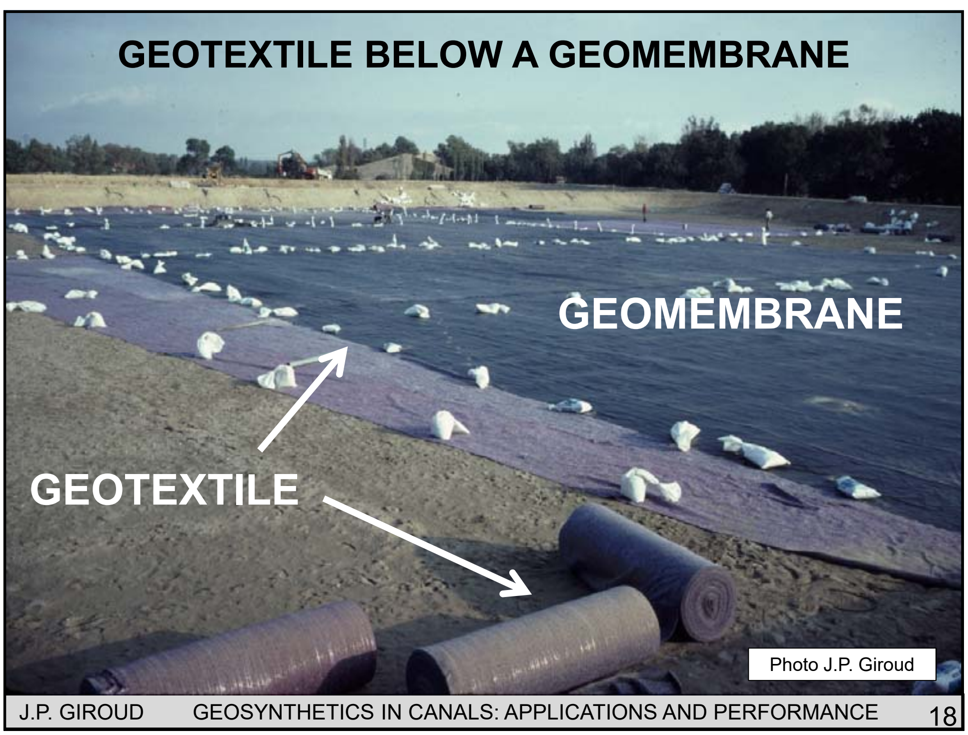
GEOTEXTILE BELOW A GEOMEMBRANE
GEOMEMBRANE
GEOTEXTILE
Photo J.P. Giroud
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Some **composite geomembranes** consist of a geomembrane bonded to a geotextile.

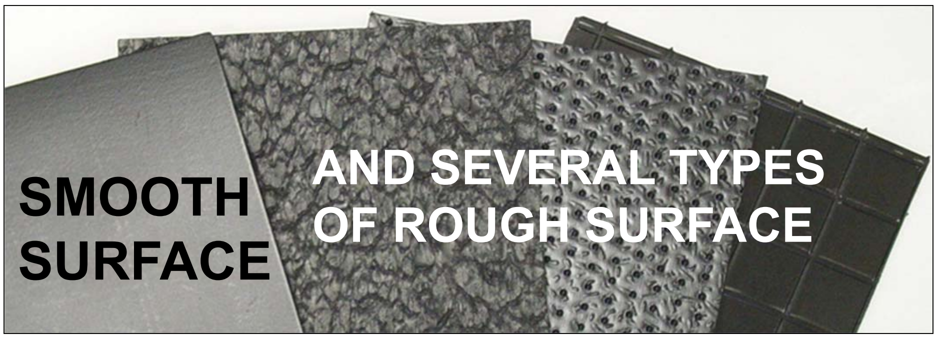
Photo Carpi

The surface of a geomembrane is important:

- If **low friction** is desired: a geomembrane with a **smooth surface** is used.
- If **high friction** is desired: a geomembrane with a **rough surface** is used.

EXAMPLES OF GEOMEMBRANE SURFACE

HDPE Geomembranes



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Another important aspect of **geomembrane surface** is the **color**.

Geomembranes are generally **black**,
because they are protected
from ultra violet radiation by **carbon black**,
which consists of fine particles of carbon
mixed with the polymer
at the manufacturing stage.

But **black color** exposed to sunlight
results in **high temperature**,
which has detrimental effects,
such as accelerated aging and thermal expansion.

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Courtesy GSE

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It was mentioned earlier that
geomembranes are **flexible**.

More importantly,
geomembranes are **extensible**.

Extensibility is an essential property:
geomembranes **remain watertight**
even after **significant elongation**.

This is illustrated hereafter.

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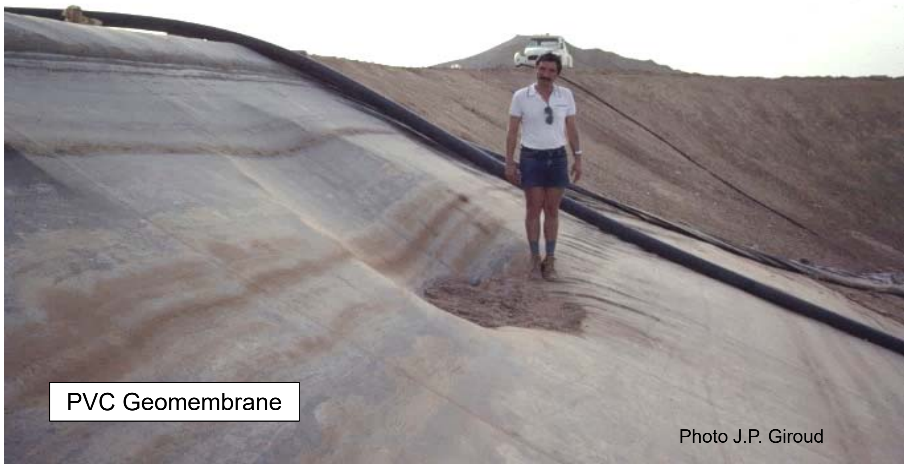
This geomembrane **remained watertight** after deflecting into a depression.



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This geomembrane **remained watertight** in spite of deflection into a depression and deformation over protruding blocks.

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This geomembrane **remained watertight** in spite of extensive bank deformation due to wave action.

Elastomeric Geomembrane

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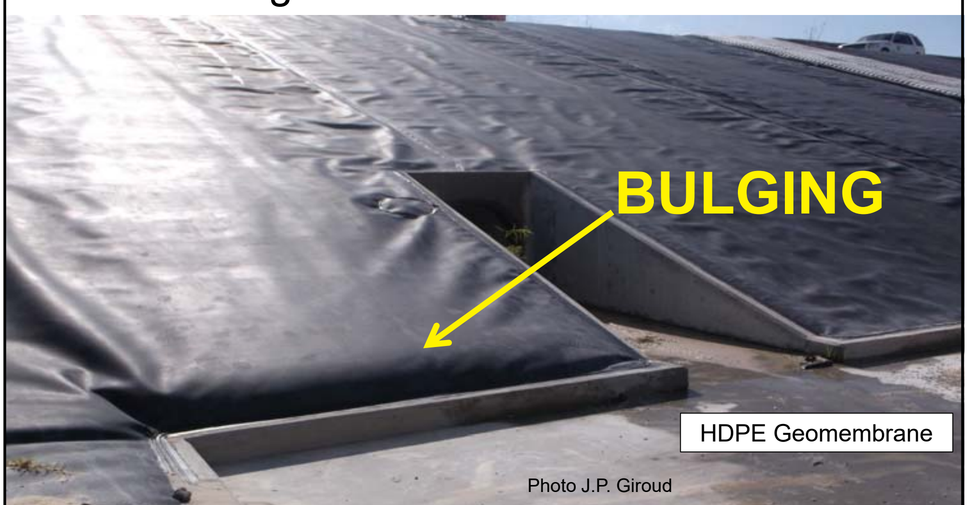
This geomembrane **remained watertight** in spite of bulging due to water trapped under the geomembrane liner.



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This geomembrane **remained watertight** even though it was inflated by gas emanating from the landfill.

LLDPE Geomembrane

Courtesy G. Richardson

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This geomembrane **remained watertight** in spite of extensive deformation due to organic gas from the ground.

PVC Geomembrane

Photo J.P. Giroud

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This geomembrane **remained watertight** in spite of extensive deformation due to protruding stones as a result of erosion of the ground under the geomembrane.

Bituminous Geomembrane

Photo J.P. Giroud

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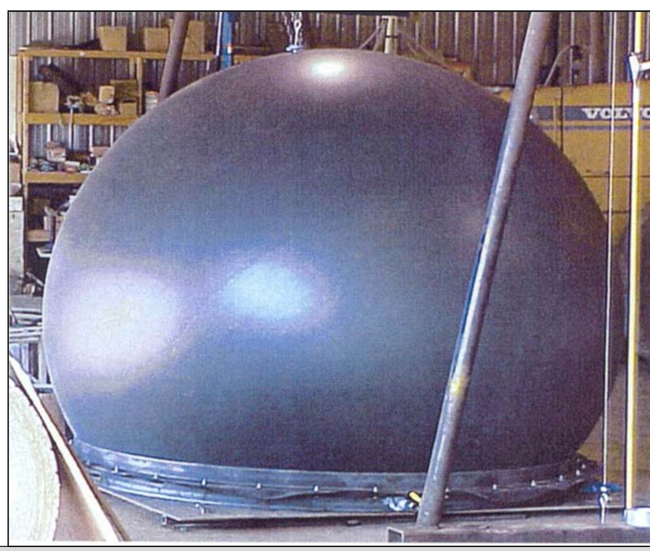
This geomembrane **remained watertight** after elongation in a multiaxial test.



Courtesy TRI

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These examples show that
geomembranes are **extensible**.

Therefore, geomembranes
can accommodate significant deformation
of the supporting medium
and undergo large extension
while remaining **watertight**.

Extensibility is a major advantage
of geomembranes compared to concrete.

Geomembranes are used
in a variety of applications
to **contain water** and other liquids,
as well as gas in some cases.

In these applications,
all types of geomembranes are used:

- **Polymeric geomembranes**:
  HDPE, PVC, Polypropylene, EPDM, etc.
- **Bituminous geomembranes**.


Courtesy
Firestone
IRRIGATION RESERVOIR
LINED WITH GEOMEMBRANE
Saint-Pierre-le-Vieux, France, 2006
EPDM
Geomembrane
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WASTE DISPOSAL LANDFILL
LINED WITH GEOMEMBRANE
HDPE Geomembrane
Courtesy
SOLMAX
2005
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WASTEWATER RESERVOIR LINED WITH GEOMEMBRANE
Aerators
HDPE GEOMEMBRANE
Whytes Gully Waste and Recovery Center, Australia
Photo J.P. Giroud
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At the PANAMA CANAL
PVC Geomembrane
Courtesy CARPI
The WATER BASINS FOR THE NEW LOCKS are lined with geomembrane.
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FISH FARMS lined with geomembrane

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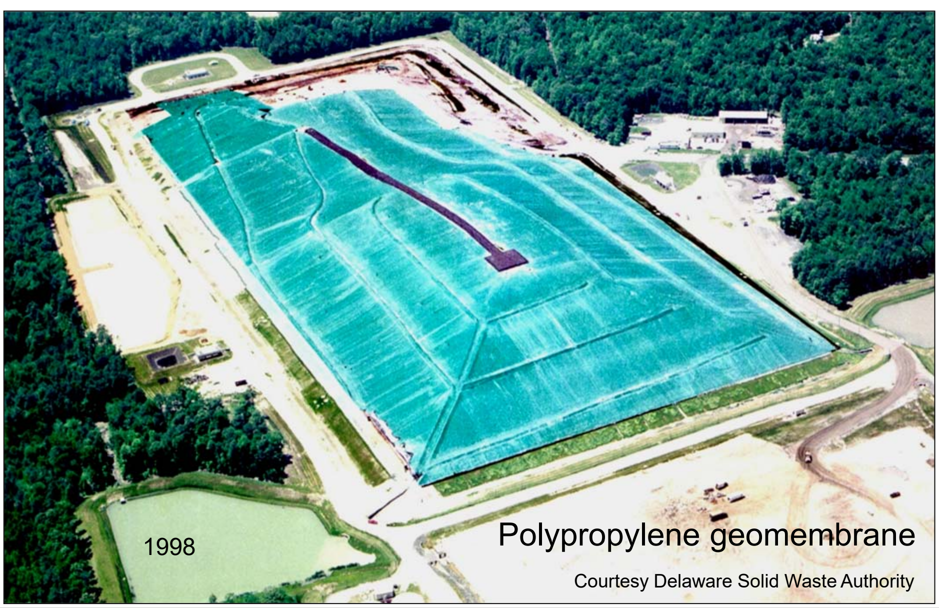
GEOMEMBRANE AS LANDFILL COVER



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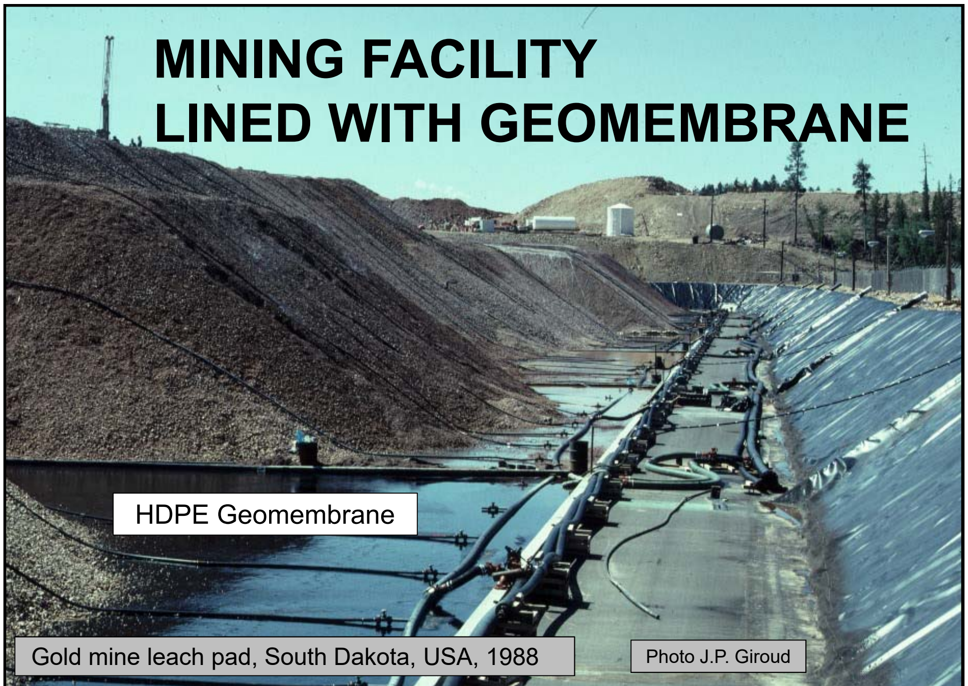

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ROAD AND RAILWAY TUNNELS LINED WITH GEOMEMBRANE

Photo taken during geomembrane installation. The geomembrane is then covered with concrete.

Courtesy NAUE

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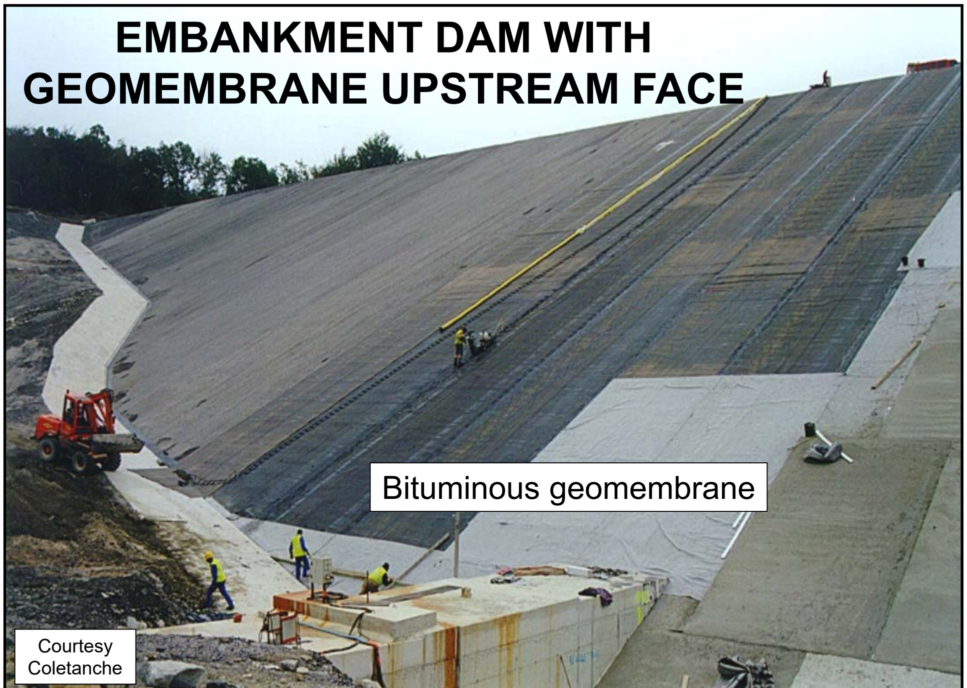
EMBANKMENT DAM WITH GEOMEMBRANE UPSTREAM FACE



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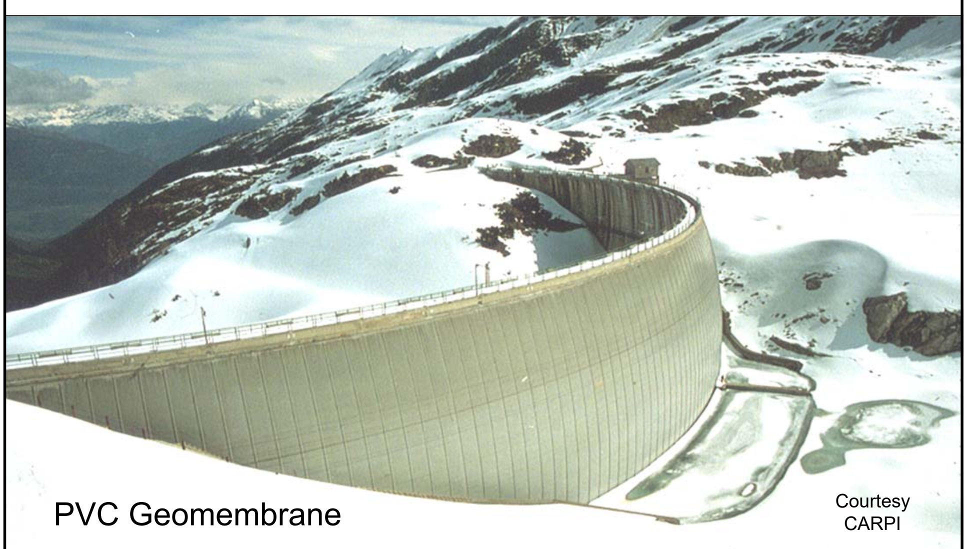
CONCRETE DAM WITH GEOMEMBRANE UPSTREAM FACE



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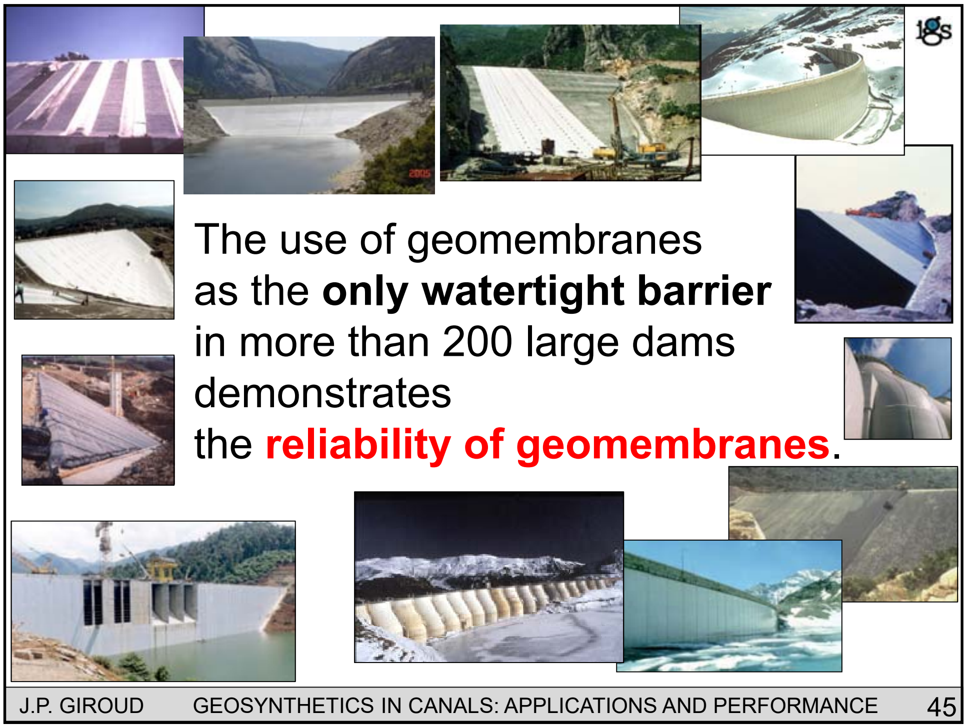
The use of geomembranes
as the only watertight barrier
in more than 200 large dams
demonstrates
the reliability of geomembranes.
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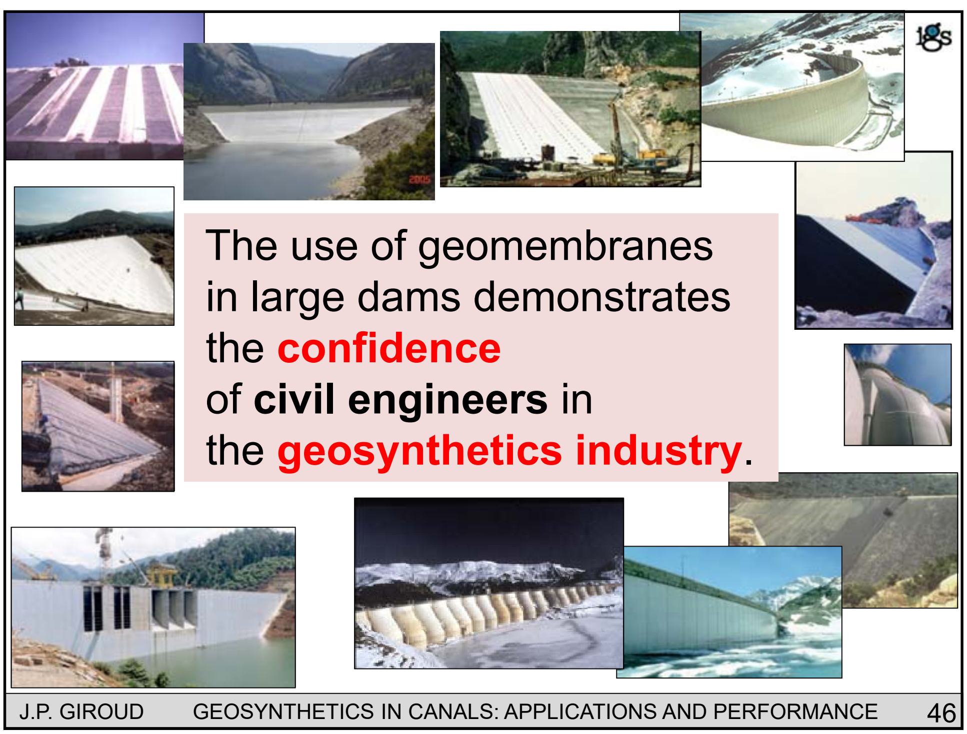
The use of geomembranes
in large dams demonstrates
the confidence
of civil engineers in
the geosynthetics industry.
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And, for decades, geomembranes have been used in a variety of canals.

HYDROPOWER CANALS

PONTE DE PEDRA CANAL, BRAZIL, 2003-2004

Courtesy F. Wieckert

NAVIGATION CANALS

LLANGOLLEN CANAL, UK, 2000

Courtesy Coletanche

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IRRIGATION CANALS

ESFAHAN CANAL, IRAN, 1977

Archive J.P. Giroud

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Large canals . . .

TEKAPO CANAL, NEW ZEALAND, 2013
Courtesy Carpi

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. . . and small canals.

YAKIMA CANAL, USA, 2002
Courtesy Coletanche

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The geomembrane can be protected

TARIM CANAL, CHINA, Late 1990s — Photo H. Pusquellec

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. . . or exposed.

CANAL DE PROVENCE, FRANCE, 2021 — Courtesy Coletanche

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Forerunners of geomembranes
were used in canals
in the 1950s and the 1960s.

Examples include
asphalt sprayed on jute
and, mostly,
films of **PVC** and **polyethylene**
(typically 0.2 mm thick).

ASPHALT SPRAYED ON JUTE, 1950s

UTAH STATE UNIVERSITY, LOGAN, USA, 1950s Courtesy USBR

FIRST CANAL LINED WITH A PVC FILM, 1954

FORT COLLINS, COLORADO, USA

Courtesy USBR

EARLY INSTALLATION OF PVC FILM, 1961

TUCAMARI CANAL NEW-MEXICO, USA, 1961

Courtesy USBR

EARLY INSTALLATION OF POLYETHYLENE FILM, 1960s

Here, a polyethylene film is **protected** by precast concrete panels.

IRRIGATION CANAL, UZBEKISTAN

FAO Photo, Courtesy H. Plusquellec

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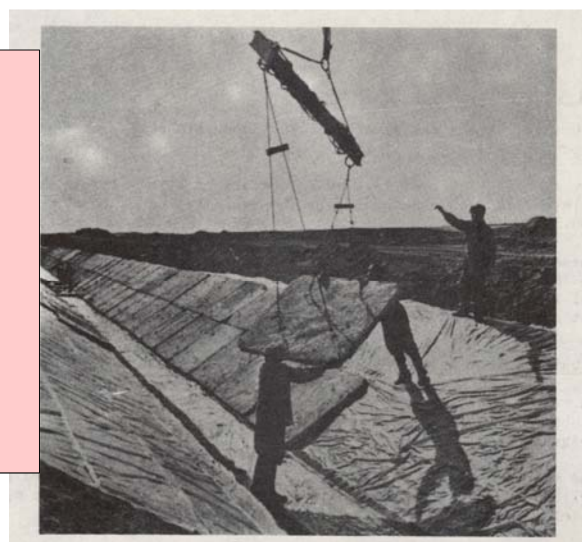
POLYETHYLENE FILM

This is typical of numerous uses of films in canals in the former **Soviet Union** from the 1960s to the 1990s.



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The **thin films**
used in these early applications
were not **modern geomembranes**,
which are generally
thicker than 1 mm.

However, significant experience
was gained from these installations
in the 1950s and 1960s.

More details
on the uses of geomembranes in canals
can be found in the book

Geomembranes for Lining Canals

by J.P. Giroud & H. Plusquellec

To be published in 2022
Taylor and Francis, Publishers

In spite of this **long history**
of **geomembranes** used in canals,
and in spite of the fact
that **geomembranes** are today
the **dominant watertight materials**
in waste storage landfills,
water reservoirs
and mining applications,
many canals
are still lined with concrete only.

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There are two types of concrete linings:

Cast-in-situ concrete

Precast concrete panels

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Cast-in-situ concrete linings
are used, in particular, in large canals
where concrete is often placed
with large canal lining machinery ("paving machine").

ALL AMERICAN CANAL, CALIFORNIA, USA, 2008 Courtesy GOMACO

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Cast-in-situ concrete linings
are also used in medium-size or small canals.

ZAGORA CANAL, MOROCCO, 2013 Photo H. Plusquellec

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As mentioned before,
there are two types of concrete linings:

Cast-in-situ concrete

Precast concrete panels

We just reviewed cast-in-situ concrete linings,
let's now discuss precast concrete panels.

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Precast concrete panels
are typically installed using hand labor.

PHU NINH CANAL, VIETNAM, 2000 Photo H. Plusquellec

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Precast concrete panels
are often used in small canals.

IRRIGATION CANAL, INDIA, 1990s Photo H. Plusquellec

The preceding slides show that there is **considerable experience** with **concrete linings**.

It is important
to understand the **state of practice of concrete linings**
to evaluate the **revolution**
that **geomembranes**
and other **geosynthetics**
bring to this field.

Concrete linings have drawbacks.
Concrete linings
are **not flexible** and **not extensible**.

As a result, concrete linings tend to **crack**
if they are not uniformly supported by the soil,
because of:
- Differential **settlement**
- Localized soil **subsidence**
- **Dissolution** of gypsum in soil
- **Collapse** of karst or loess-type soil
- **Swelling** clay
- **Erosion** of soil under the lining, and
- **Instability** of soil under the lining.

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Several of these problems, in particular:
- *Differential **settlement**,*
- ***Erosion** of soil under the lining, and*
- ***Instability** of soil under the lining,*

are caused by **poor construction**
(*poor compaction of the soil,*
low quality concrete, and
concrete lining thickness below specified value).

And, all problems
could be avoided or mitigated
by proper **design**.

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In contrast with concrete linings,
which are not flexible and not extensible,
geomembranes
are **flexible** and **extensible**.

Unlike concrete linings,
geomembranes **remain watertight**
even if they are not uniformly supported
by the underlying soil.

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Here we see a longitudinal crack
in a concrete lining.

ARMAVIR CANAL, ARMENIA Courtesy BRL

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Longitudinal cracking is typical
in canals lined with cast-in-situ concrete.

Longitudinal cracking is due to
differential settlement,
in particular
if the lower part of the canal is in **cut**
and the upper part is in **fill**.

A **horizontal joint**, filled with a sealant,
is often used to prevent longitudinal cracking
of cast-in-situ concrete linings.

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Here, a **horizontal joint** did not prevent cracking.

BALIKH IRRIGATION PROJECT, SYRIA, 1977 Photo J.P. Giroud

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There had been an unsuccessful attempt at sealing the cracks with **adhesive tape**.

BALIKH IRRIGATION PROJECT, SYRIA, 1977 Photo J.P. Giroud

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The failure of
this cast-in-situ concrete canal lining
was caused by **dissolution** of the soil
by **water leaking from the canal**.

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This canal is located in an area where the soil has a high content of **gypsum**.

Gypsum is soluble in water.

Photo J.P. Giroud

Water leaking
through joints and
through **small cracks** of the concrete lining
dissolved some gypsum,
which caused **soil subsidence**,
which increased the concrete cracking,
thereby **increasing the leakage**,
which caused **more gypsum dissolution**,
which resulted in more subsidence,
which further opened cracks and joints,
and so on,
until the canal was put out of commission.

At the same site, the concrete lining collapsed into a **cavity** formed by **gypsum dissolution**.

BALIKH IRRIGATION PROJECT, SYRIA, 1977 Photo J.P. Giroud

As seen in this example,
water leaking through concrete cracks
can cause a major failure
if the soil is sensitive to water.

In the Middle East,
several failures of concrete-lined canals
have been caused by gypsum dissolution.

These canals have been **repaired**
using **geomembrane lining**.

Gypsum **dissolution** occurs in arid zones,
in particular in the Middle East,
but is relatively rare in the rest of the world.

However, everywhere in the world,
similar problems are caused by **erosion**.

Water **leaking through initial cracks**
or **through joints** in the concrete lining
erodes the soil under the concrete lining.

As a result of **erosion of the soil**,
the concrete lining
is no longer uniformly supported.

This causes **cracking**
of **cast-in-situ concrete linings**
and causes **differential displacement**
of **precast concrete panels**.

This is shown on the next slide.

Here is an example of **differential displacement** affecting precast concrete panels.

IBER-LEPENC CANAL, KOSOVO Photo H. Plusquellec

The preceding slides show that there are several mechanisms that deteriorate concrete linings.

Therefore,
a number of
concrete canal linings
have been repaired
or need to be repaired.

There are many examples
of defective **concrete-lined canals**
that have been **repaired**
using geomembranes,
but there are **no examples**
of **geomembrane-lined canals**
that have been
repaired using concrete lining.

It should be noted that
many **geomembrane linings**
having excellent performance
are **protected with concrete**.

A good way to use **concrete in canals**
is as **protective layer**
of the geomembrane lining.

The **geomembrane ensures watertightness**
while the **concrete ensures protection**.

Watertightness is discussed in the following slides.

In the preceding slides, we have seen that geomembranes are **flexible** and **extensible** and, therefore, **remain watertight** even if they are not uniformly supported by the underlying soil.

In contrast, we have seen that concrete linings exhibit cracks and, therefore, **do not remain watertight**.

Evaluation of **seepage**/**leakage** from canals is presented in the following slides.

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Estimates of water **seepage** and **leakage** from canals, based on theory, field measurements and experience, are presented in detail in the book.

A summary of the conclusions of the book is presented in the following slide.

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Estimated **seepage** or **leakage** from canals, for a typical depth of water of 3 m:

- Unlined canal on silt to sandy soil: 100 to 1000 mm/day
  A value of 250 mm/day is often mentioned.
- **Concrete lining in good condition**: 25 to 50 mm/day
- Concrete lining in poor condition: > 100 mm/day
- **Geomembrane well installed**: 0.1 to 1 mm/day
- Geomembrane poorly installed: 1 to 10 mm/day
- Geomembrane with large holes: > 100 mm/day

Seepage/Leakage is **100 times lower** with **geomembrane** than with concrete.

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It should be noted that:

The leakage values given for concrete in the preceding slide are only for cast-in-situ concrete linings. No values are given for precast concrete linings. Their performance is not as good as the performance of cast-in-situ concrete linings.

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A leakage analysis,
based on experimental data
and theoretical calculations,
shows that
even relatively thin cracks in concrete
result in **significant leakage**,
which is sufficient to deteriorate
the underlying soil (for example by erosion),
thereby creating poor support conditions
for the concrete lining
and, consequently, **more leakage**.

AN IMPORTANT COMMENT:
Based on the results presented,
both,
a **concrete lining** in poor condition
and a **geomembrane** with large holes
are not better than an unlined soil.

CONSEQUENTLY:
Precautions should be taken
to prevent the development
of large holes in geomembranes.

Precautions to prevent large holes in geomembranes include proper selection of materials:

- Selection of a **high-quality geomembrane**
- Proper selection of the geomembrane **thickness**
- Proper selection of the **materials** adjacent to the geomembrane
- Proper selection of **geotextiles** to protect the geomembrane, and
- Proper selection of the **cover material** (*concrete, soil layer, concrete-filled geomattress, soil-filled or concrete-filled geocell*)

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Precautions to prevent large holes in geomembranes also include:

- Proper **geotechnical design** to minimize displacements of the soil and appurtenant structures
- Proper **compaction** of the soil supporting the geomembrane
- Quality control and construction quality assurance of geomembrane **installation**, including electrical leak location and
- Careful **maintenance** operations

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Questions are often asked about
the **durability** of geomembranes.

Durability is often treated
as an intrinsic property
of a given geomembrane.

It is more appropriate to consider
the **service life** that can be predicted
for a **given geomembrane**
in a **given structure**, such as a given canal.

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For modern geomembranes
supplied by experienced manufacturers
and
covered with an adequate **protective layer**,
a **service life** longer than **100 years**
can generally be predicted.

For **exposed** geomembranes,
the service life depends on:

- Geomembrane type, composition and thickness;
- Exposure conditions.

Predicted service lives of exposed geomembranes
may vary from 20 to 100 years.

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Concerns about durability or service life are pointless in case of **premature failure** of the geomembrane.

Premature failure occurs too frequently:

- **Failure during construction**,
  or as a consequence of construction,
  due to lack of survivability of the geomembrane
  or inadequate design of the lined structure.
- **Failure in early stage of service**
  due to inadequate design of the lined structure.

Failures due to inadequate design
are a greater concern than durability,
hence the need to educate engineers.

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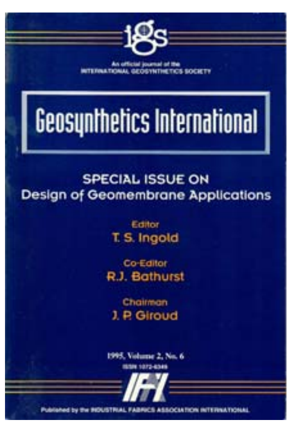
Methods for the **safe design**
of **geomembrane linings**
have been published and used
in reservoirs, landfills, dams and canals.



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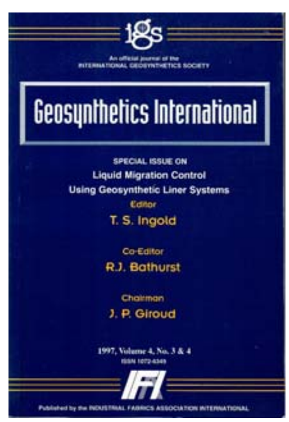

247 pages

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Now, let's review
a few **examples**
of canals lined with
geomembranes.

Let's start with the first example of
modern canal design.

In the mid-1970s,
the era of **thin plastic films** was over
and **modern geomembranes** were being used.

The Esfahan Canal
(constructed in Iran,1976-1979), was the
first large irrigation canal lined with a
geomembrane (***not a plastic film***).

4 m deep, 15 m wide at top, 50 km long

The existing concrete lining (100 mm thick)
constructed in the early 1970s
deteriorated rapidly
due to **dissolution of gypsum**
present in the ground
(*which is frequent in arid areas*).

The dissolution of gypsum was caused by
water leaking through cracks in the concrete
and through **defective joints**.

Soil **subsidence** due to gypsum dissolution
increased the cracks and **opened the joints**
thereby **increasing leakage**, and so on.

As a result,
the existing concrete lining
was severely cracked
5 years after construction.

The canal had to be **relined**.

Since **concrete was not working**,
it was clear (even as early as 1975)
that a geomembrane had to be used.

The geomembrane of choice at that time
was **butyl rubber**.

The specifications called for
a **maximum leakage** rate of 1 mm / day.

This is easily achieved with a geomembrane.

The **challenge** was to meet this goal
with a geomembrane placed on concrete
with **cracks** that could evolve with time
and where new **cracks** could appear.

In 1975, this was a **new challenge**.

An extensive **theoretical study**
was undertaken
(summarized by Giroud & Ah-Line 1984).

The theoretical study showed that,
placing a geotextile
next to the geomembrane
would significantly **reduce** the
the **tensile stress** in the geomembrane .

As a result of this study,
the following configuration was adopted.

CROSS SECTION
from top to bottom

- Cast-in-situ concrete,
  120 mm thick (bottom), 90 mm (slopes)
- Polyester needle-punched nonwoven geotextile, 270 g/m^2
- Butyl rubber geomembrane, 0.75 mm thick
- Polyester needle-punched nonwoven geotextile, 270 g/m^2
- Existing concrete lining (for repaired canals) or excavated soil for new canals

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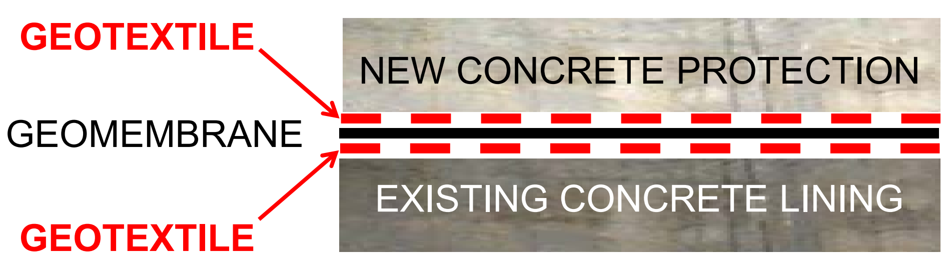
CROSS SECTION



ESFAHAN CANAL, IRAN, 1976

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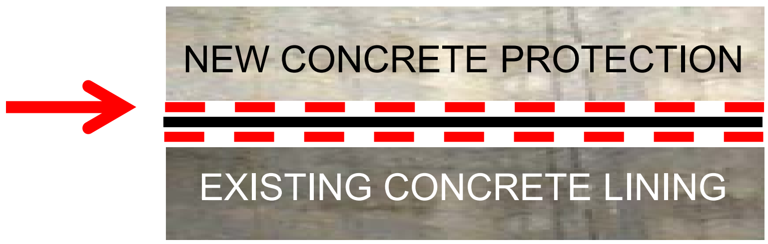
Role of geotextile above geomembrane:

- **protection** of geomembrane during construction
- **reinforcement** of concrete during placement on slope
- **drainage** of excess water from fresh concrete



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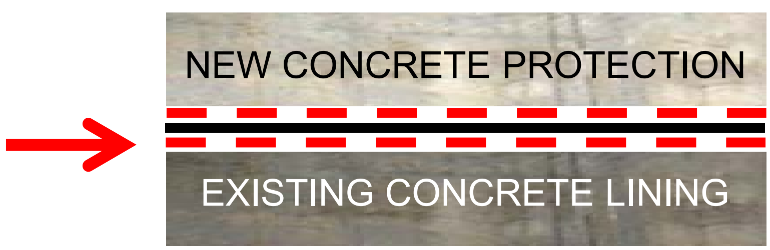

Role of geotextile below geomembrane:

- **protection** of geomembrane from puncturing by underlying concrete
- **low-friction interlayer** decreasing stresses in the geomembrane when a crack opens in the existing concrete lining
- **support** of geomembrane to prevent the geomembrane from bursting under water pressure while bridging cracks of the existing concrete lining

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750,000 m^2
of butyl rubber geomembrane
and 1.5 million m^2
of nonwoven geotextile
were installed at the Esfahan Canal
in 1976-1979.

It was the largest geomembrane project at that time.

Now, a few slides of the Esfahan Canal

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Geomembrane unrolled
on top of geotextile

The geomembrane panels were 16 m x 50 m.

ESFAHAN CANAL, IRAN, 1976-1979 Archive J.P. Giroud

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Two geomembrane panels (800 m^2 each) were placed and seamed every day.

Archive J.P. Giroud

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HISTORIC SEAMING MACHINE
FOR BUTYL RUBBER GEOMEMBRANE

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Modern seaming machines
are much smaller and more sophisticated.

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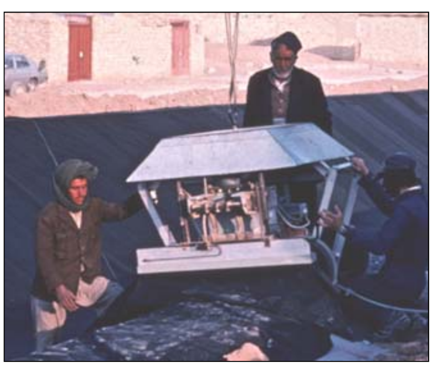
OLD AND MODERN SEAMING MACHINES



1975
Butyl rubber geomembrane

2010
HDPE geomembrane

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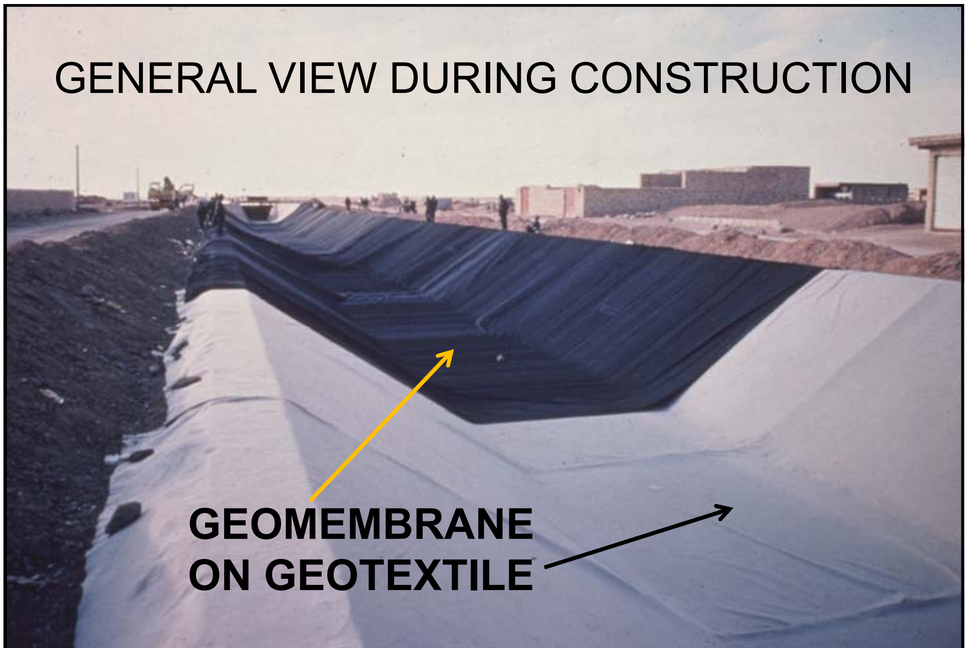

ESFAHAN CANAL, IRAN, 1976-1979 Archive J.P. Giroud

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UNREINFORCED CONCRETE AT BOTTOM Archive J.P. Giroud

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UNREINFORCED CONCRETE AT BOTTOM Archive J.P. Giroud

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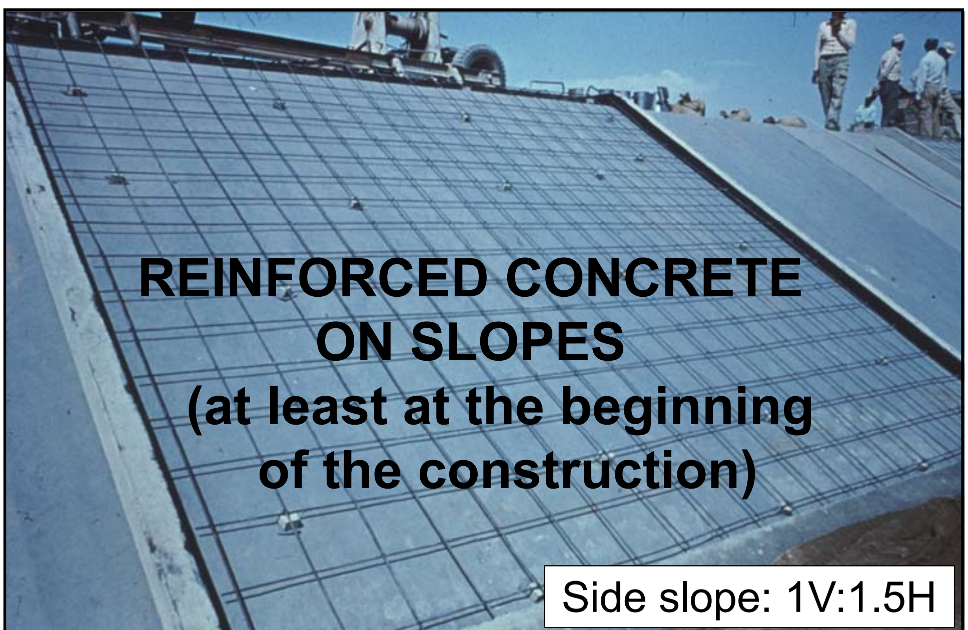

REINFORCED CONCRETE ON SLOPES Archive J.P. Giroud

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Placing concrete on slopes was labor-intensive. Archive J.P. Giroud

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Field tests showed that **unreinforced** concrete was **stable** when cast **on geotextile**, but was **unstable** when cast directly on the geomembrane.

The geotextile ensured stability by providing reinforcement of fresh concrete and drainage of excess water from the concrete.

Therefore, unreinforced concrete was finally used on the slopes.

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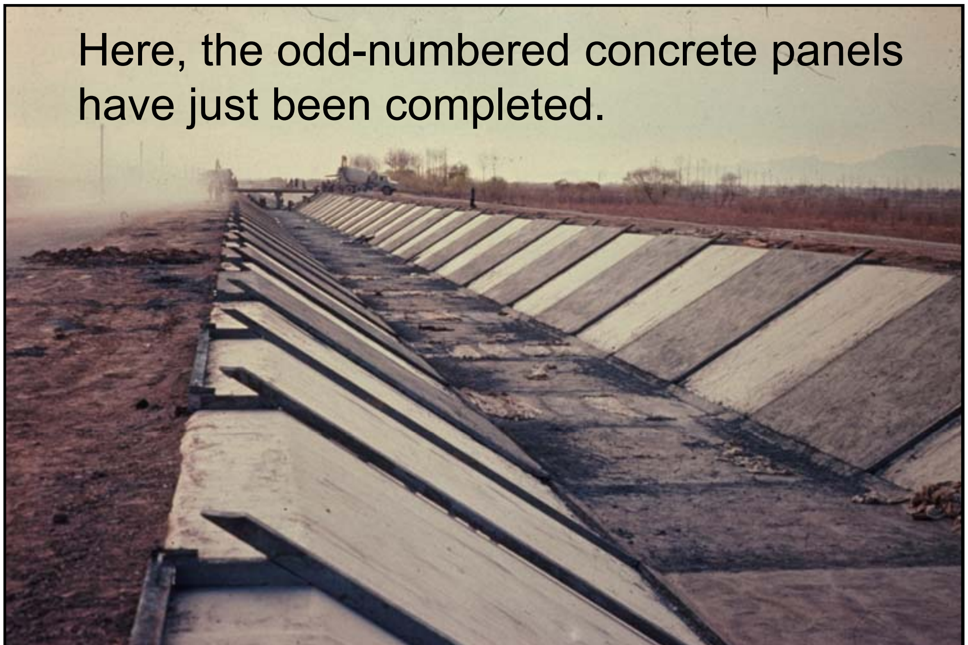

ESFAHAN CANAL, IRAN, 1976-1979 Archive J.P. Giroud

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Then, the **even-numbered** concrete panels were cast, with open joints between panels.

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The Esfahan Canal is still in service, 45 years after being lined with butyl rubber geomembrane.

Today, butyl rubber has been replaced by **another elastomer**, EPDM, which is even **more durable**.

Following are examples of EPDM geomembranes in canals.

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INSTALLATION OF AN EPDM GEOMEMBRANE IN A CONCRETE-LINED CANAL

HARLINGEN CANAL TEXAS 2003

Courtesy Firestone

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HARLINGEN
CANAL
TEXAS
2003

Courtesy
Firestone

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INSTALLATION OF AN EPDM GEOMEMBRANE
IN AN EARTH CANAL

LOST HILLS CANAL, CALIFORNIA

Courtesy Firestone

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EPDM GEOMEMBRANE

LOST HILLS CANAL, CALIFORNIA

Courtesy Firestone

The presentation of the Esfahan Canal
showed the rehabilitation
of an **existing canal**
using a geomembrane.

The next example presents
a **new canal**
lined with a geomembrane.

The Toshka New Valley Project
also known as "Toshka Project"
is a large irrigation project in Egypt.

Launched in 1997 and on-going

This is perhaps
the **largest geosynthetic project**
in the world
with 20 million square meters
of geomembrane.

DESCRIPTION OF THE MAIN CANAL

- 60 m wide at the top, 7.5 m deep
- Side slopes 2H:1V
(not steep, compared to typical 1.5H:1V)
- **Safety** considered more important than **economy**
(*which is remarkable and not frequent in irrigation canals*)
- This approach led to the selection
of a relatively **thick geomembrane**
protected by **thick concrete layer**
placed on **slopes that are not steep**.

Hereafter, the main canal is referred to as "the Toshka Canal".

TOSHKA CANAL CROSS SECTION

FROM TOP TO BOTTOM

- 200 mm fiber-reinforced concrete
- 100 mm shotcrete
- **1.5 mm HDPE** geomembrane (textured both sides)
- shotcrete
- sandy subgrade

NO GEOTEXTILE

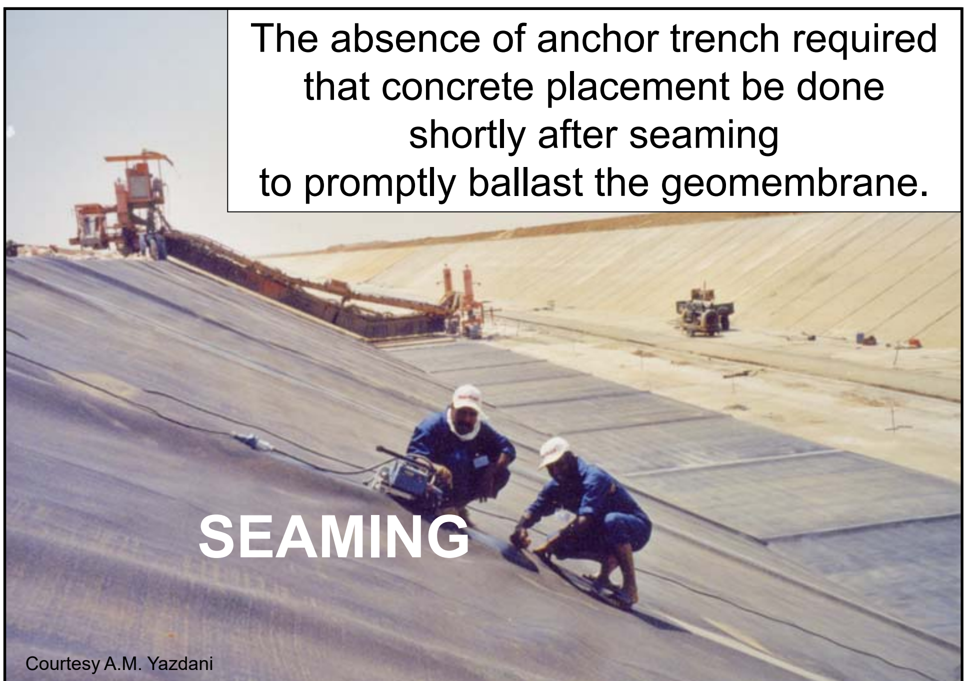
A special detail of the Toshka Canal is that there is **no anchor trench** at the crest of the side slopes.

As a result,
700,000 square meters
of geomembrane
were saved.

NO ANCHOR TRENCH

Courtesy A.M. Yazdani

The absence of anchor trench required that concrete placement be done shortly after seaming to promptly ballast the geomembrane.



Courtesy A.M. Yazdani

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To avoid the formation of wrinkles
in the HDPE geomembrane
at the Toshka Canal,
the geomembrane was installed
at night and early morning
in the summer.

Wrinkles are a known problem
with HDPE geomembranes,
as illustrated on the next slide.

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Wrinkles with HDPE geomembranes

IRRIGATION CANAL, AUSTRALIA   Courtesy H. Plusquellec

J.P. GIROUD   GEOSYNTHETICS IN CANALS: APPLICATIONS AND PERFORMANCE   139

Wrinkles cause problems to exposed HDPE geomembranes:

- Wrinkles slow down the **flow of water**.
- Wrinkles are prone to **mechanical damage**.
- Wrinkles induce **stress concentration** in the geomembrane.
- Wrinkles reduce **intimate contact**
  between the geomembrane and the supporting material,
  which is **detrimental** to geomembrane **stability**
  and to **leakage control**.

IRRIGATION CANAL, AUSTRALIA   Courtesy H. Plusquellec

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Wrinkles cause problems to covered HDPE geomembranes:

- Wrinkles make it **difficult to place** the cover material, whether it is concrete or geosynthetic system.
- Wrinkles are likely to undergo **mechanical damage** during the placement of the cover material.
- Wrinkles locked under the cover material are likely to undergo **stress concentration**.

IRRIGATION CANAL, AUSTRALIA   Courtesy H. Plusquellec

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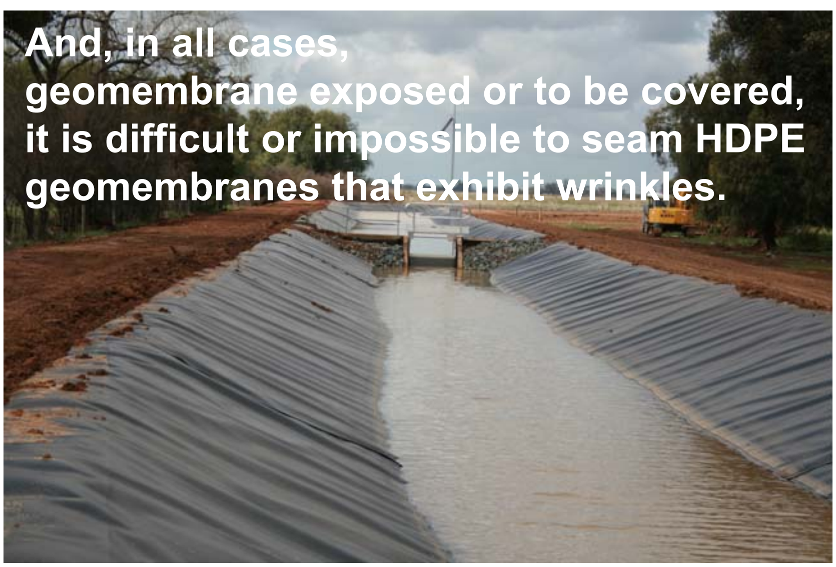
Wrinkles with HDPE geomembranes

And, in all cases, geomembrane exposed or to be covered, it is difficult or impossible to seam HDPE geomembranes that exhibit wrinkles.



IRRIGATION CANAL, AUSTRALIA   Courtesy H. Plusquellec

J.P. GIROUD   GEOSYNTHETICS IN CANALS: APPLICATIONS AND PERFORMANCE   142

Wrinkles result from **thermal expansion**.

Therefore, to reduce the formation of wrinkles, the geomembrane **temperature** should be kept as **low** as possible:

The most effective way is to **construct at night**, which was done at Toshka Canal.

But, constructing at night reduces the amount of geomembrane that can be installed every day.

Another possibility is to use a geomembrane with a **white surface** or a **reflective surface**.

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Clearly, wrinkles are controlled by using geomembranes with **white surface** or **reflective surface**.

Courtesy GSE

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The examples presented so far showed the use of **polymeric geomembranes** (PVC, HDPE, polypropylene, and elastomeric geomembranes such as butyl rubber and EPDM).

The following slides will present the use of **bituminous geomembranes**.

A bituminous geomembrane is essentially a needle-punched **nonwoven geotextile impregnated** and **coated** with a compound of **bitumen** and **elastomer**.

Photo Coletanche

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Bituminous geomembranes have also been used for the rehabilitation of concrete canals.

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In preceding examples,
geomembranes were either exposed . . .

SOUSTEN-FINGES HYDROPOWER CANAL, SWITZERLAND, 1993 Courtesy Carpi

. . . or covered.

by concrete panels or by cast-in-situ concrete

TARIM CANAL, CHINA, Late 1990s

Photo H. Pusquellec

ESFAHAN CANAL, IRAN, 1975-1979

Archive J.P. Giroud

Leaving a **geomembrane exposed** has some advantages:

- The cost is minimized
- The **flow of water is faster** if a **smooth geomembrane** is used.

However, covering a geomembrane has more advantages.

This is discussed in the next slide.

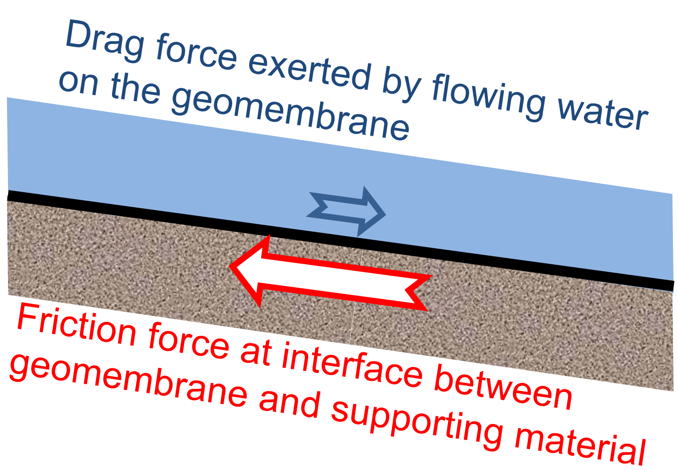
Covering a geomembrane has many advantages:

- **Protection** against **deterioration** by animals and humans
- **Protection** against **damage** by falling objects and hail
- **Protection** against **temperature variations**
- **Protection** against **solar radiation**
- **Ballasting** the geomembrane **seams** against peeling
- **Ballasting** the geomembrane against **uplift by wind**, and
- **Ballasting** the geomembrane against **displacement** by **action of water**

The last item deserves an explanation.

The **drag forces** due to flowing water tend to **displace the geomembrane**.

However,
if the geomembrane is **intimate contact** with the underlying medium,
the geomembrane is not displaced
because the **interface friction forces beneath** the geomembrane
are **higher than the drag forces above** the geomembrane.



The **friction force** is higher than the **drag force**
if there is **intimate contact** between
the geomembrane and the supporting material.

But, if the geomembrane is uplifted, there is **no intimate contact** between the geomembrane and the supporting material.

As a result, the drag forces are **not counteracted** by interface friction forces under the geomembrane.

Therefore, in this case, **the geomembrane is dragged downstream**, unless it is properly anchored or ballasted.

Here is a canal where the geomembrane left of the **anchorage beam** was uplifted and then removed by the drag forces.

ANCHORAGE BEAM

Photo M. Bacchelli

Here is a canal where the geomembrane left of the **anchorage beam** was uplifted and then removed by the drag forces.

Photo M. Bacchelli

It is important to understand the **mechanism of geomembrane uplift**.

The uplift mechanism is triggered by a **hole in the geomembrane**.

If there is **no hole** in the geomembrane, the **static pressure** applied by the water present in the canal keeps the **geomembrane in contact** with the underlying medium and the drag forces are not effective.

If there is a **hole in the geomembrane**, and if **water** leaking through this hole **accumulates** under the geomembrane (in other words, if the material under the geomembrane is *not draining*), a **dynamic pressure** is established under the geomembrane in accordance with the general Bernoulli's equation.

The water pressure **beneath** the geomembrane is then the **total pressure** or **stagnation pressure** given by:

$$p_{total} = \rho_w\, g\, d + \frac{\rho_w V^2}{2}$$

The water pressure **above** the geomembrane is the **static pressure** given by:

$$p_{stat} = \rho_w\, g\, d$$

The geomembrane is then **uplifted** by the **difference** between the total pressure and the static pressure, in other words, by the **dynamic pressure**:

$$p_{total} - p_{stat} = p_{dyn} = \frac{\rho_w V^2}{2}$$

It is interesting to compare
geomembrane **uplift by water** flow in canals
with the well known phenomenon
of geomembrane **uplift by wind**.

DENSITY VELOCITY

The **same equation** is used:

$$p_{dyn} = \frac{\rho V^2}{2}$$

A calculation using this equation shows that
the possibility of geomembrane uplift in a canal
is similar to
the possibility of geomembrane uplift by wind.

DENSITY VELOCITY

$$p_{dyn} = \frac{\rho V^2}{2}$$

In the equation,
the **velocity is squared**.

In a canal, the water **flow velocity** is low (1 m/s) compared to **wind velocity** (say 30 m/s or more); therefore, the **velocity squared** may be 900 times higher for wind than for water flow.

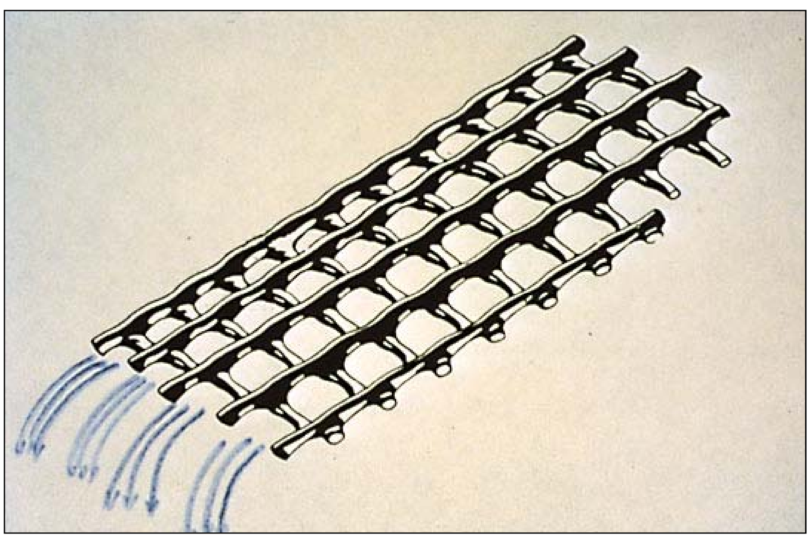
But, **water density** is 800 times the **density of air**.

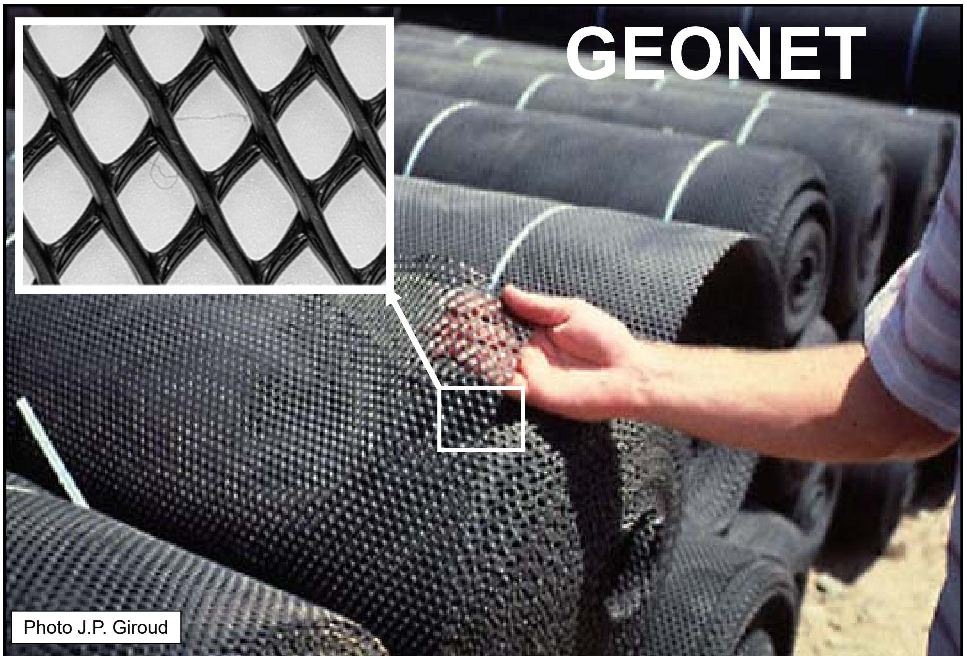
Therefore, the two phenomena are equivalent and geomembrane **uplift by flowing water** is as likely as geomembrane **uplift by wind**.

Drainage under the geomembrane
is a possible solution
against geomembrane uplift
due to accumulation of leaking water
under the geomembrane
if the soil has a low permeability.

Gravel or geosynthetics can be used
to construct a **drainage layer**
under a geomembrane liner.

Here is a **geonet**,
a typical geosynthetic used for drainage.





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DRAINAGE GEOCOMPOSITE WITH GEONET DRAIN AND GEOTEXTILE FILTER

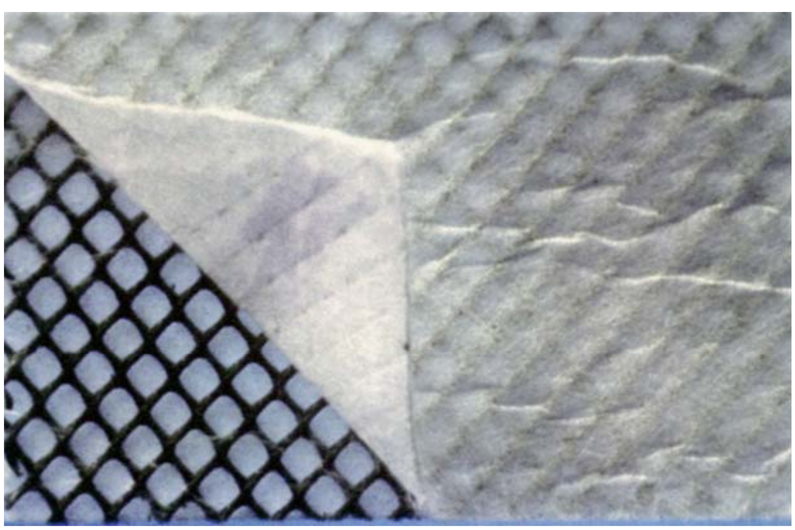

Photo J.P. Giroud

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A challenge with drainage under a canal lining is to establish **outlets** to evacuate the drained water.

Furthermore, drainage may not be sufficient for preventing an exposed geomembrane from being uplifted and dragged downstream.

Therefore, it is generally recommended to **anchor** and/or **ballast** geomembranes to prevent them from being uplifted and dragged downstream.

There are several ways to **anchor** a geomembrane.

If a geomembrane is used to **reline an existing concrete canal**, and if the concrete has sufficient strength, the geomembrane can be **nailed** in a watertight way to the concrete.

Some geomembranes can be **bonded** to concrete (bituminous geomembranes, composite geomembrane consisting of a geomembrane bonded to a geotextile).

If the geomembrane lining
is placed in an earth canal,
anchorage can be done
by attaching the geomembrane
to concrete **beams**.

This is illustrated in the next slide.

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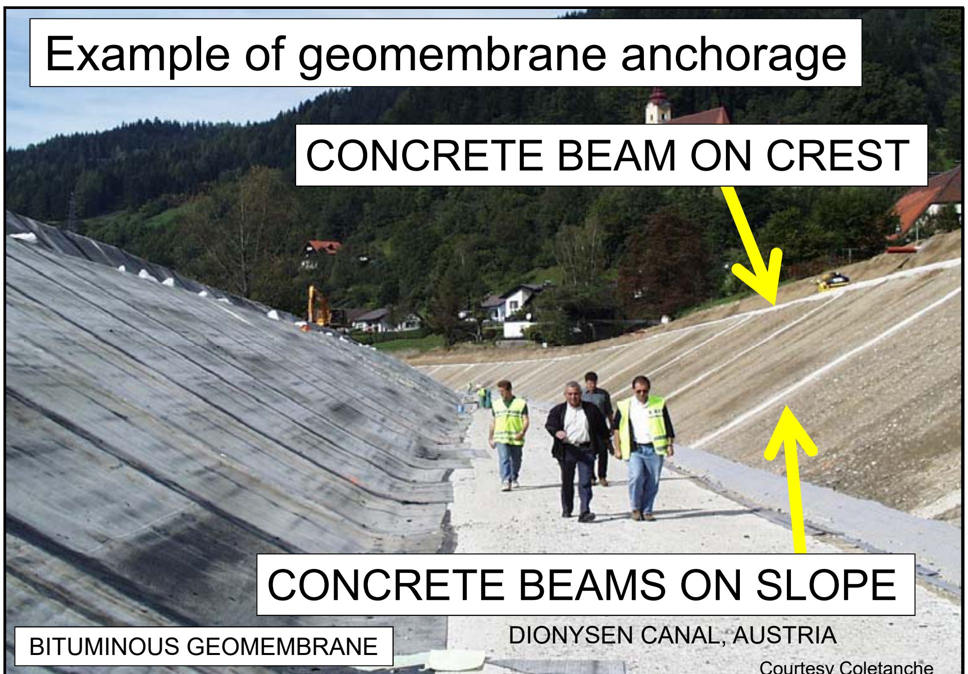

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Clearly, geomembranes in canals must be **anchored** and/or **ballasted** to prevent them from being **uplifted and dragged**.

In addition, as mentioned in an earlier slide, it is **beneficial to cover a geomembrane** by a **protective layer** against a variety of possible damage or deterioration (*animals, vandalism, falling objects, hail, temperature variation, solar radiation*)

Therefore, it is generally recommended to cover geomembranes.

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We have seen examples of canals where the geomembrane lining is **protected and ballasted by concrete** (*cast-in-situ concrete or precast panels*).

However, protection/ballasting of the geomembrane can also be done by a **variety of systems** using **different types of geosynthetics**.

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It is important to note that the systems presented in the following slides can **perform several functions** :

- They can **protect** and/or **ballast** a geomembrane.
- They can be used without geomembrane for **erosion control** and/or **bank stabilization**.
- Some of them can even **control leakage**, *in addition to erosion control and bank stabilization*, thereby acting as a watertight lining, but possibly less effectively than a geomembrane.

SLOPE PROTECTION USING ROCKS

The stability of rocks on slopes is a challenge.

In a large canal, lined with geomembrane, a geogrid placed on a **geotextile** protecting the geomembrane was used to ensure stability of the rocks.

TEKAPO CANAL, NEW ZEALAND

Photo Carpi

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In a large canal, lined with geomembrane, a geogrid placed on a **geotextile** protecting the geomembrane was used to ensure stability of the rocks.

Three geosynthetics are on top of each other:
geogrid / geotextile / geomembrane

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Another way to ensure rock stability is to use gabions.

CANAL BANK PROTECTION, BRAZIL

Courtesy F. Wieckert

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The next slide shows:

GABION MATTRESS
ON TOP OF
GEOTEXTILE AND GEOMEMBRANE
AND COVERED WITH
GEOMAT FOR VEGETATION GROWTH

CROSS SECTION FROM TOP TO BOTTOM

- Geomat reinforced with steel mesh
- Gabion mattress
- Geotextile
- Geomembrane
- Geotextile

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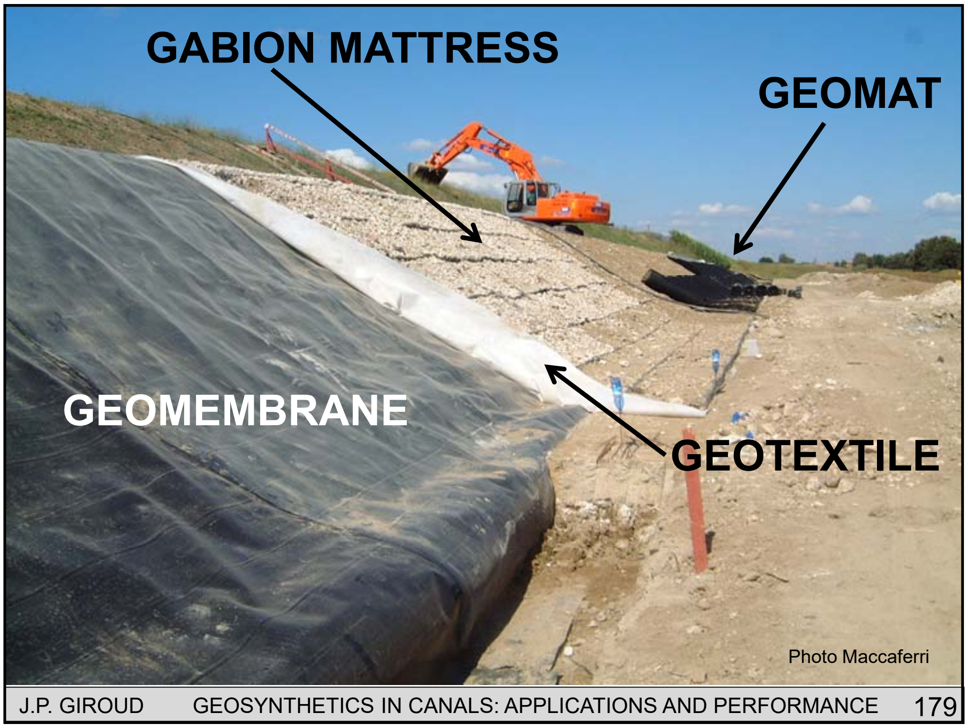
GABION MATTRESS
GEOMAT
GEOMEMBRANE
GEOTEXTILE
Photo Maccaferri
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ARTICULATED CONCRETE BLOCKS
SUPPORTED BY GEOTEXTILE
CANAL IN BURGUNDY, FRANCE
Photo J.P. Giroud
J.P. GIROUD GEOSYNTHETICS IN CANALS: APPLICATIONS AND PERFORMANCE 180

ARTICULATED CONCRETE BLOCKS

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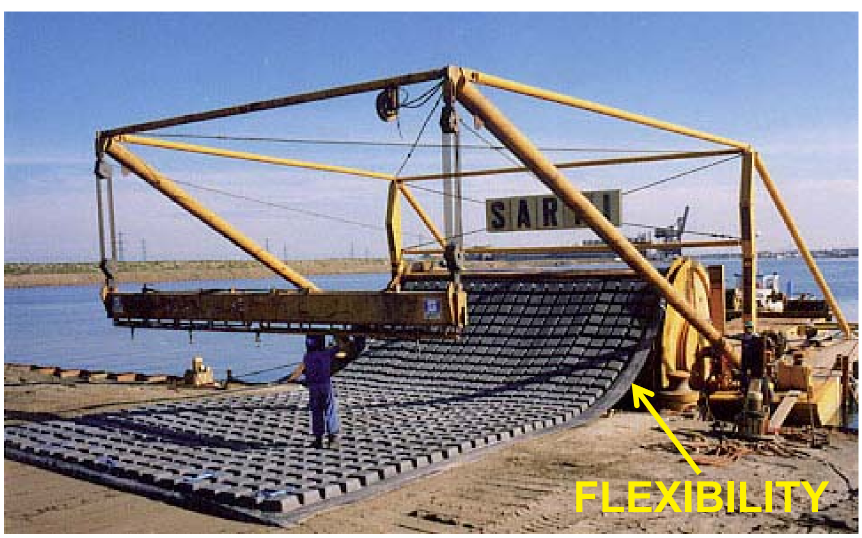
ARTICULATED CONCRETE BLOCKS
SUPPORTED BY GEOTEXTILE
INSTALLATION FRAME



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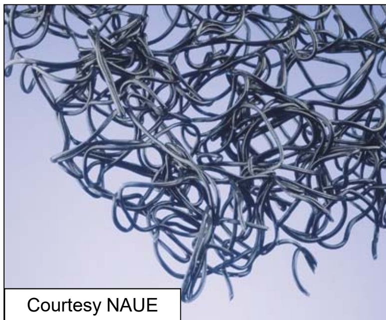
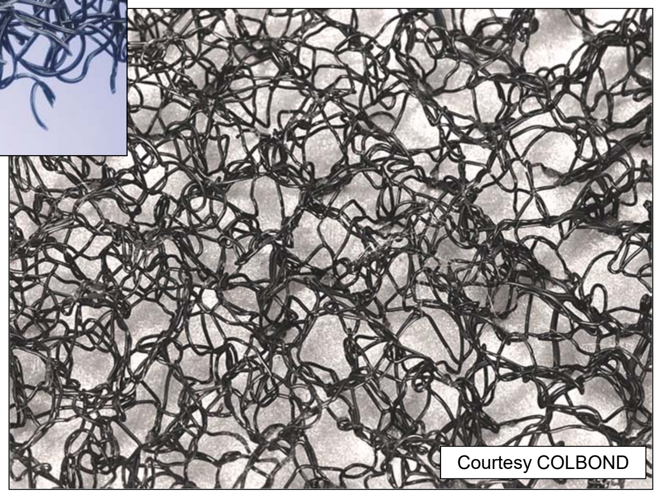
GEOMATS



Courtesy NAUE



Courtesy COLBOND

Tortuous structures with coarse fibers.

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Thanks to the **high porosity** of geomat there is excellent **interlocking** between geomat and soil.

Hence the use of geomats for **erosion control**

Courtesy COLBOND

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Geomat rolls used for erosion control


Courtesy COLBOND

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GROWTH OF VEGETATION THROUGH A GEOMAT


Courtesy NAUE

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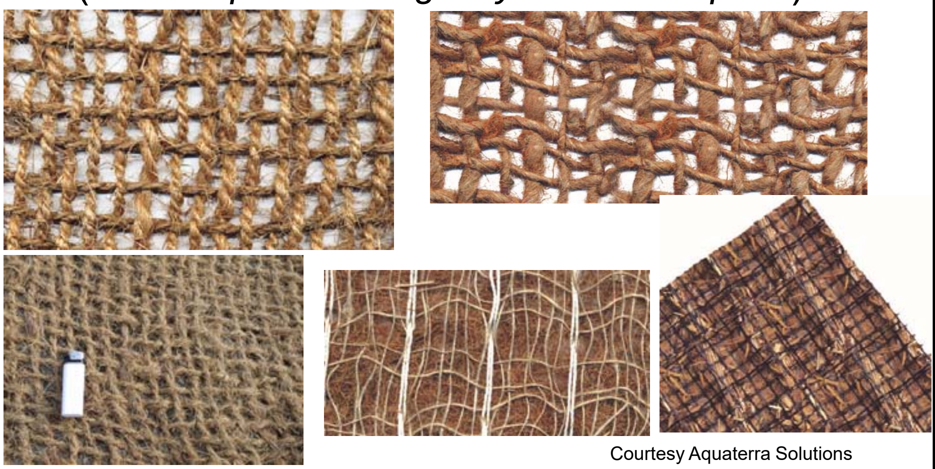
EROSION CONTROL PRODUCTS MADE OF NATURAL FIBERS

also called biomats or bionets

(*now adopted in the geosynthetic discipline*)



Courtesy Aquaterra Solutions

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EROSION CONTROL WITH NATURAL FIBERS

FRANCE Courtesy Aquaterra Solutions

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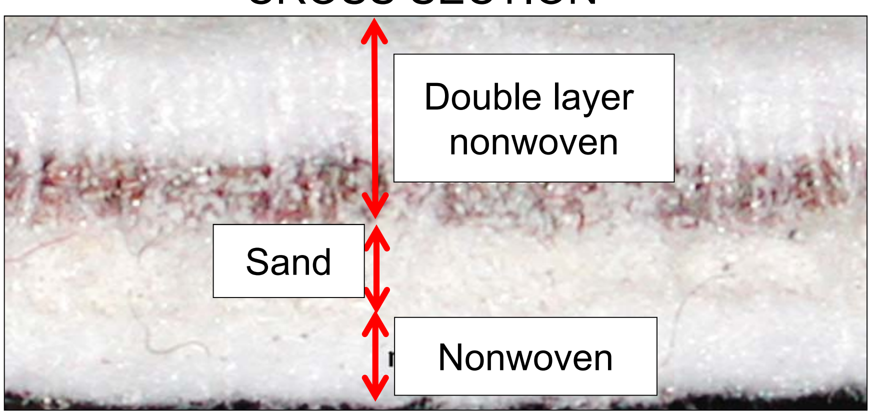
SAND-GEOTEXTILE COMPOSITE USED FOR BANK PROTECTION

CROSS SECTION



Courtesy NAUE

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UNDERWATER INSTALLATION OF SAND-GEOTEXTILE COMPOSITE IN CANAL

Courtesy NAUE

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Another association of sand and geotextile is used in a **sand-filled geomattress**, which consists of two layers of fabric linked with uniformly spaced parallel stitches.

Photo TENCATE

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Geomattress filled with sand

Empty geomattress being deployed

Photo TENCATE

Stitches separating the tubes

DETAILED VIEW OF A GEOMATTRESS FILLED WITH SAND

Photo TENCATE

EXAMPLE OF A BANK PROTECTED BY A SAND-FILLED GEOMATTRESS

Photo TENCATE

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BANK PROTECTION USING GEOCELL

CANAL BANK PROTECTION, OKLAHOMA, USA Courtesy Presto

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A geocell consists of multiple cells.

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GEOCELL BEING PLACED ON GEOTEXTILE

CANAL BANK PROTECTION, OKLAHOMA, USA Courtesy Presto

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GEOCELL FILLED WITH SOIL
FOR BANK PROTECTION AND VEGETATION

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GEOCELL FILLED WITH CONCRETE
FOR BANK PROTECTION AND LEAKAGE CONTROL

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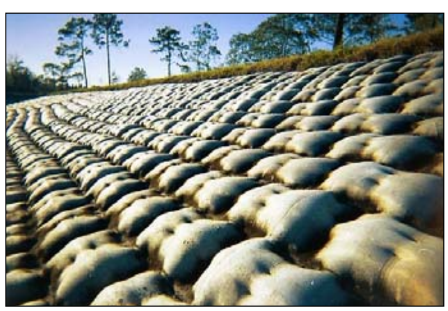
On long slopes and steep slopes, geocells can be **reinforced** with tendons anchored at the crest of the slope.

Photo Presto

BANK PROTECTION USING GEOMATTRESSES



Courtesy FABRIFORM

A geomattress consists of two parallel fabrics attached with **strings**.

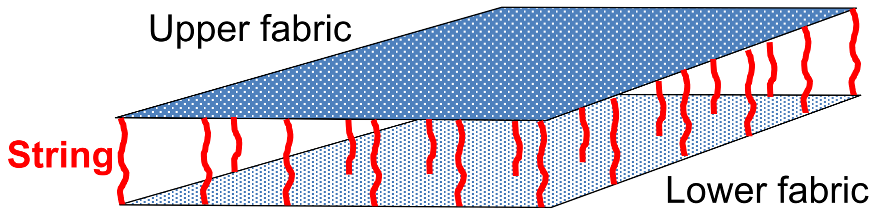
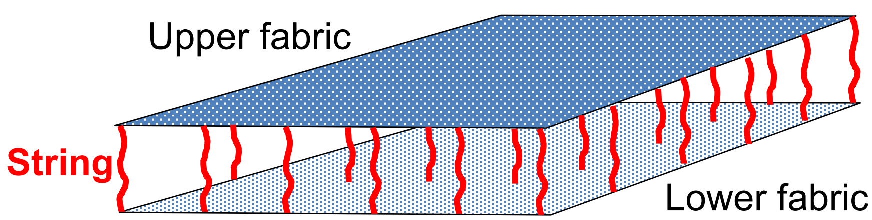


Photo showing the strings between the two fabrics

Photo Huesker

A geomattress consists of two parallel fabrics attached with **strings**.



Geomattress after **filling with concrete** the space between the two fabrics

Courtesy Huesker

GEOMATTRESS BEING FILLED WITH CONCRETE

Courtesy FABRIFORM

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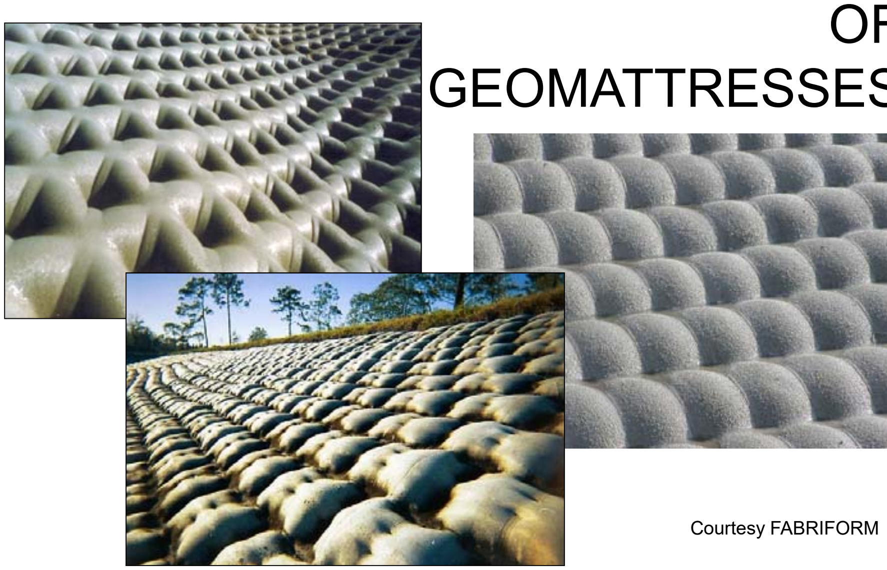
DIFFERENT SHAPES OF GEOMATTRESSES



Courtesy FABRIFORM

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J.P. GIROUD GEOSYNTHETICS IN CANALS: APPLICATIONS AND PERFORMANCE 207

The **geosynthetic systems** presented in the preceding slides can be used in **three different ways**:

- They can be used to **protect and/or ballast** a geomembrane lining.
- They can be used without geomembrane to **control erosion**.
- The systems that are filled with concrete can be used without geomembrane to serve as a **low-permeability lining**.

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The slope protection systems which are **filled with concrete**, and can be used (without geomembrane) as **low-permeability lining**, are:

GEOCELLS

GEOMATTRESSES

Here, **concrete is the low-permeability lining**.

In fact, this is a way to construct a concrete lining.

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There is an **innovative type of geomattress**, which comprises **two geomembranes** rather than two fabrics:

- The **upper geomembrane** is a woven fabric coated with PVC.
- The **lower geomembrane** is a high-quality **composite geomembrane** that consists of a PVC geomembrane **bonded** to a nonwoven geotextile.

J.P. GIROUD GEOSYNTHETICS IN CANALS: APPLICATIONS AND PERFORMANCE 210

Canal lined using a geomembrane-formed geomattress **installed under water** and filled with concrete

Courtesy Carpi

This geomembrane-formed geomattress is designed to be **installed underwater**, **while water is flowing in the canal**.

The two geomembranes of this geomattress have different functions :

- The **upper geomembrane** prevents dispersion of cement into the canal water during underwater installation.
- The **lower geomembrane** is a watertight canal lining.

There is a **major difference** between
the classical geomattress where concrete is contained between two fabrics (which are **permeable**)
and the innovative geomattress
where concrete is contained
between two geomembranes (which are **watertight**):

- In the case of the fabric-formed geomattress, **the canal lining is concrete**.
- In the case of geomembrane-formed geomattress, the canal lining is a **high-quality geomembrane**.

As shown in this presentation, geomembranes are far superior to concrete for leakage control.

Another way to associate
concrete and geosynthetics:

CONCRETE GEOCOMPOSITE

which consists of
fiber-reinforced dry concrete mix
between two layers of geotextile.

The geotextiles are either nonwoven or knitted.

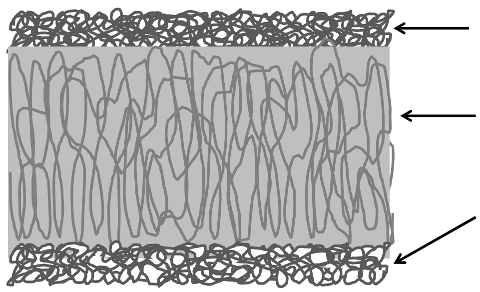
A geomembrane
can be associated to this geocomposite.

CONCRETE GEOCOMPOSITE

(also known as GCCM)

TYPE WITHOUT GEOMEMBRANE AT THE BOTTOM

CROSS SECTION



The geotextiles are either nonwoven or knitted.

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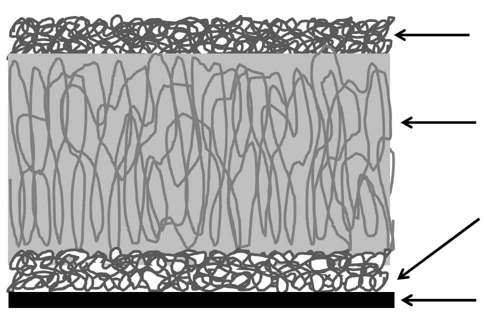
CONCRETE GEOCOMPOSITE

(also known as GCCB)

TYPE **WITH GEOMEMBRANE** AT THE BOTTOM

CROSS SECTION



The geomembrane is either an HDPE geomembrane or a thick coating on the lower face of the geotextile.

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Canal lined using concrete geocomposite

Courtesy Concrete Canvas

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In addition to concrete,
another usual low-permeability material,
bentonite, can be used to line canals.

Courtesy NAUE

J.P. GIROUD GEOSYNTHETICS IN CANALS: APPLICATIONS AND PERFORMANCE 218

In addition to concrete,
another usual low-permeability material,
bentonite, can be used to line canals.

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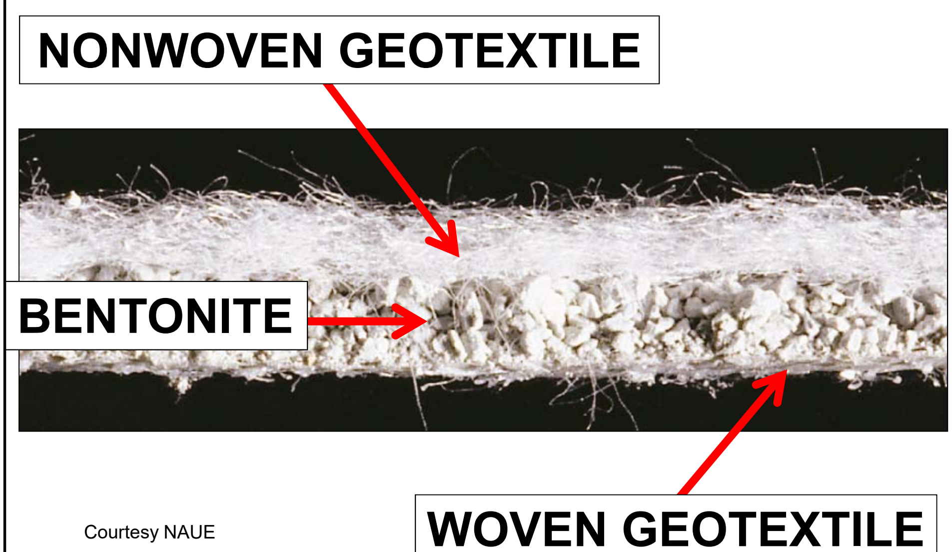
BENTONITE GEOCOMPOSITE



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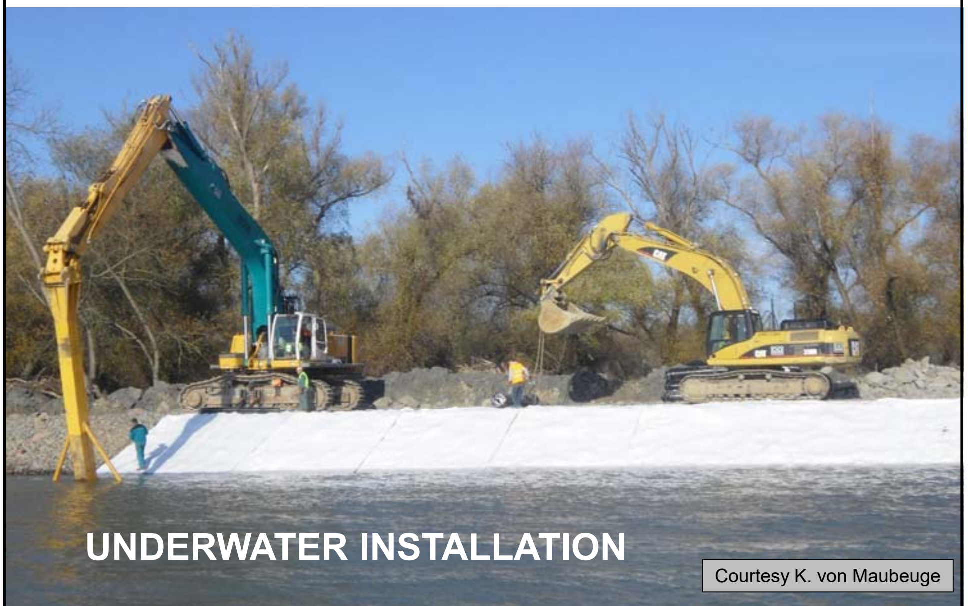
Canal lined using bentonite geocomposite



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CONCLUSION

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This review of geosynthetics in canals shows that geosynthetics offer all possibilities:

- Geomembranes are **far superior** to all other materials for **watertightness**.
- Geosynthetics other than geomembranes may provide **a degree of watertightness** that is sufficient in some situations.
- Several geosynthetic systems provide:
  - **protection of geomembrane**
  - **erosion control**
  - **bank stabilization**.

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In summary, geosynthetics in canals offer **all possibilities** with **superior performance**.

Therefore, geosynthetics should be the material of choice for all canal applications.

However, there are still **engineers** who **systematically prefer concrete** to line canals.

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Many engineers prefer concrete
because they prefer **traditional solutions**.

Many engineers prefer concrete
because they prefer "**hard**" solutions
even though **flexibility** and **extensibility**
ensure better performance,
as shown in this presentation.

Essentially,
many engineers prefer concrete
because they are **not informed**
of the possibilities offered by geosynthetics.

J.P. GIROUD GEOSYNTHETICS IN CANALS: APPLICATIONS AND PERFORMANCE 225

Clearly, we need to **educate engineers**
who design canals.

Therefore,
I hope that many of you will be able
to use the information
presented in the book
as an education tool and a guide
for the **use of geosynthetics in canals**.

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Using geosynthetics in canals is a way to address the challenge of **water conservation**:

- According to the FAO, approximately
  70% of the available water is used for irrigation
  20% for industry and
  10% for municipal/domestic water supply.
- Approximately half of the irrigation water is transported in canals, many of them unlined.

Therefore, approximately 35% of the available water is transported in canals.

Based on experience, it can be assumed that half the irrigation canals are unlined or poorly lined, and it is generally estimated that 30% of the water from these canals is lost by seepage.

All calculations done, approximately **5% of the available water** is lost due to **seepage** from irrigation canals.

This is approximately **half the municipal/domestic water supply**.

Clearly, seepage from unlined or poorly lined canals is probably the **main cause of water waste** on Earth.

As shown in the preceding slide,
seepage from unlined canals is probably
the **main cause of water waste** on Earth.

We have seen that **leakage** through
geomembranes is extremely low.

Therefore **seepage** into the ground
is extremely low
when geomembranes are used to line canals.

Thus, using geomembranes in canals
is the **most effective way** to **save water**.

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Thus,
by using geomembranes
and other **geosynthetics** in **canals**,
we act in a way that is
beneficial to society at large,
because **water** is
one of the great challenges
of the 21st century.

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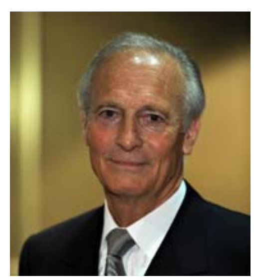
Thank You

J.P. Giroud

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, founder and Chairman Emeritus of Geosyntec Consultants, past president of the International Geosynthetics Society (the IGS), former chairman of the Editorial Boards of *Geotextile and Geomembranes* and *Geosynthetics International*, and a member of the U.S. National Academy of Engineering.

Dr. Giroud has been involved with geosynthetics since 1970. He coined the terms “geotextile” and “geomembrane” in 1977. He has developed numerous design methods used in geosynthetics engineering, for lining systems, leakage control, drainage, geotextile filters, and geosynthetic-stabilized roads.

Dr. Giroud is author of more than 400 publications, and he has presented several prestigious lectures, such as: the Vienna Terzaghi Lecture, the ASCE Terzaghi Lecture (the highest honor for a geotechnical engineer in the United States), the Victor de Mello Lecture, the Szechy Lecture, the Mercer Lecture, the Jack Hilf Lecture, the Raoul Dutron Lecture, the Kersten Lecture.

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. The IGS has named his highest honor “the Giroud Lecture” and he became Honorary Member of the IGS in 2002 with the citation “Dr. Giroud is truly the father of the IGS and the geosynthetic discipline”.