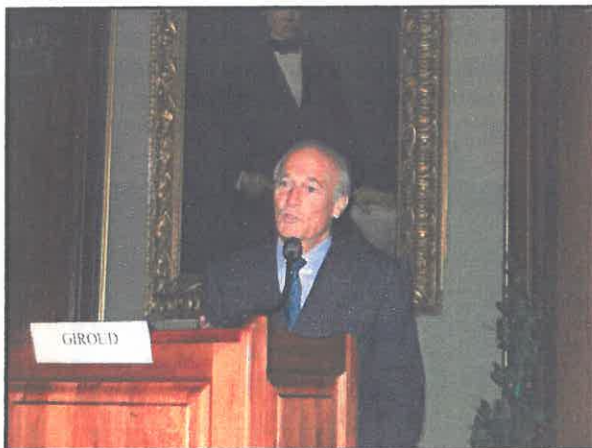


VIENNA, 2005

The Terzaghi Lecture

**GEOSYNTHETICS ENGINEERING:
SUCCESSSES, FAILURES
AND LESSONS LEARNED**

J.P. GIROUD



YOKOHAMA, 2006

The Terzaghi Lecture

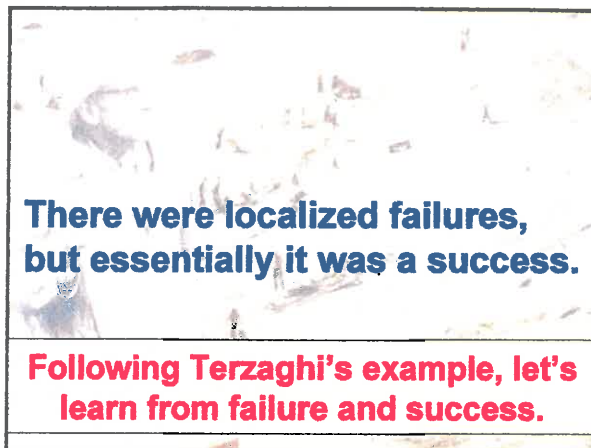
**GEOSYNTHETICS ENGINEERING:
SUCCESSSES, FAILURES
AND LESSONS LEARNED**

J.P. GIROUD

**Karl Terzaghi
and Mission Dam
(now Terzaghi Dam)
1960**

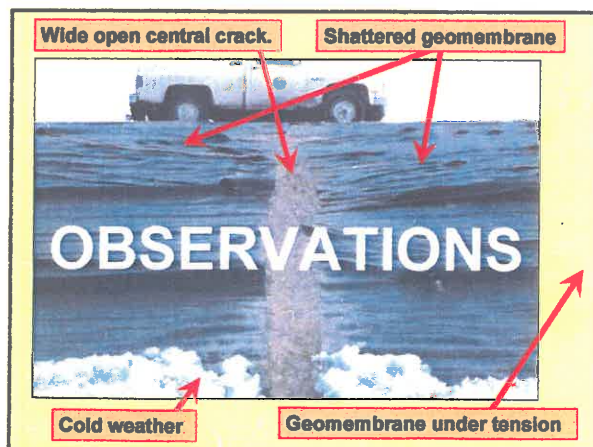
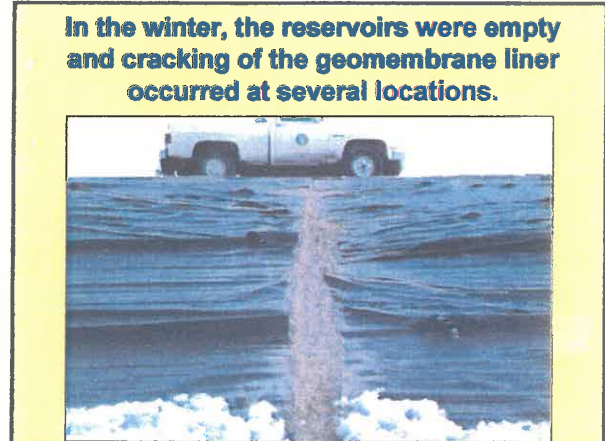
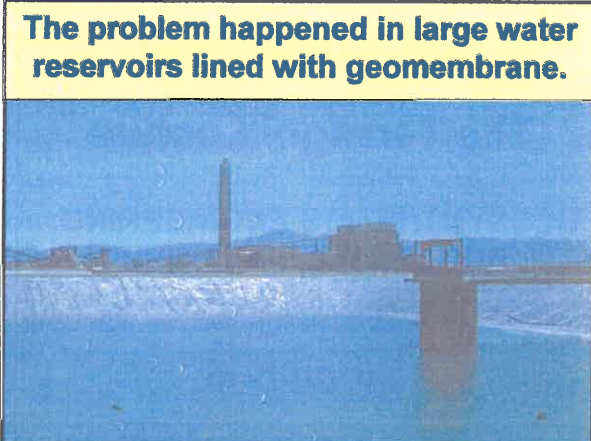


**Terzaghi used a
PVC membrane
at Mission Dam.
Today we would say:
a PVC geomembrane.**



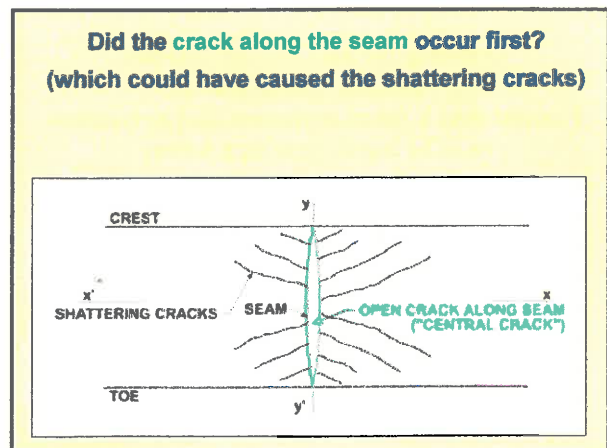
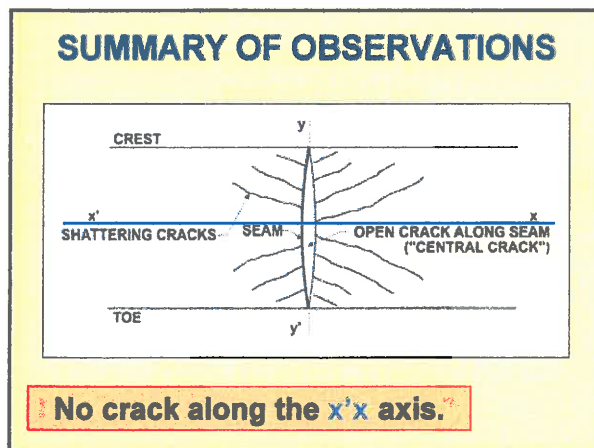
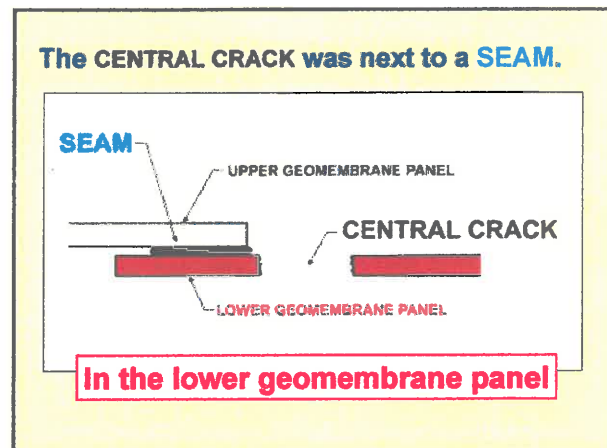
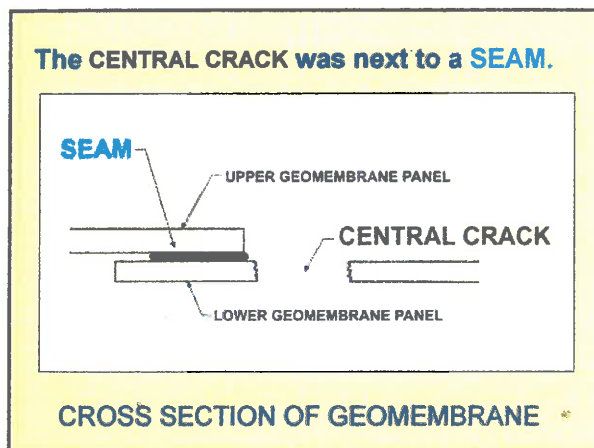
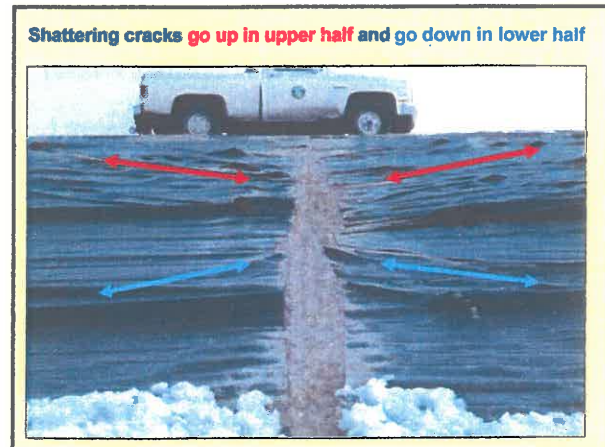
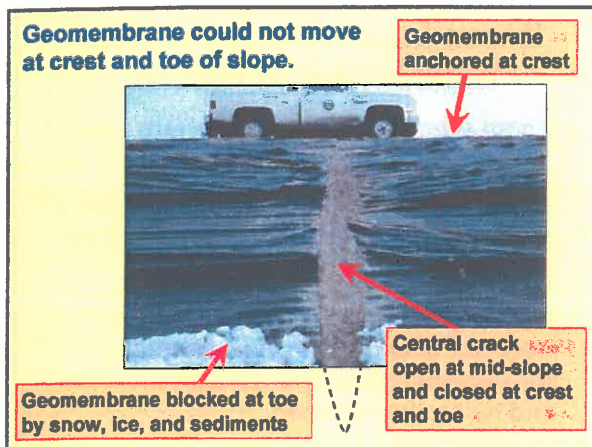
FIRST EXAMPLE

**INVESTIGATION
OF
GEOMEMBRANE
CRACKING FAILURE**



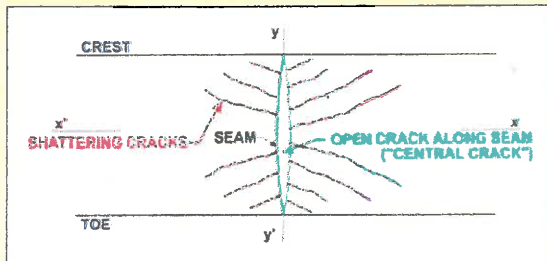
Just before cracking occurred, the cold weather tended to contract the geomembrane, but the contraction was **restrained which resulted in geomembrane **tension**.**

Thermal contraction was **restrained because the geomembrane could not move at crest and toe.**



Did the **crack along the seam** occur first?
(which could have caused the shattering cracks)

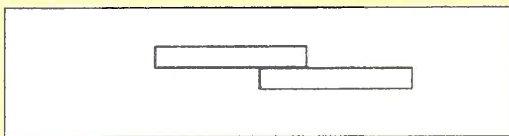
Did the **shattering cracks** occur first?



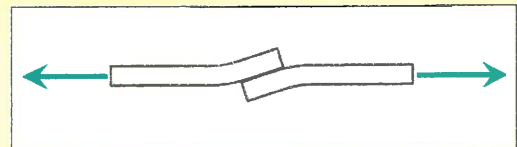
It was important to find the
mechanism of failure.

- If the opening of the central crack triggered the shattering cracks, then the **geomembrane tension** played a role, and reducing the tension could be the solution.
- If the shattering cracks were not linked to the central crack, the **geomembrane was defective** and had to be replaced.

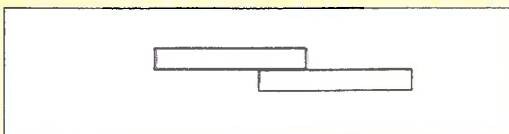
To explain the mechanism,
I looked for something special
next to the seam,
I noted that a geomembrane under tension
has to **bend** next to a seam
to ensure that the tensile forces are aligned.



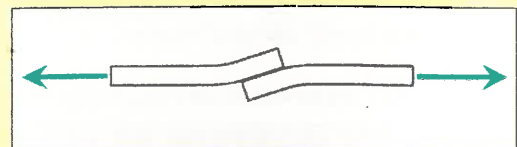
Looking for something special
next to the seam,
I noted that a geomembrane under tension
has to **bend** next to a seam
to ensure that the **tensile forces** are aligned.



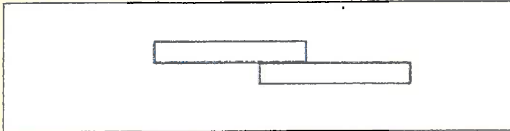
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to ensure that the tensile forces are aligned.



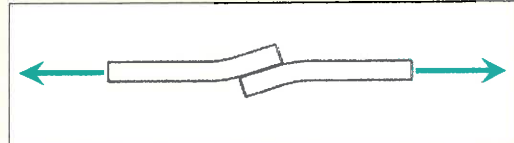
Looking for something special
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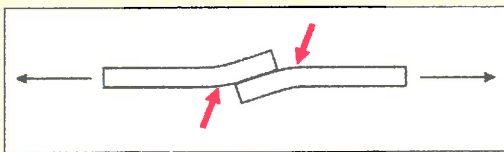
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Looking for something special
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to ensure that the **tensile forces** are aligned.

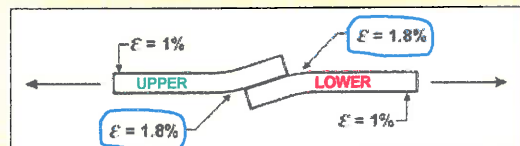


I calculated the geomembrane strain
at the **locations of maximum bending**.



Results on the next slide →

CALCULATED GEOMEMBRANE STRAINS

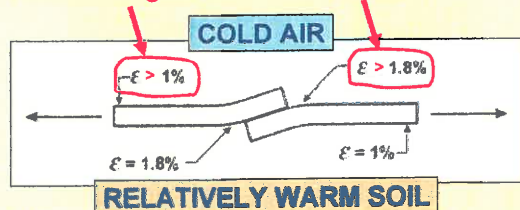


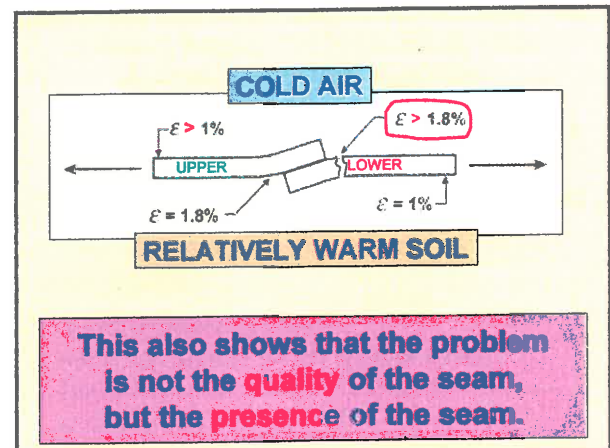
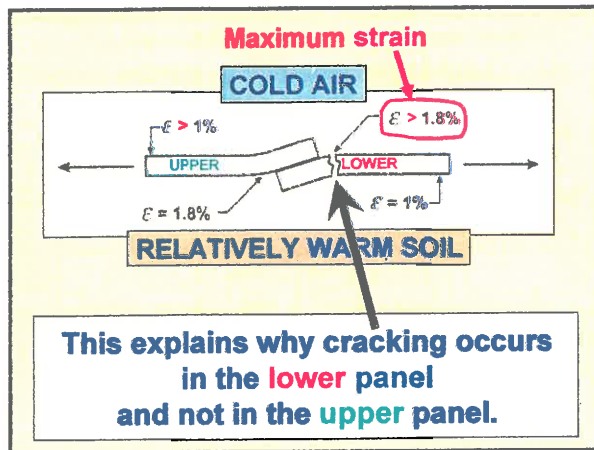
This 80% explains why cracking is more likely
to occur next to seams than away from seams,

but it does not explain why cracking occurs
in the **lower** geomembrane panel
and not in the **upper** geomembrane panel.

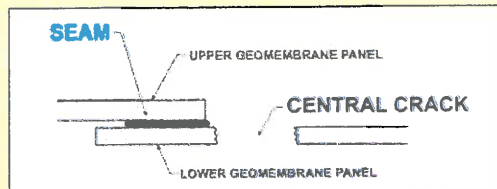
However,
there was a difference
between the situation of
the **upper** panel
and the situation of
the **lower** panel.

Additional geomembrane strain





At this point, we had an explanation for the development of the central crack **next** to the seam, in the lower panel.

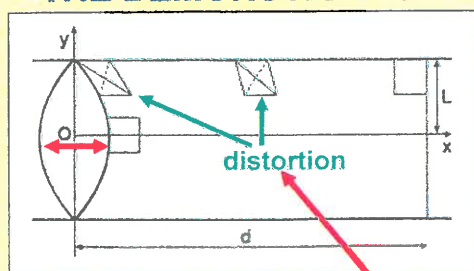


But . . . we had not demonstrated that the central crack had **triggered** the shattering cracks.

To be convincing, the demonstration had to be based on engineering principles.

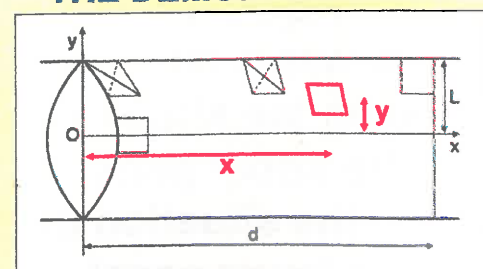
[ALL SORTS OF "COMMON SENSE" EXPLANATIONS HAD BEEN PROPOSED.]

MODEL USED FOR THE DEMONSTRATION

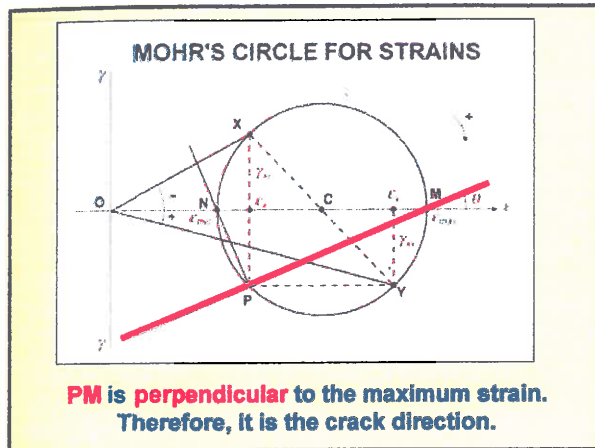


ASSUMPTION: Opening of the central crack occurs first

MODEL USED FOR THE DEMONSTRATION



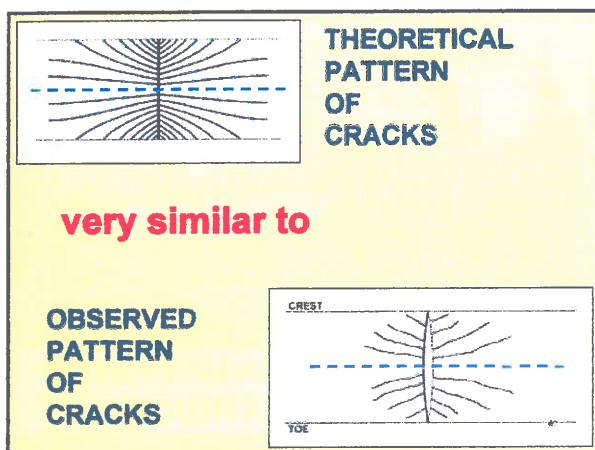
Using this model: Mohr's circle for strains in the geomembrane as a function of x and y .



The Mohr's circle depends on **x** and **y**.
Therefore, the direction of cracks depends on **x** and **y**.

The entire process is analytical.
Therefore, I obtained the equation for a **family of curves**.

This family of curves is the **theoretical pattern of cracks**.



CONCLUSION OF THE ANALYSIS

- The analysis was based on the **assumption** that the **central crack occurred first**.
- The analysis explained the observations.
- Therefore, the assumption was correct.
- The opening of the central crack was caused by geomembrane tension in cold weather.
- Therefore, the **geomembrane tension** in cold weather had **to be reduced**.



LESSON LEARNED

from this failure investigation

Complex mechanisms associated with geosynthetics can be **rationally analyzed** using methods typically used in **engineering disciplines**.

Clearly, geosynthetics engineering is one of the engineering disciplines.

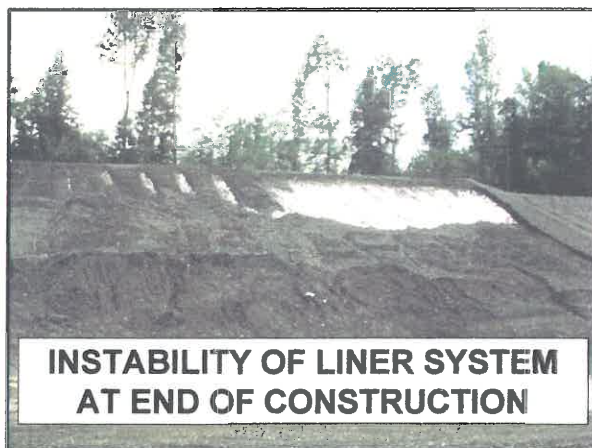
SECOND EXAMPLE

INSTABILITY OF GEOMEMBRANE/SOIL LAYERED SYSTEM ON SLOPE

**In landfills, reservoirs, dams, etc.
we use layered systems
composed of:**

- **Soil layers**
(sometimes reinforced with geogrid)
- **Geotextiles**
- **Geonets**
- **Geocomposites**
- **Geomembranes**

**A slip surface
may develop
at one of the interfaces
between these layers,
which results in
instability.**

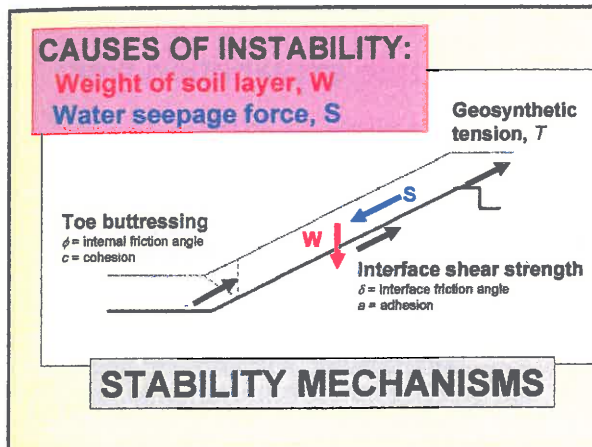


INSTABILITY OF TEMPORARY COVER



INSTABILITY OF LANDFILL COVER





SLOPE STABILITY EQUATIONS (full water depth)

$$FS_A = \frac{\gamma_b \tan \delta_A}{\gamma_{sat} \tan \beta} + \frac{a_A}{\gamma_{sat} t \sin \beta} + \frac{\gamma_b t \tan \phi / (2 \sin \beta \cos^2 \beta)}{\gamma_{sat} h} + \frac{c}{\gamma_{sat} h} \frac{1/(\sin \beta \cos \beta)}{1 - \tan \beta \tan \phi} + \frac{T}{\gamma_{sat} t h}$$

$$FS_B = \frac{\tan \delta_B}{\tan \beta} + \frac{a_B}{\gamma_{sat} t \sin \beta} + \frac{\gamma_b t \tan \phi / (2 \sin \beta \cos^2 \beta)}{\gamma_{sat} h} + \frac{c}{\gamma_{sat} h} \frac{1/(\sin \beta \cos \beta)}{1 - \tan \beta \tan \phi} + \frac{T}{\gamma_{sat} t h}$$

A = above geomembrane B = below geomembrane

SLOPE STABILITY EQUATIONS

FIRST TERM WITHOUT WATER

$$FS = \frac{\tan \delta}{\tan \beta}$$

FIRST TERM WITH WATER

ABOVE

$$FS_A = \frac{\gamma_b \tan \delta}{\gamma_{sat} \tan \beta}$$

BELOW

$$FS_B = \frac{\tan \delta}{\tan \beta}$$

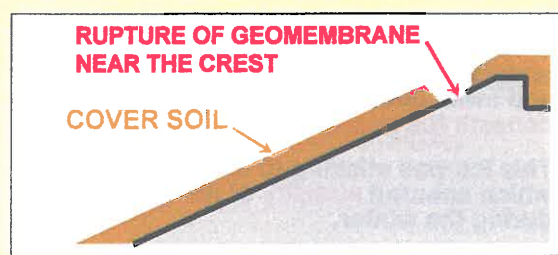
$$\frac{\gamma_b}{\gamma_{sat}} = 0.50 \text{ to } 0.55 \approx 0.5 \quad \text{VERY SIGNIFICANT}$$

Important lesson from theoretical analysis

Water above the geomembrane
has little influence on slope stability
if the slip surface is **below** the geomembrane,
but has significant influence on the stability
if the slip surface is **above** the geomembrane.

**This lesson was used
for a forensic analysis.**

A landfill cover failed
with geomembrane rupture
near the crest of the slope,
and large downward displacement.



The facts were simple:

- Instability occurred **after a thaw**
(at the end of a cold winter).
- The geomembrane **ruptured**
near the crest of the slope.

**The explanation offered by
all observers was **simple**:**

- Instability occurred after a thaw.
- The thaw caused water to **flow** along the slope.
- **It is known** that water flowing along a slope causes instability.
- Therefore, the observed instability was caused by water **flowing** along the slope.

This **simple explanation was:**

- consistent with experience, [failures are often caused by water]
- consistent with common sense, [water is not good for soil]
- easily understood and accepted, and
- **incorrect !**

The **real explanation was:**

- not provided by experience,
- not provided by common sense,
- not provided by engineering judgment.

**The real explanation
was provided by
theoretical analysis.**

Remember: the geomembrane rupture occurred **near the crest** of the slope, with **large downward displacement** of both cover soil and geomembrane.

**RUPTURE OF GEOMEMBRANE
NEAR THE CREST**

COVER SOIL

**Therefore, slippage had occurred
at the geomembrane-subgrade interface.**

The real explanation was:

- Slippage had occurred at the geomembrane-subgrade interface (i.e. **below** the geomembrane).
- Water flowing along a slope does not significantly affect the factor of safety for **slippage below** the geomembrane.
- Therefore, the failure was **probably not caused by water** flowing along the slope.

**Based on this rational analysis,
I could convince other participants
that further investigation was necessary.**

**As shown by further investigation,
there was a two-step mechanism.**

STEP 1, WINTER

- In the winter, due to frost, there was migration of water vapor in the subgrade soil toward the geomembrane; and formation of **ice beneath the geomembrane**.
- This ice was sticking to the geomembrane, which ensured **stability** of the slope during the winter.

As shown by further investigation,
there was a two-step mechanism.

STEP 2, SPRING

- In the spring, due to a thaw, the ice melted under the geomembrane.
- The resulting water created a **very low interface shear strength** beneath the geomembrane, which caused **instability** of the slope along the interface between the geomembrane and the underlying soil.

**LESSON LEARNED
from this failure investigation**

- **Common sense** is often wrong and should not be used as a basis for engineering decisions.
- Good observations and **theoretical analyses** lead to rational explanations.

**I have presented
two examples of
failure investigation,
and lessons were learned.**

**LESSONS LEARNED
FROM FAILURES**

- Complex mechanisms associated with geosynthetics can be rationally analyzed using **engineering principles**.
- Common sense is not an engineering principle.

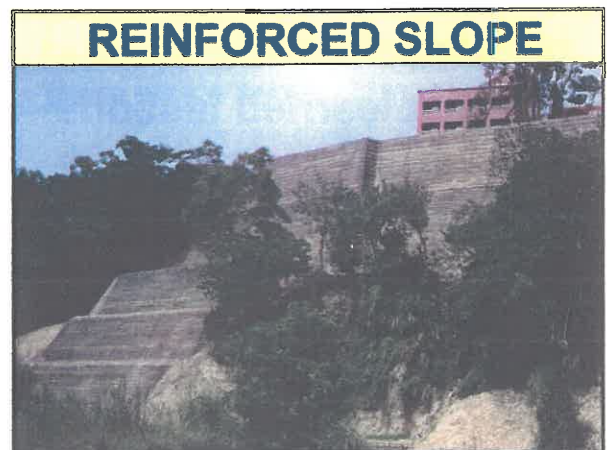
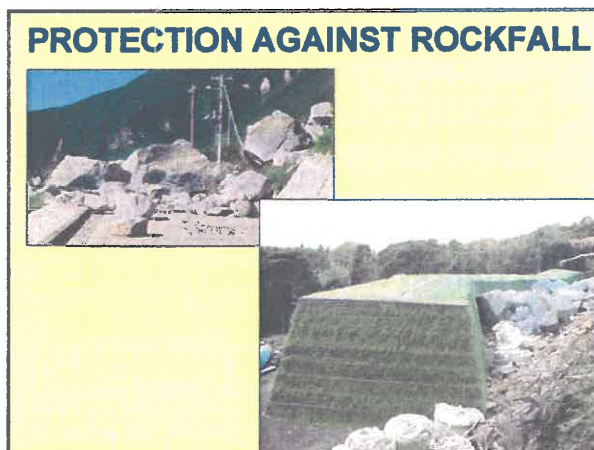
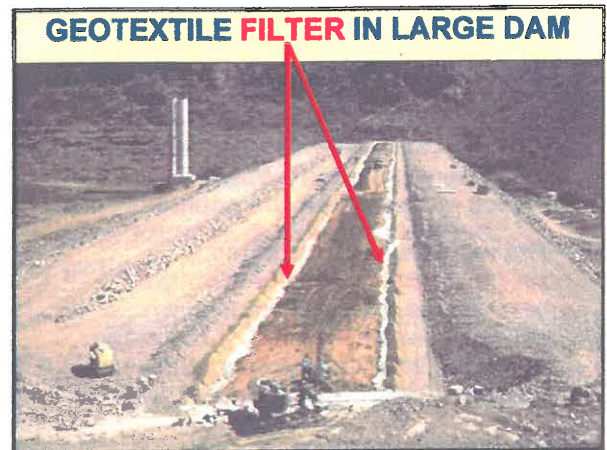
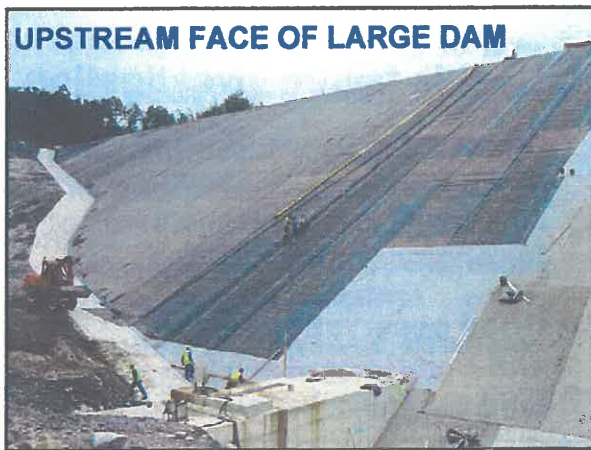
**We just learned lessons
from **failures**
and, now,
we will learn lessons
from **successes**.**

FAILURES AND SUCCESSSES IN PERSPECTIVE

**The rate of significant failures
in geosynthetics applications
has been estimated as 0.1 %.**

**Whereas, to date,
20 billion m² of geosynthetics
have been used successfully
in several million projects.**

a number of them significant and spectacular



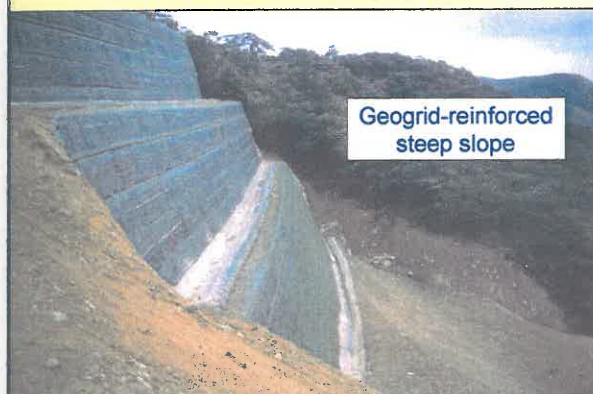
REINFORCED SLOPE



REINFORCED LANDSCAPING



LANDSLIDE REPAIR

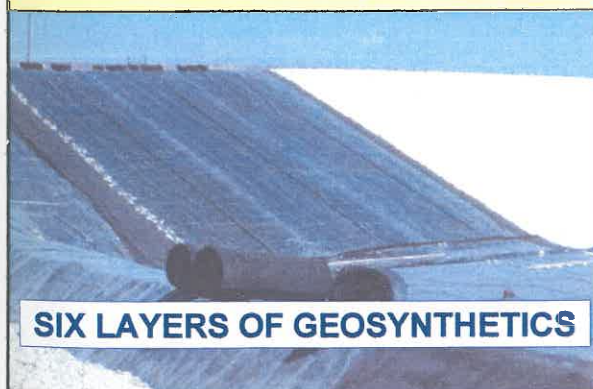


Geogrid-reinforced
steep slope

REINFORCED LANDFILL



HAZARDOUS WASTE LANDFILL



SIX LAYERS OF GEOSYNTHETICS

LANDFILL IN CANYON



**EXPOSED GEOMEMBRANE
AS LANDFILL COVER**



MINING

LEACH PAD



SURFACE DRAINAGE



CANAL LINING



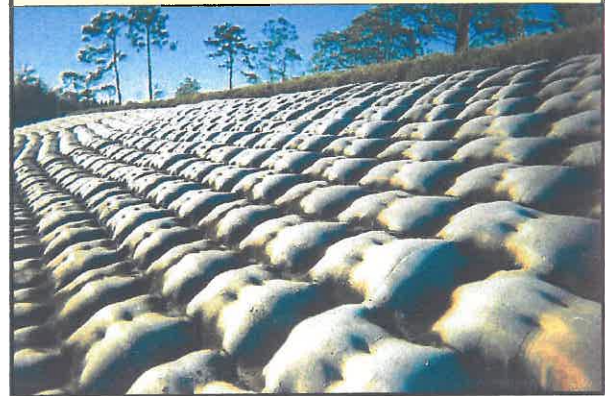
CANAL BANK PROTECTION



RIVER BANK PROTECTION



BANK PROTECTION



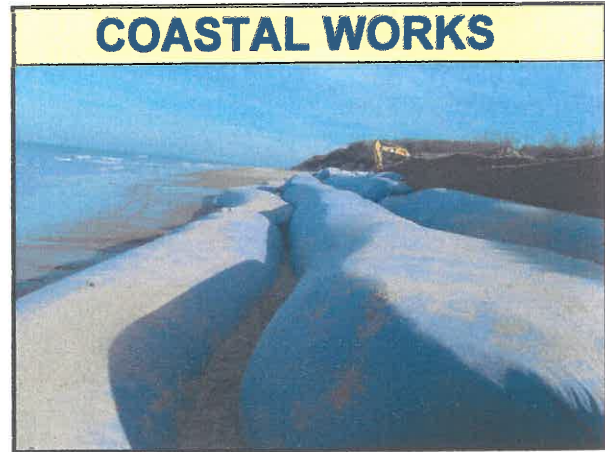
CONCRETE FORMING



CONTAINMENT DIKES FOR ARTIFICIAL ISLAND



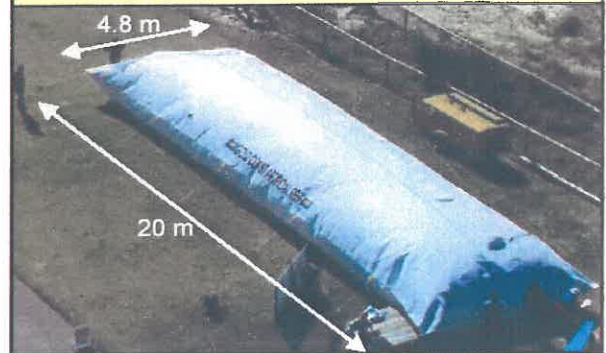
COASTAL WORKS



UNDERWATER INSTALLATION



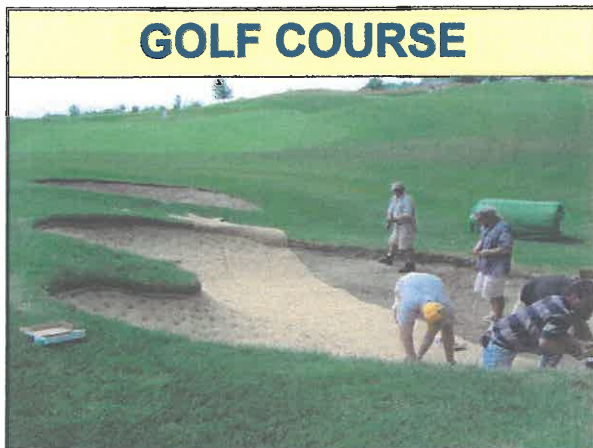
LARGE SAND CONTAINERS FOR ARTIFICIAL REEF



DELIVERED USING A SPECIAL BARGE



GOLF COURSE



EROSION CONTROL WITH GEOGRIDS

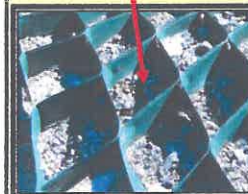


EROSION CONTROL WITH GEOMATS



**EROSION
CONTROL
WITH
GEOCELLS**

To be filled with soil



**SOIL CONSOLIDATION
USING VERTICAL DRAINS**



CONSTRUCTION ON SOFT SOIL



CONSTRUCTION ON SOFT SOIL



HIGHWAY EMBANKMENT



LOG YARD



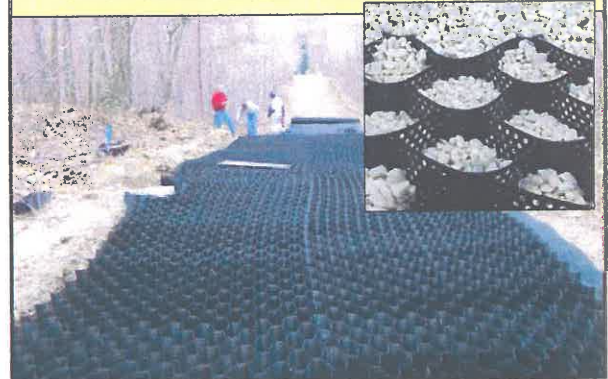
AREA STABILIZATION



**REINFORCED
UNPAVED
ROAD**



**UNPAVED ROAD CONSTRUCTED USING
GEOCELL FILLED WITH AGGREGATE**



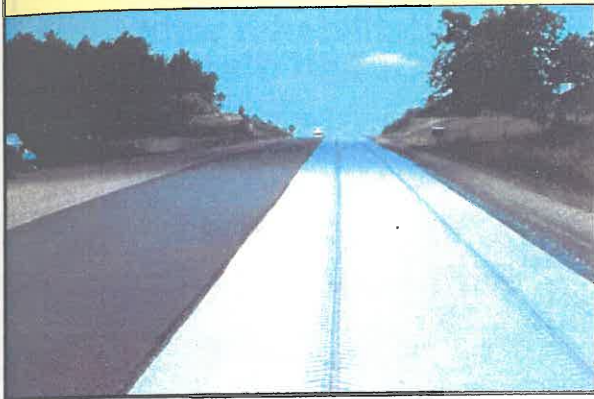
ROAD CONSTRUCTION



ROAD BASE



ROAD PAVEMENT



ASPHALT OVERLAY



RAILWAY TRACK REPAIR



RAILWAY TRACK CONSTRUCTION



TUNNEL LINING



PILE FOUNDATION



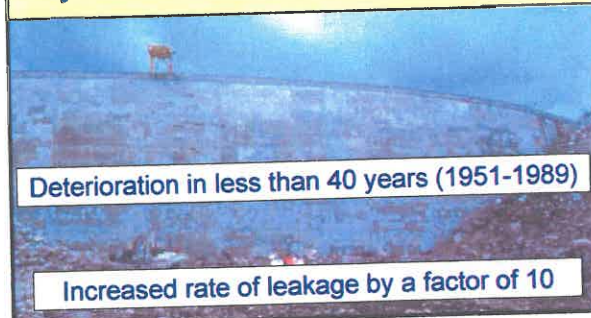
These examples
demonstrate that
geosynthetics have
successfully pervaded
**all branches of
geotechnical engineering.**

Now, I will discuss
in more detail
two examples
of successes
with geosynthetics.

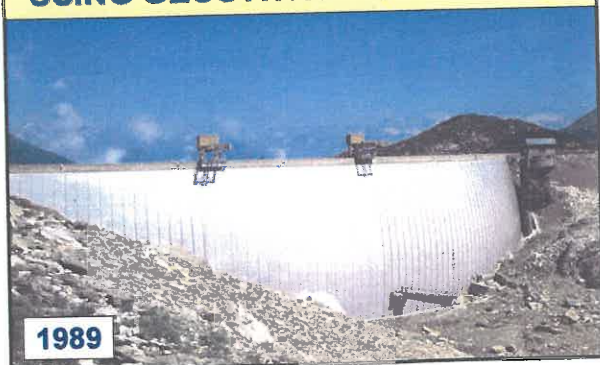
FIRST EXAMPLE

**USE OF
GEOSYNTHETICS
TO REHABILITATE
OLD CONCRETE DAMS**

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



**DAM FACE REHABILITATED
USING GEOSYNTHETICS**



REHABILITATION IN PROGRESS

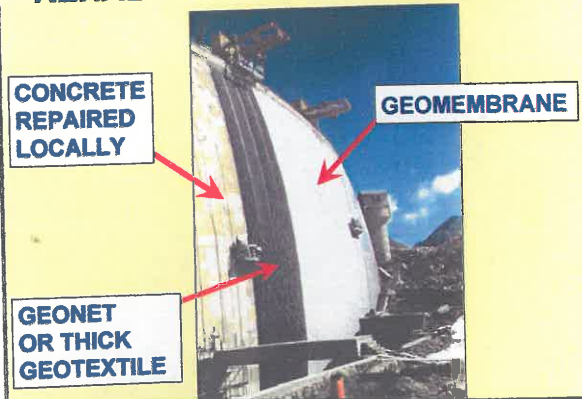


Photo taken 10 years after rehabilitation



REHABILITATION CONCEPT

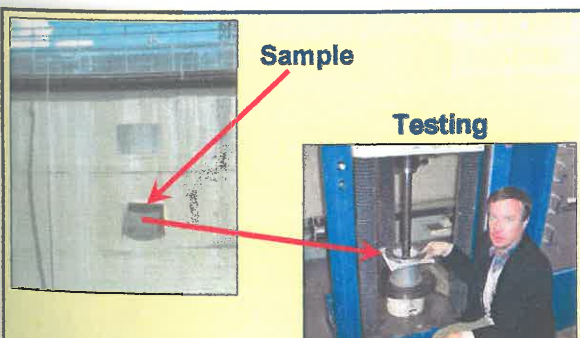
- The geomembrane provides impermeability.
- A **geonet** or a thick **geotextile** placed between the geomembrane and the concrete is acting as a **drain**.
- The main purpose of the system is to allow the concrete to **progressively dry**.
- **Removing water from concrete** decreases to a negligible level frost action and alkali-aggregate reaction.
- The geomembrane also decreases to a negligible level the **leakage** associated with concrete deterioration.

DURABILITY

- Durability is a major consideration in this application.
- In the rehabilitated dams, the concrete had deteriorated to a critical level in 40-60 years.

GEOSYNTHETIC DURABILITY

- In this application, the geosynthetics are exposed to harsh conditions (sunlight, weather, floating debris).
- To ensure durability, the geosynthetics have been carefully selected.
- To check durability, the geosynthetics are tested periodically.



Based on 20 years of testing,
a durability of 50 years is predicted.

SYSTEM DURABILITY

- The geosynthetics on the dam face can be **easily replaced** at the end of their service life.
- This increases the durability of the dam **indefinitely**.
(since the concrete does not deteriorate behind the geosynthetics)

A good example of complementarity between
geosynthetics and traditional construction materials

LESSON LEARNED

from this successful application

The **durability** of geosynthetics is not a problem (if properly selected and properly used).

In some specific cases, the **durability** of geosynthetics can be similar to the **durability** of traditional construction materials such as concrete.

GEOMEMBRANES IN LARGE DAMS

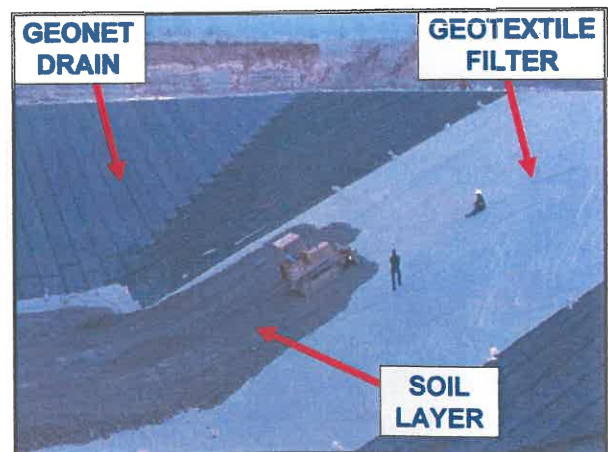
- Geomembranes have been used as the **only waterproofing barrier** in more than 200 large dams according to the ICOLD.
- The first large dam with a geomembrane was constructed **46 years** ago and is still in service.
- The highest dam with a geomembrane is **174 m** high.

SECOND EXAMPLE OF LEARNING FROM SUCCESS

DEVELOPMENT OF A RETENTION CRITERION FOR GEOTEXTILE FILTERS

Filters are used

in geotechnical engineering
to **separate drainage materials**
(such as gravel or geosynthetic drains)
from soils that could clog them.



RETENTION CRITERION

How should we select
the **maximum allowable opening size**
of a geotextile filter to retain a soil?

A simple answer consists of adapting
Terzaghi's criterion for granular filters

$$d_{15 \text{ FILTER}} < 5 d_{85 \text{ SOIL}}$$

$$O_{\text{FILTER}} \approx d_{15 \text{ FILTER}} / 5$$

hence $O_{\text{FILTER}} < d_{85 \text{ SOIL}}$

$$O_{\text{FILTER}} < d_{85 \text{ SOIL}}$$

- This equation means that a filter should **only** retain **large** soil particles.
- (This is against common sense.)
- Retaining **only** large soil particles works if the **large** particles **retain smaller** particles.

In other words, if the soil is **internally stable**.

Therefore,
an ideal retention criterion
should take into account
not only the **opening size**
of the filter,
but also the **internal stability**
of the soil.

To a certain degree,
granular filters may work even if
the soil is not internally stable
because they **are thick**.

The mechanism is:
Particles that are not retained
may accumulate in the filter, thereby
decreasing the filter opening size,
until the filter works.

In other words, a granular filter
adapts itself to the soil
(**to a certain degree**).

As a result, a granular filter can be designed
(**to a certain degree**)
using a retention criterion
(i.e. Terzaghi's retention criterion)
that does **not** take into account
the **internal stability** of the soil.

Essentially, **granular filters**,
because they **are thick**,
can be designed using
a simple retention criterion
(Terzaghi's retention criterion).

However, this is true only **to a certain degree**,
which limits the applicability
of Terzaghi's retention criterion
to soils with maximum particle size 4.75 mm.

hence, the practice of truncation

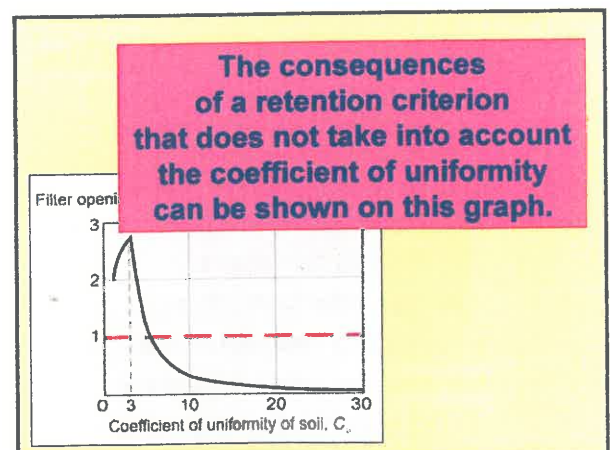
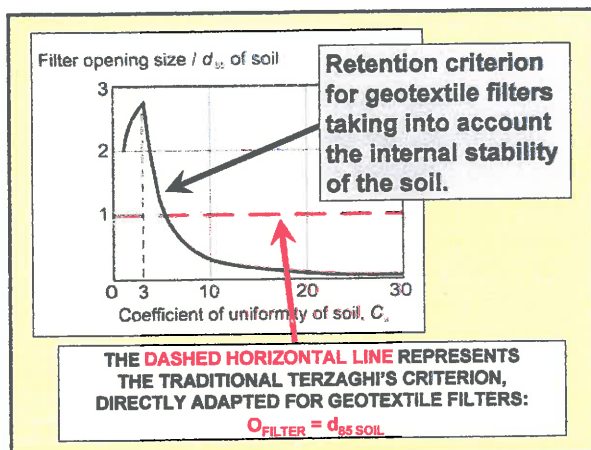
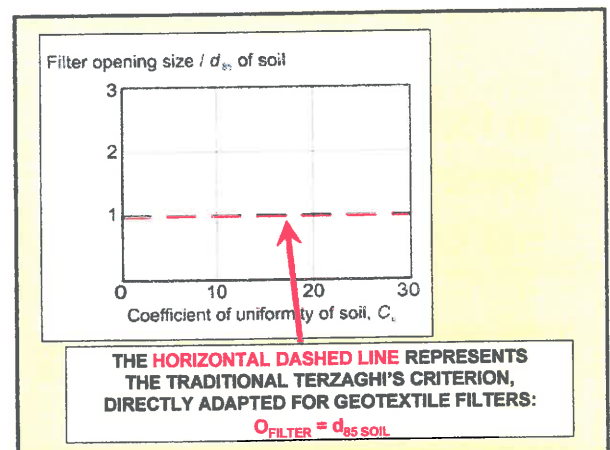
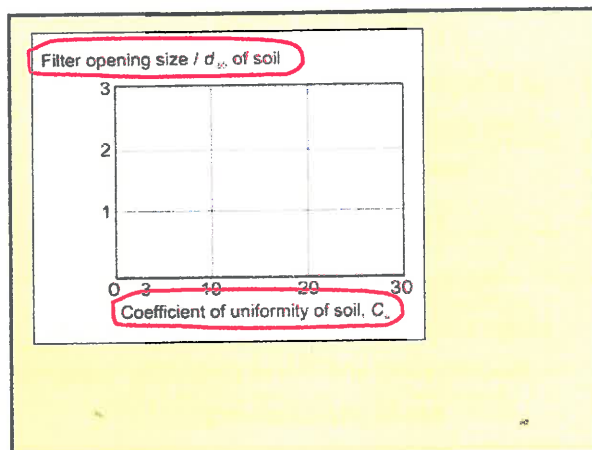
While granular filters benefit
(to a certain degree) from their thickness,

geotextile filters are thin,
which has created
an incentive for developing
a more accurate
retention criterion.

A criterion that takes into account
the **internal stability** of the soil.

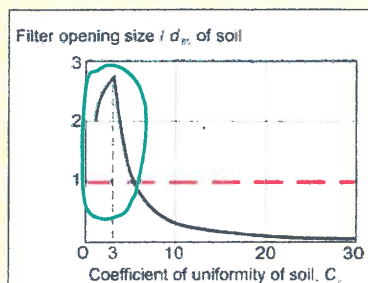
Internal stability depends on the
particle size distribution of the soil,
which is characterized by
the **coefficient of uniformity**.

Therefore,
an accurate retention criterion
should take into account the
coefficient of uniformity of the soil.



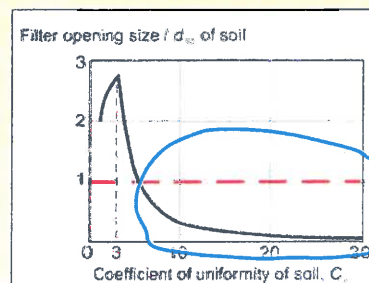
If the coefficient of uniformity is **small**,
the criterion represented by the **red line**
allows filter openings that are too small.

**Risk of
filter
clogging**



If the coefficient of uniformity is **large**,
the criterion represented by the **red line**
allows filter openings that are too large.

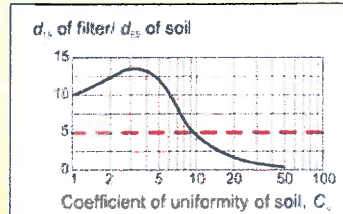
**Risk of
soil
piping**



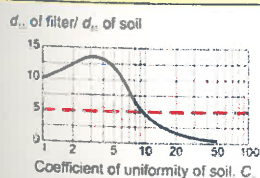
Therefore,
a geotextile filter is **safer**
if it is designed with
the retention criterion
that **takes into account**
the **internal stability**
of the soil.

**The same can be done
with granular filters.**

The retention
criterion
developed for
geotextile filters
has been
extended for
granular filters.



Here, the vertical axis is d_{15} / d_{85}
to be consistent with the practice
for granular filters.



**RETENTION
CRITERION
FOR
GRANULAR
FILTERS**

- This retention criterion is applicable regardless of maximum particle size.
- The limitation of Terzaghi's retention criterion to 4.75 mm is eliminated.
- The tedious operation of truncating particle size distribution curves at 4.75 mm is eliminated.

Therefore,
by extending to granular filters
the retention criterion
developed for geotextile filters,
we have obtained a tool
for designing granular filters
that is **simpler** and **safer**
than the traditional criterion
in the case of soils having
a large coefficient of uniformity.

LESSON LEARNED from this successful method

What started as **technology transfer**
from geotechnical engineering to geosynthetics engineering
ended as **technology transfer**
from geosynthetics engineering to geotechnical engineering.

Geosynthetics engineering
is a new discipline
with innovative research that can
benefit a mature discipline
such as geotechnical engineering.

Just imitating the great masters
is not the best approach
to solving modern problems.

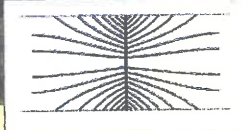
We do not have to do today
what Terzaghi would have
done 50 years ago.

We need to do today
what Terzaghi would do today.

CONCLUSION

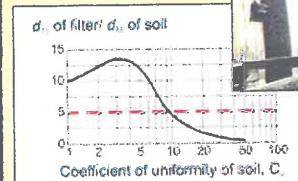
$$FS = \frac{\tan \delta}{\tan \beta} + \frac{a}{\gamma t \sin \beta} + \frac{t \tan \phi / (2 \sin \beta \cos^2 \beta)}{h} + \frac{c}{\gamma h} \frac{1/(\sin \beta \cos \beta)}{1 - \tan \beta \tan \phi} + \frac{T}{\gamma h t}$$

We learned
from failures



CONCLUSION

We learned
from
successes



CONCLUSION

Essentially, we learned that
engineering problems
(with geosynthetics or not)
are solved by **rational analyses**
based on engineering principles,
and good **observations**,
not by common sense.

This is consistent with
the theory and practice approach
advocated by Terzaghi.

Thank you