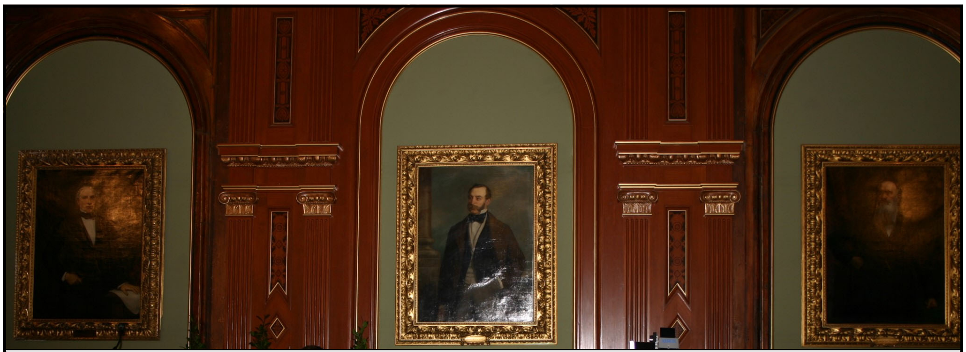


VIENNA, 2005

The Vienna Terzaghi Lecture

J.P. GIROUD

JP GIROUD THE VIENNA TERZAGHI LECTURE 1

The historic lecture hall in Vienna

JP GIROUD THE VIENNA TERZAGHI LECTURE 2

JP GIROUD THE VIENNA TERZAGHI LECTURE 3

The presentation from the lectern used by Karl Terzaghi

JP GIROUD THE VIENNA TERZAGHI LECTURE 4

VIENNA 2005

The Vienna Terzaghi Lecture

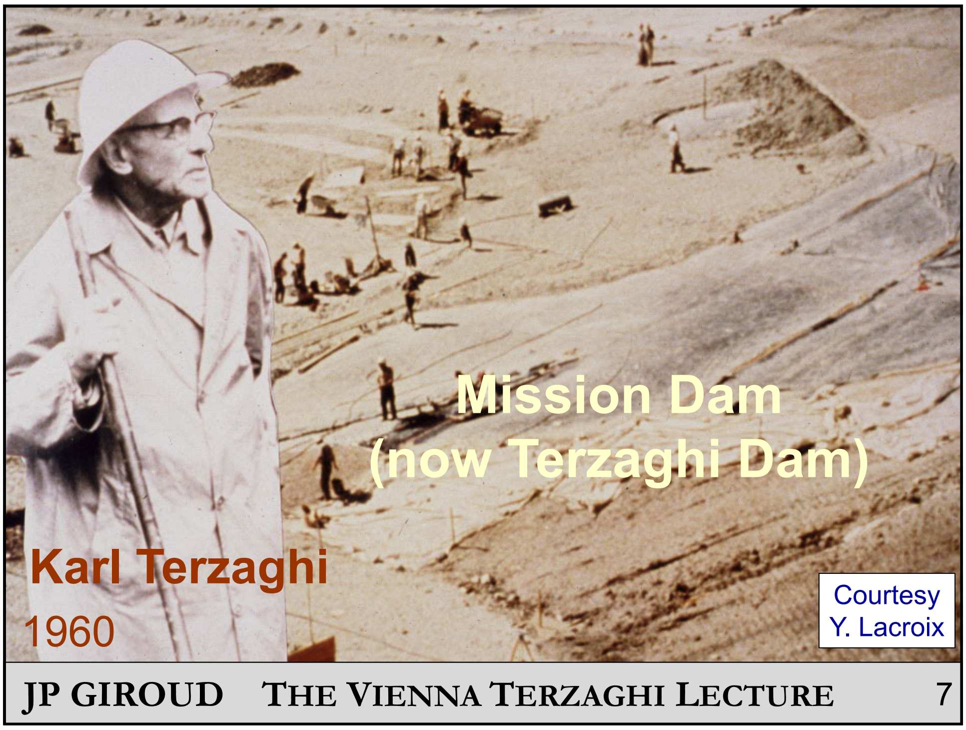
**GEOSYNTHETICS ENGINEERING:
SUCCESSES, FAILURES
AND LESSONS LEARNED**

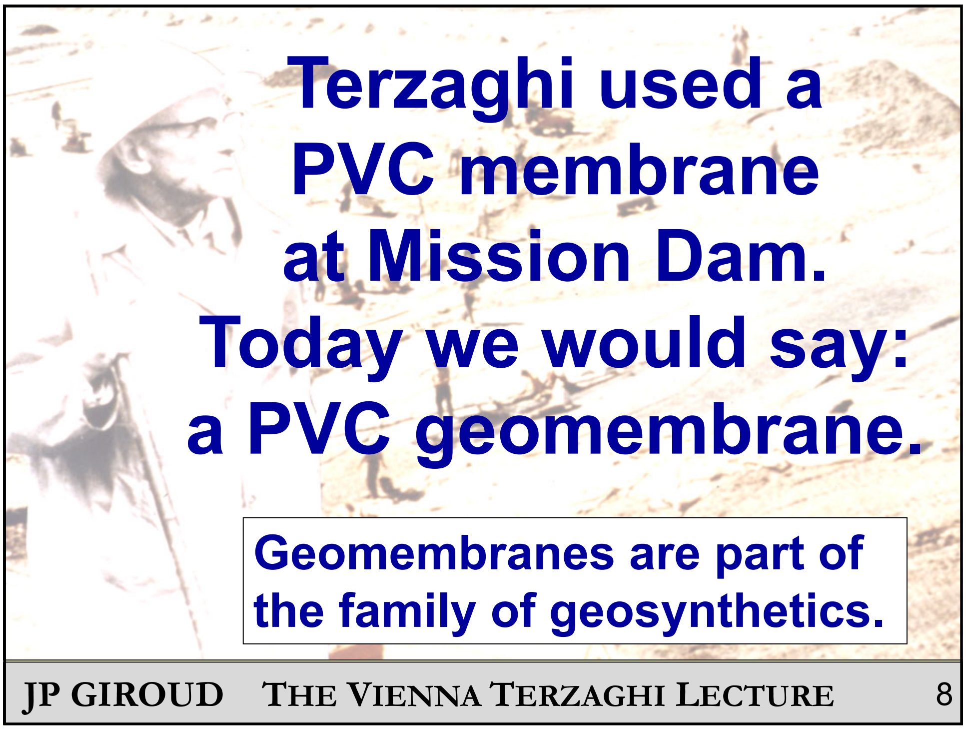
J.P. GIROUD

JP GIROUD THE VIENNA TERZAGHI LECTURE 5

Clearly, the purpose of this lecture
is to **learn lessons**
from **failures** and **successes**.

JP GIROUD THE VIENNA TERZAGHI LECTURE 6


Mission Dam
(now Terzaghi Dam)
Karl Terzaghi
1960
Courtesy
Y. Lacroix
JP GIROUD THE VIENNA TERZAGHI LECTURE 7


Terzaghi used a
PVC membrane
at Mission Dam.
Today we would say:
a PVC geomembrane.
Geomembranes are part of
the family of geosynthetics.
JP GIROUD THE VIENNA TERZAGHI LECTURE 8

The family of Geosynthetics:

- GEOMEMBRANES
- GEOTEXTILES
- GEONETS
- GEOGRIDS
- GEOMATS
- GEOCELLS
- GEOFOAM
- GEOCOMPOSITES
  including **bentonite geocomposites** and **drainage geocomposites**

JP GIROUD THE VIENNA TERZAGHI LECTURE 9

GEOMEMBRANES

Photo J.P. Giroud

used as liquid and gas barriers

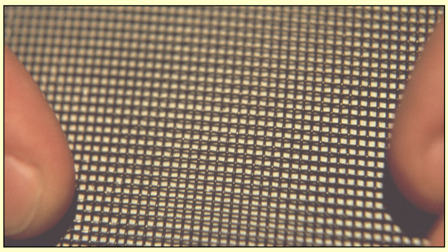
JP GIROUD THE VIENNA TERZAGHI LECTURE 10

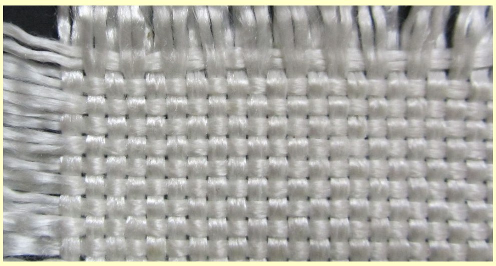
GEOTEXTILES

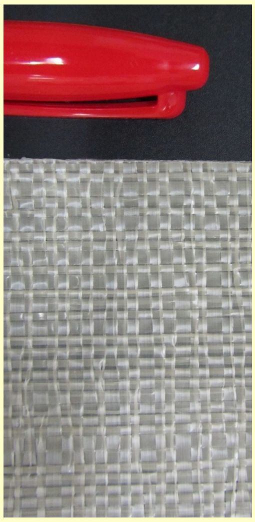
used for a variety of functions

JP GIROUD THE VIENNA TERZAGHI LECTURE 11

WOVEN GEOTEXTILES





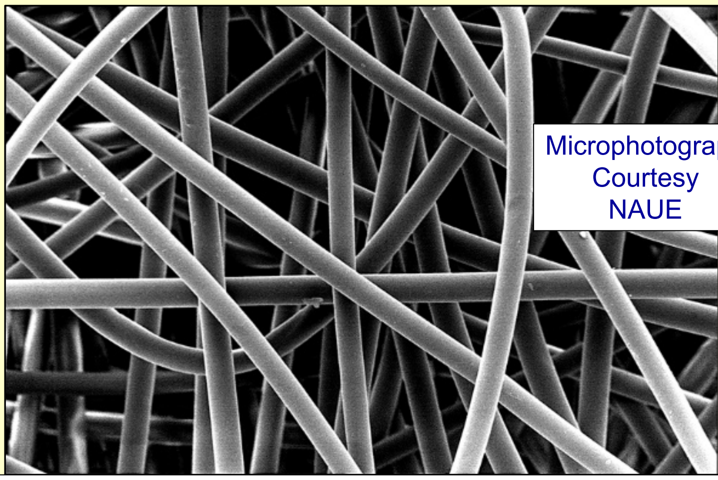


Photos
J.P. Giroud

used as filter or for soil reinforcement

JP GIROUD THE VIENNA TERZAGHI LECTURE 12

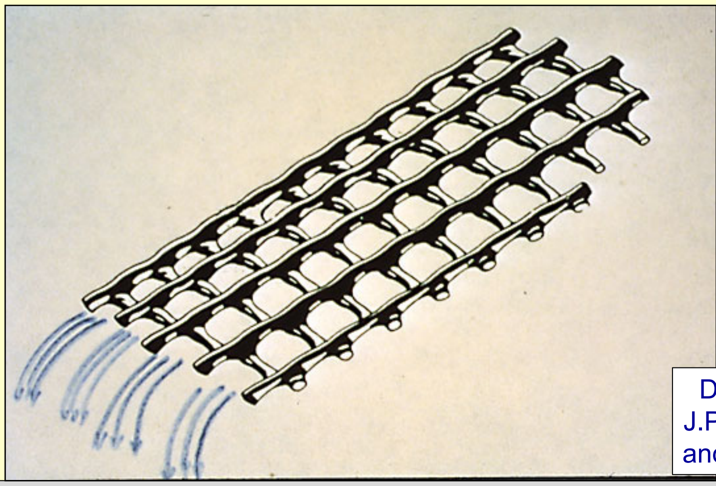
NONWOVEN GEOTEXTILES



used in numerous applications, e.g. filters or cushions for geomembrane protection

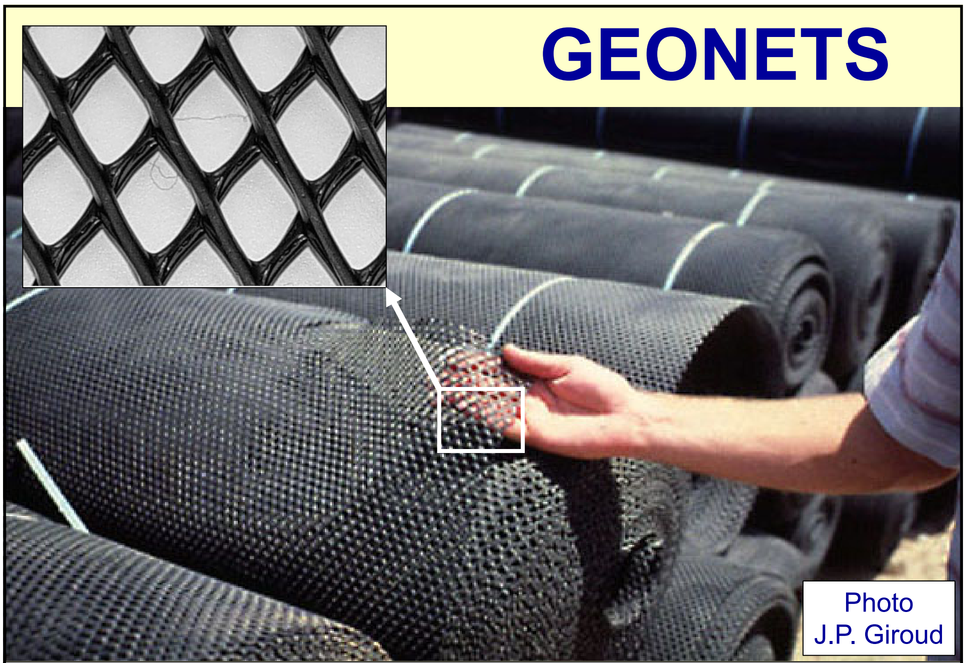
JP GIROUD THE VIENNA TERZAGHI LECTURE 13

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



JP GIROUD THE VIENNA TERZAGHI LECTURE 14

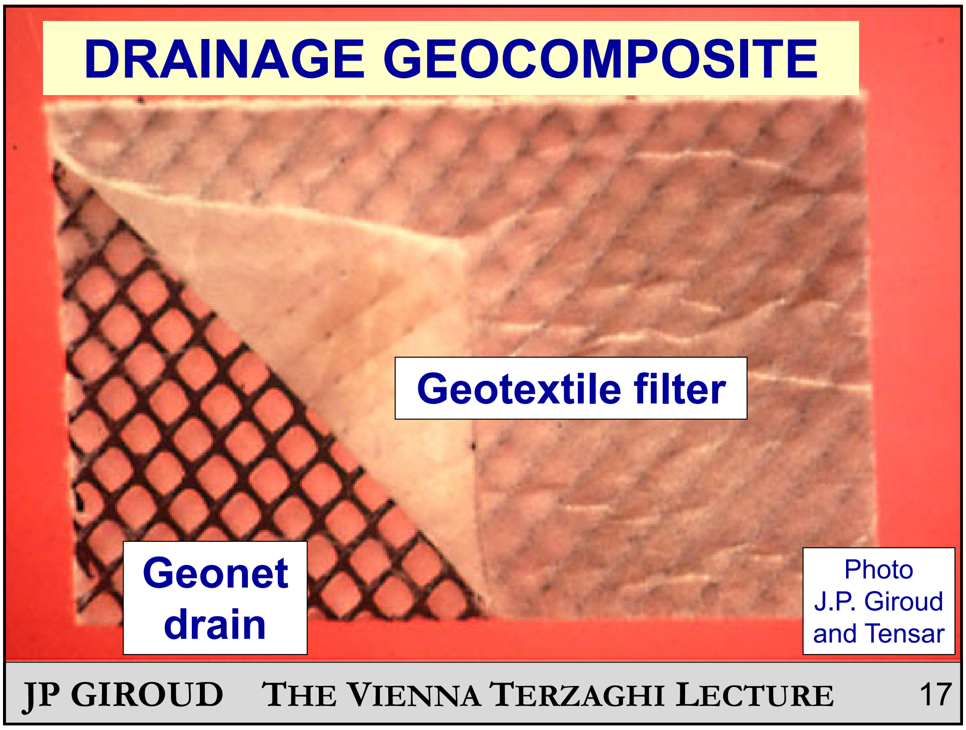
GEONETS

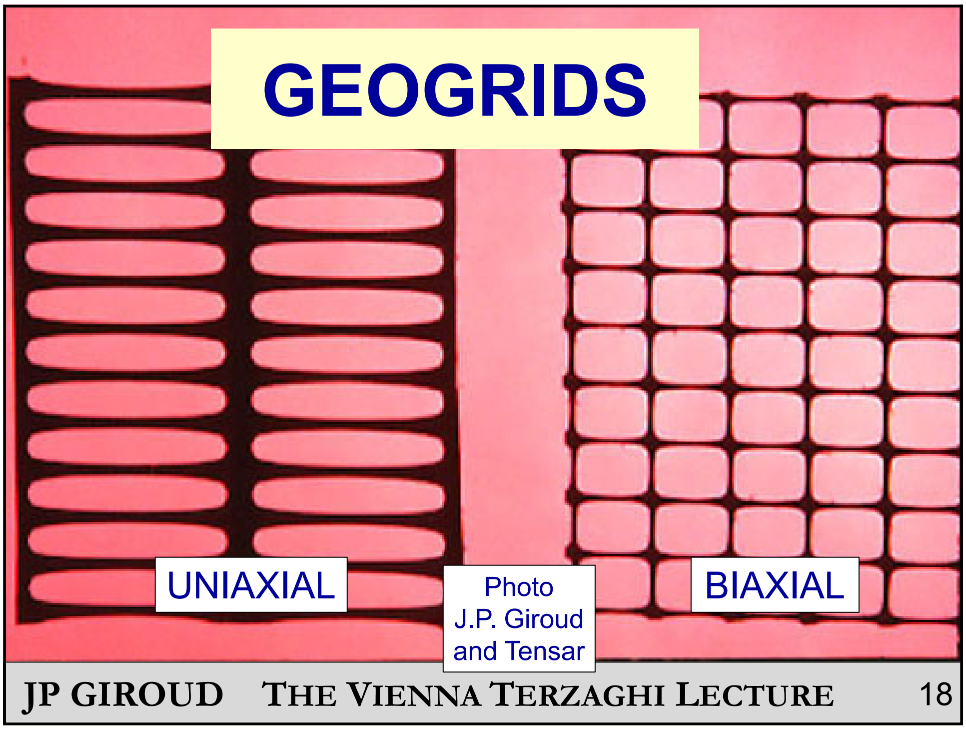


JP GIROUD THE VIENNA TERZAGHI LECTURE 15

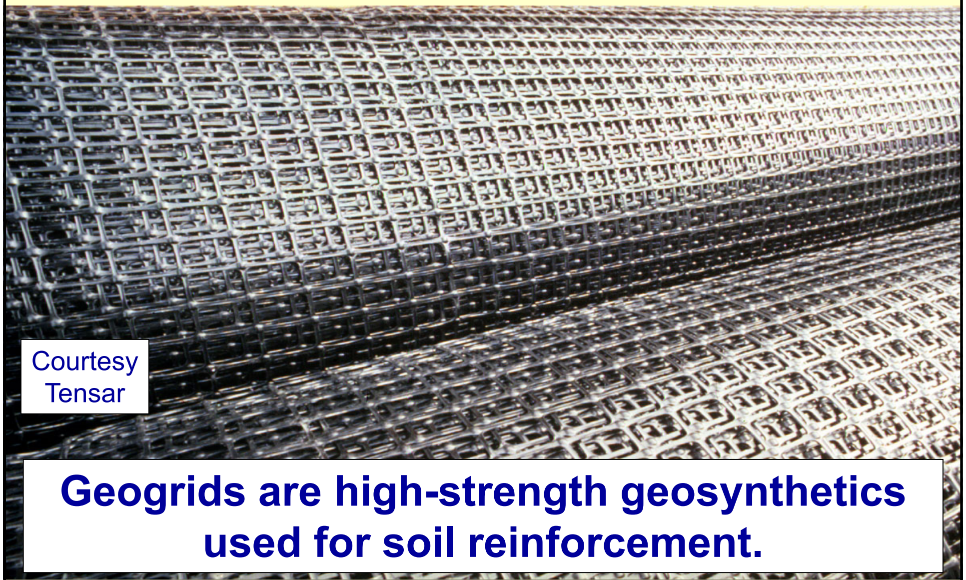
Geonets and geotextiles
can be **installed separately**
or can be **combined**
to form a
drainage geocomposite.

JP GIROUD THE VIENNA TERZAGHI LECTURE 16


DRAINAGE GEOCOMPOSITE
Geotextile filter
Geonet drain
Photo J.P. Giroud and Tensar
JP GIROUD THE VIENNA TERZAGHI LECTURE 17


GEOGRIDS
UNIAXIAL
Photo J.P. Giroud and Tensar
BIAXIAL
JP GIROUD THE VIENNA TERZAGHI LECTURE 18

ROLLS OF GEOGRIDS

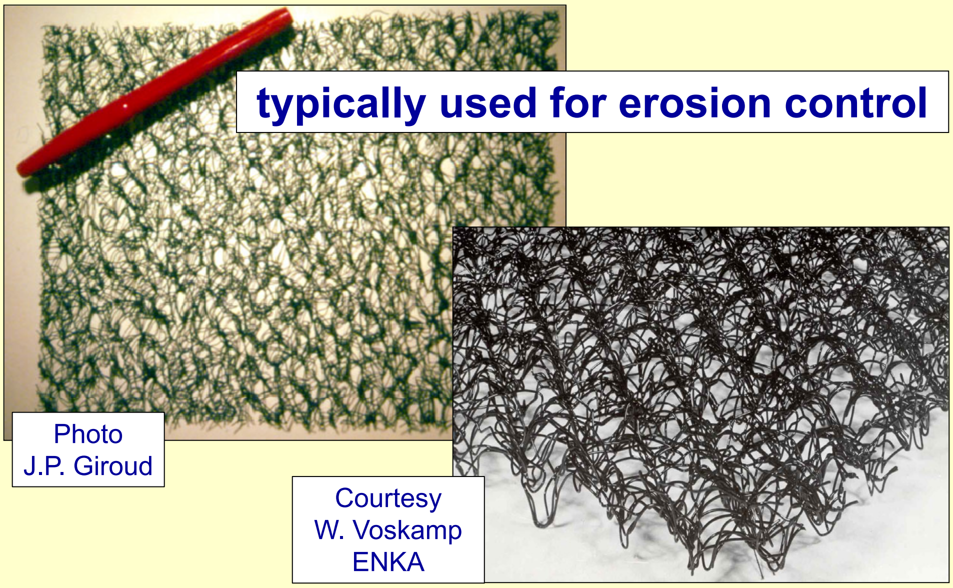


Geogrids are high-strength geosynthetics used for soil reinforcement.

JP GIROUD THE VIENNA TERZAGHI LECTURE 19

GEOMATS

typically used for erosion control



JP GIROUD THE VIENNA TERZAGHI LECTURE 20

Geomat rolls used for erosion control

Courtesy
M.S. Theisen
Geosolutions

JP GIROUD THE VIENNA TERZAGHI LECTURE 21

GEOCELLS are honeycomb structures

Courtesy
PRESTO

JP GIROUD THE VIENNA TERZAGHI LECTURE 22

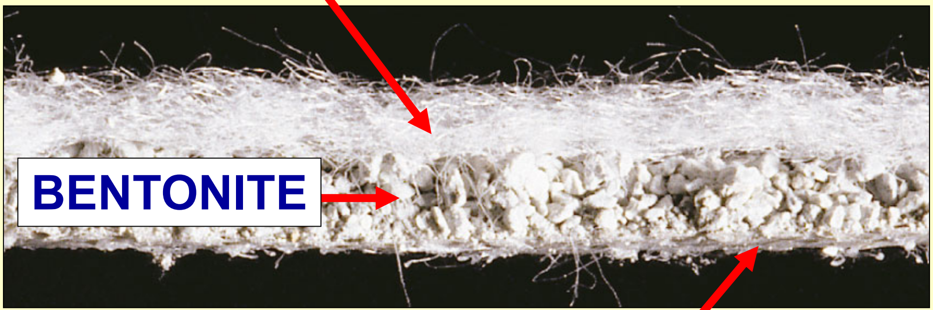
Geocell, to be filled with soil, used to create a stable soil layer on a slope

JP GIROUD THE VIENNA TERZAGHI LECTURE 23

GEOFOAM is light polymeric material
used to construct embankments
on compressible soils or soils with low bearing capacity.

JP GIROUD THE VIENNA TERZAGHI LECTURE 24

BENTONITE GEOCOMPOSITES
comprise three layers.



Courtesy
NAUE

JP GIROUD THE VIENNA TERZAGHI LECTURE 25

BENTONITE GEOCOMPOSITES
are used as liquid barriers.

Courtesy
CETCO

JP GIROUD THE VIENNA TERZAGHI LECTURE 26

Back to Terzaghi and the use of a geosynthetic at Mission Dam

There were localized failures, but essentially it was a success.

Following Terzaghi's example, let's learn from failure and success.

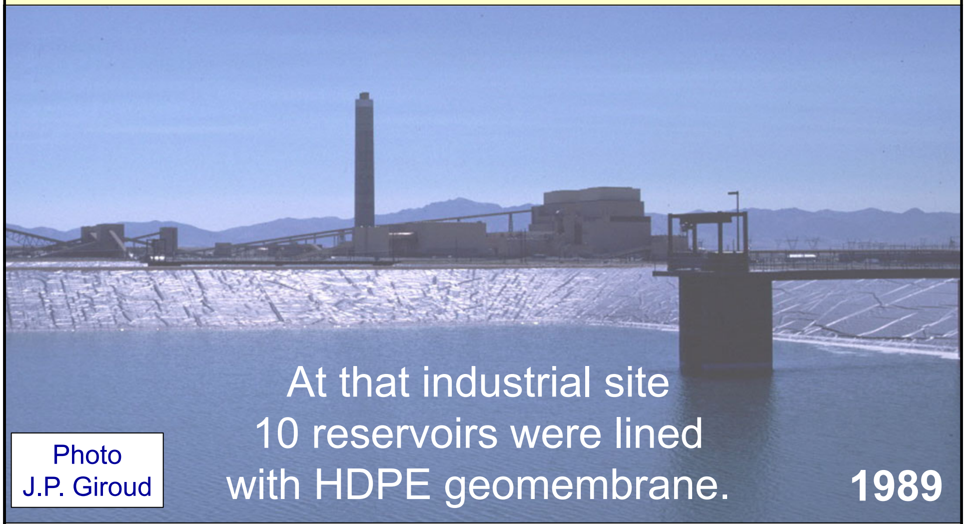
JP GIROUD THE VIENNA TERZAGHI LECTURE 27

FIRST EXAMPLE

INVESTIGATION OF GEOMEMBRANE CRACKING FAILURE

JP GIROUD THE VIENNA TERZAGHI LECTURE 28

Cracking of **HDPE geomembrane**
happened in large water reservoirs.



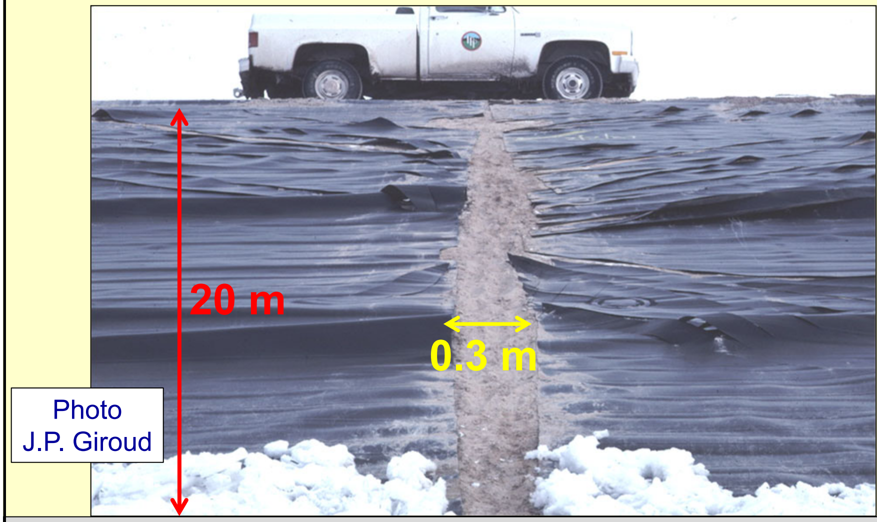
JP GIROUD THE VIENNA TERZAGHI LECTURE 29

In the winter, the reservoirs were empty and cracking of the geomembrane liner occurred in several reservoirs.

Photo
J.P. Giroud

JP GIROUD THE VIENNA TERZAGHI LECTURE 30

In the winter, the reservoirs were empty and cracking of the geomembrane liner occurred in several reservoirs.



JP GIROUD THE VIENNA TERZAGHI LECTURE 31

It was observed that the **geomembrane** was **under tension** in locations where it was not cracked.

In particular, the geomembrane was "bridging" corners of rectangular reservoirs (a configuration often called "trampolining").

Observations at a cracking location are described in the next slide.

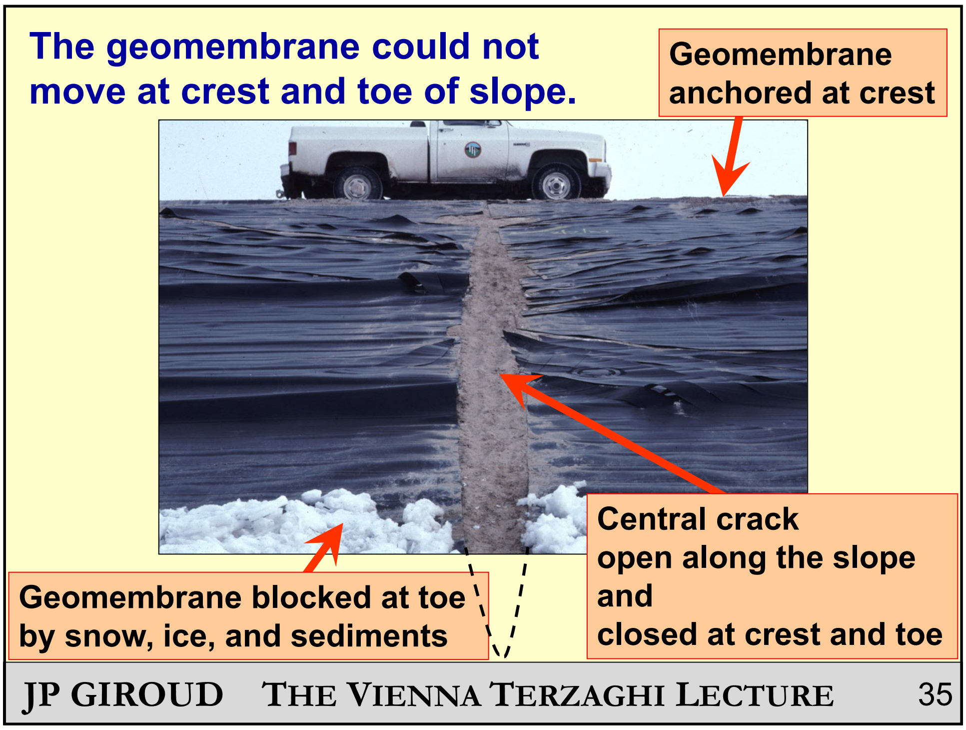
JP GIROUD THE VIENNA TERZAGHI LECTURE 32

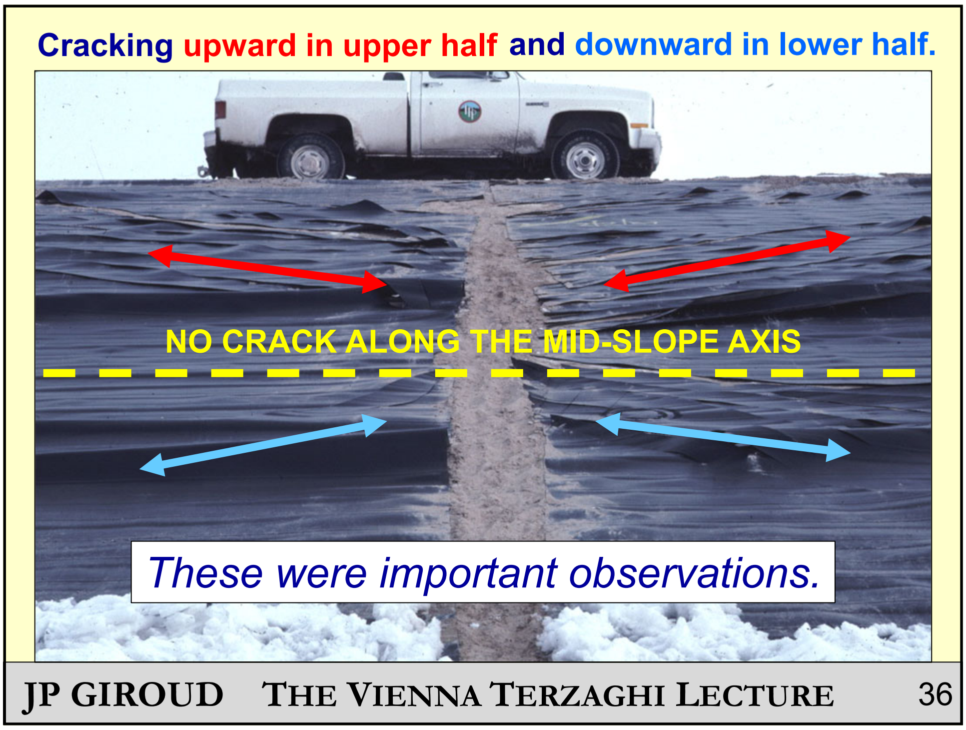
JP GIROUD THE VIENNA TERZAGHI LECTURE 33

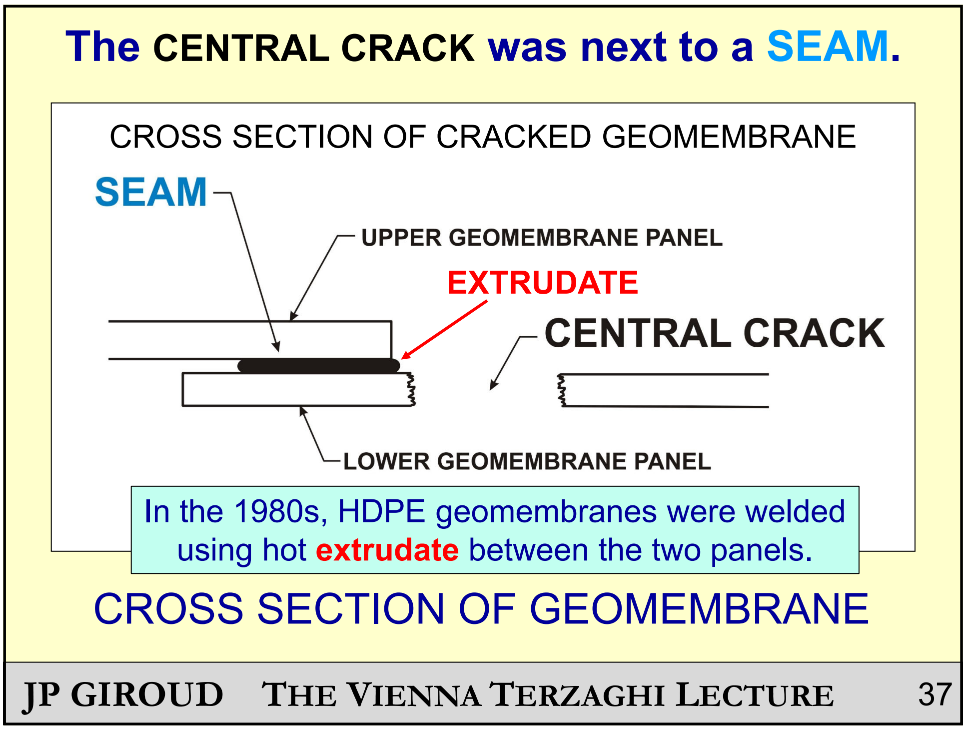
Just before cracking occurred,
the **weather** was **very cold,**
which tended to **contract**
the **geomembrane**,
but the **contraction** was **restrained**,
which resulted in geomembrane **tension**.

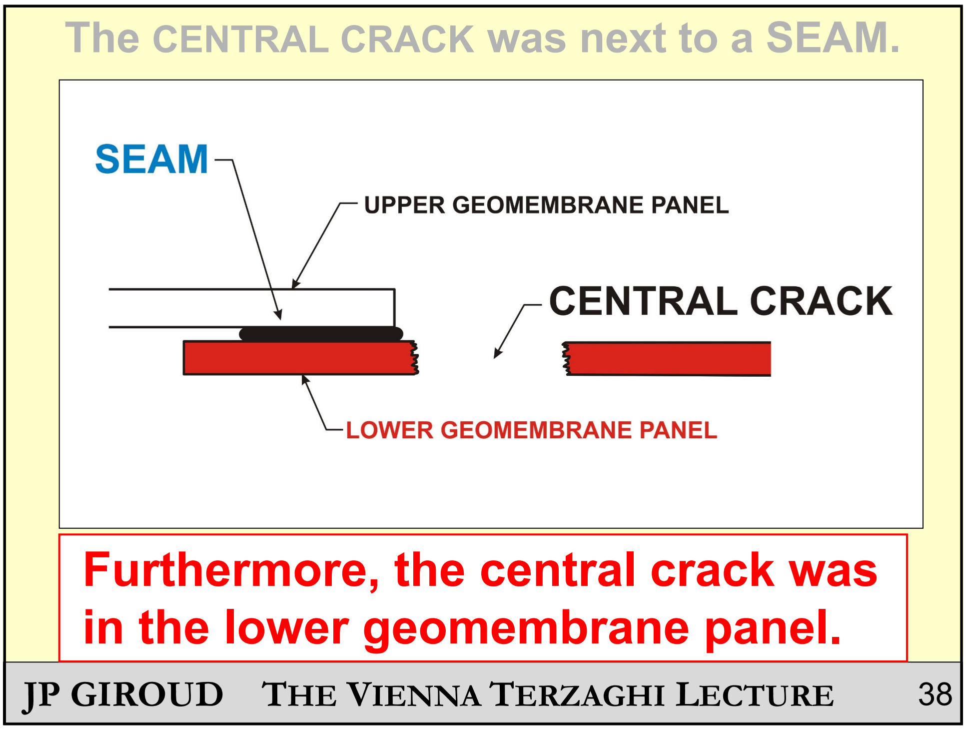
Thermal contraction was **restrained**
because
the geomembrane **could not move**
at **crest and toe** of the slope.

JP GIROUD THE VIENNA TERZAGHI LECTURE 34

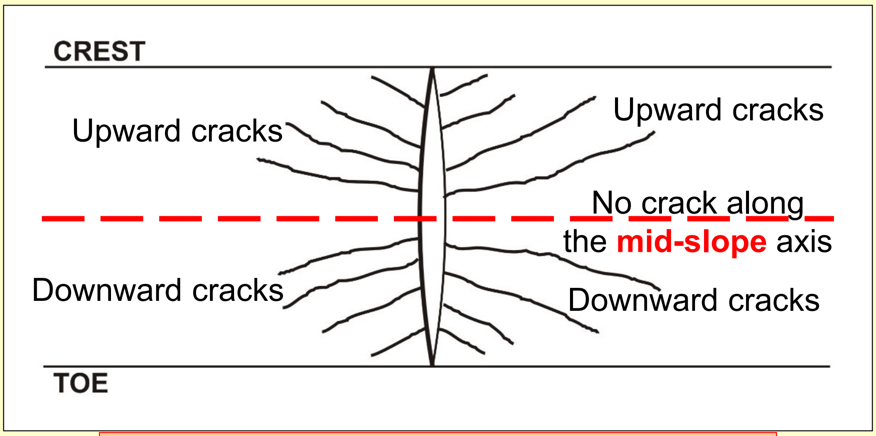

The geomembrane could not move at crest and toe of slope.
Geomembrane anchored at crest
Central crack open along the slope and closed at crest and toe
Geomembrane blocked at toe by snow, ice, and sediments
JP GIROUD THE VIENNA TERZAGHI LECTURE 35


Cracking upward in upper half and downward in lower half.
NO CRACK ALONG THE MID-SLOPE AXIS
These were important observations.
JP GIROUD THE VIENNA TERZAGHI LECTURE 36


The CENTRAL CRACK was next to a SEAM.
CROSS SECTION OF CRACKED GEOMEMBRANE
SEAM
UPPER GEOMEMBRANE PANEL
EXTRUDATE
CENTRAL CRACK
LOWER GEOMEMBRANE PANEL
In the 1980s, HDPE geomembranes were welded using hot extrudate between the two panels.
CROSS SECTION OF GEOMEMBRANE
JP GIROUD THE VIENNA TERZAGHI LECTURE 37


The CENTRAL CRACK was next to a SEAM.
SEAM
UPPER GEOMEMBRANE PANEL
CENTRAL CRACK
LOWER GEOMEMBRANE PANEL
Furthermore, the central crack was in the lower geomembrane panel.
JP GIROUD THE VIENNA TERZAGHI LECTURE 38

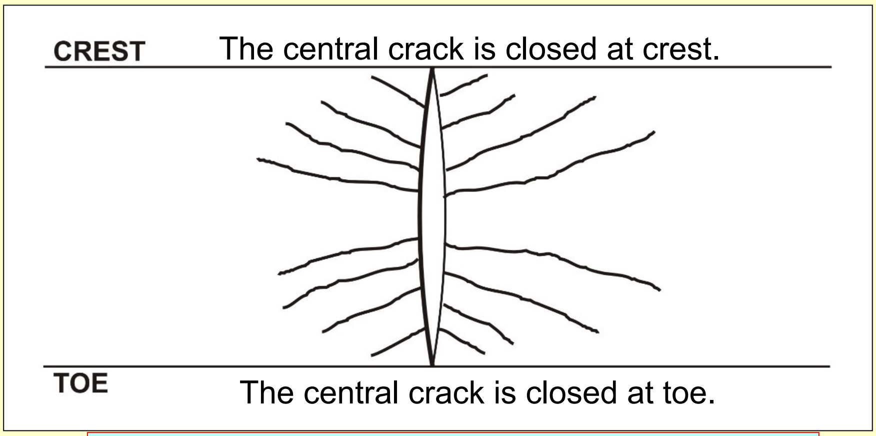
SUMMARY OF OBSERVATIONS



Shattering cracks on both sides of an open central crack.

JP GIROUD THE VIENNA TERZAGHI LECTURE 39

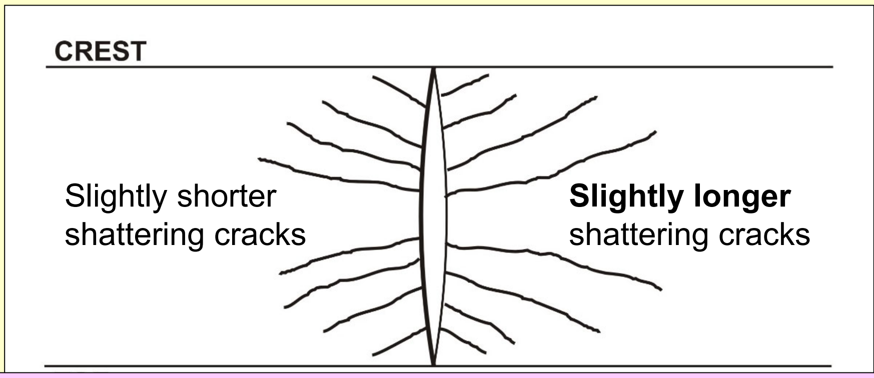
SUMMARY OF OBSERVATIONS



The central crack is along a seam.

JP GIROUD THE VIENNA TERZAGHI LECTURE 40

ADDITIONAL OBSERVATION

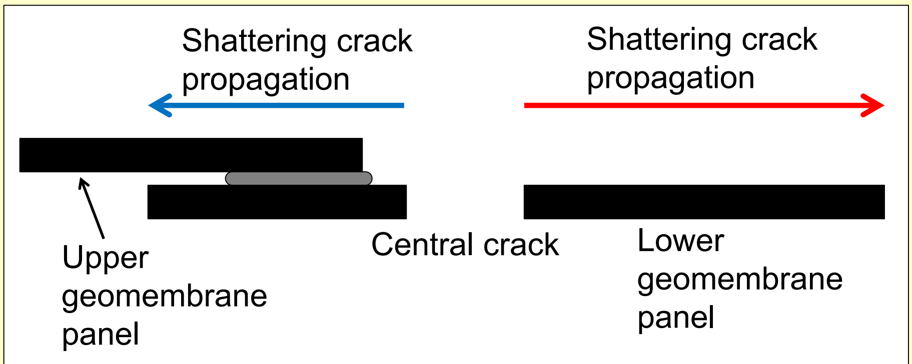


The shattering cracks were **slightly longer** on one side of the central crack, the side with the lower geomembrane panel.

Explanation in the next slide

JP GIROUD THE VIENNA TERZAGHI LECTURE 41

CROSS SECTION OF THE GEOMEMBRANE



Shattering crack propagation was **easier** through the **lower geomembrane** panel
than through the **upper geomembrane** panel
where the shattering cracks had to travel through
a **double geomembrane thickness** at the seam.

JP GIROUD THE VIENNA TERZAGHI LECTURE 42

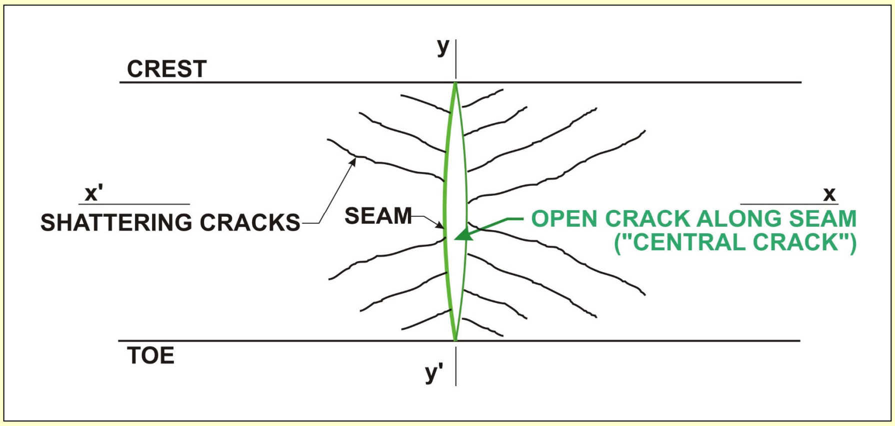
After the observations,
the investigation

JP GIROUD THE VIENNA TERZAGHI LECTURE 43

At this point, the question was:

Did the crack along the seam occur first?

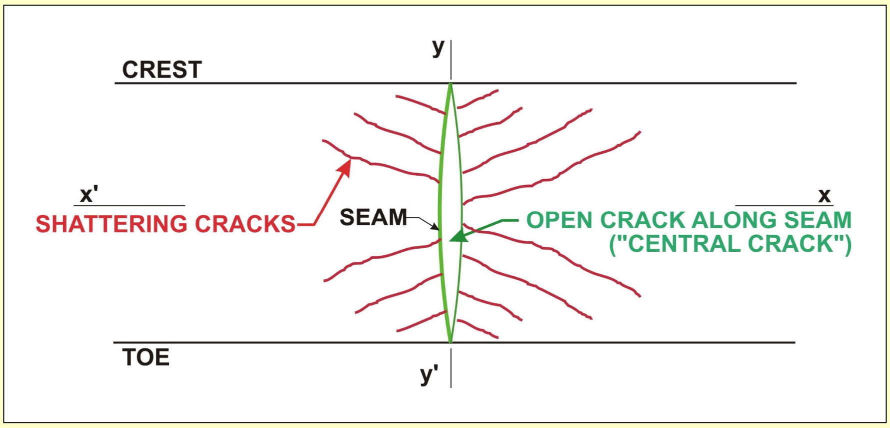
(which could have caused the shattering cracks)



JP GIROUD THE VIENNA TERZAGHI LECTURE 44

Or:

Did the shattering cracks occur first?



JP GIROUD THE VIENNA TERZAGHI LECTURE 45

The spectacular nature of the shattering cracks impressed all observers to the point that some of them felt that **common sense** dictated that the **shattering cracks** were the **main mechanism** of failure.

Therefore, they recommended **replacing the geomembrane** by a new geomembrane.

My position was that only a **rational analysis**, **not common sense**, could solve the dilemma.

JP GIROUD THE VIENNA TERZAGHI LECTURE 46

It was important to find the mechanism of failure.

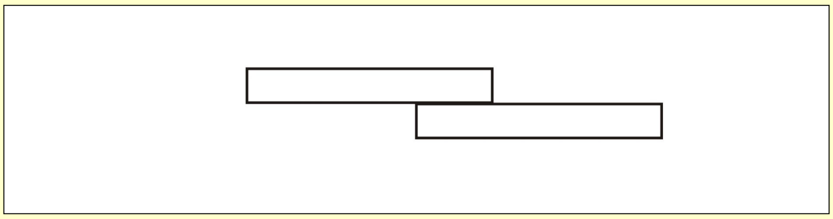
- If the opening of the central crack triggered
  the shattering cracks,
  then the **geomembrane tension** played a role,
  and **reducing the tension**
  could be the solution.

- If the shattering cracks
  were not linked to the central crack,
  the **geomembrane was defective**
  and **had to be replaced**.

JP GIROUD THE VIENNA TERZAGHI LECTURE 47

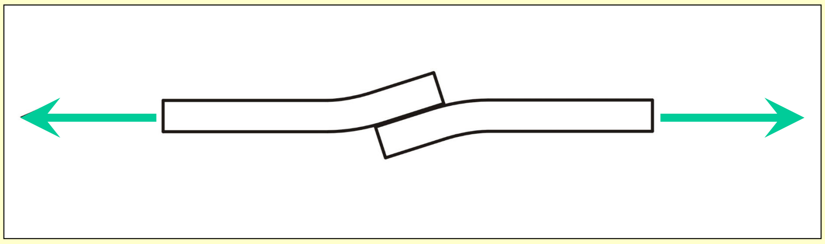
To explain the mechanism,
I looked for something special
next to the seam,

I noted that a geomembrane under tension
has to bend next to a seam
to ensure that the tensile forces are aligned.

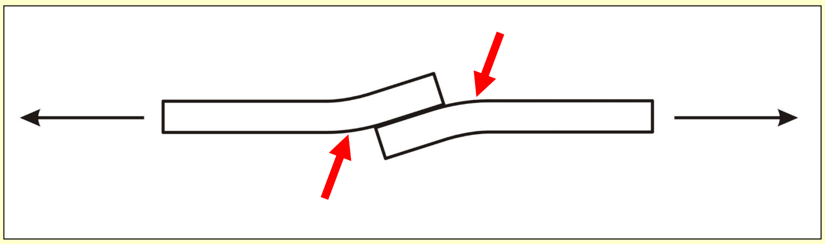


JP GIROUD THE VIENNA TERZAGHI LECTURE 48

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.

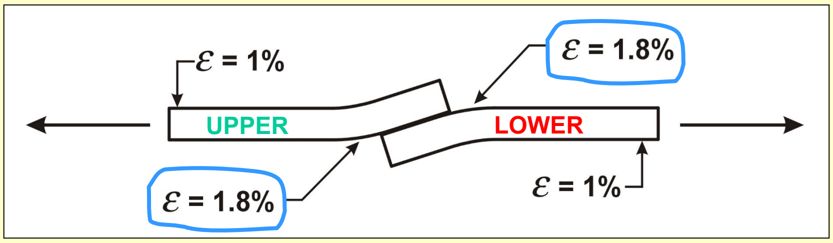


I calculated the geomembrane strain at the locations of maximum bending.



Results on the next slide

CALCULATED GEOMEMBRANE STRAINS



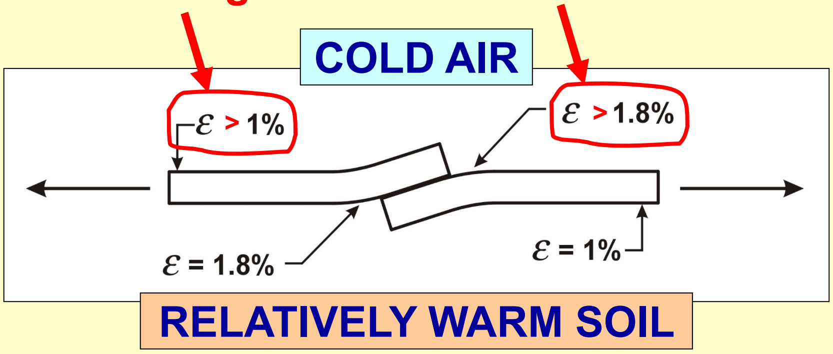
This **80% strain increase**, from 1% to 1.8%, explains why cracking is more likely to occur **next to seams** than away from seams, but it does not explain why the central crack occurred in the **lower** geomembrane panel and not in the **upper** geomembrane panel.

JP GIROUD THE VIENNA TERZAGHI LECTURE 51

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

JP GIROUD THE VIENNA TERZAGHI LECTURE 52

Additional geomembrane strain

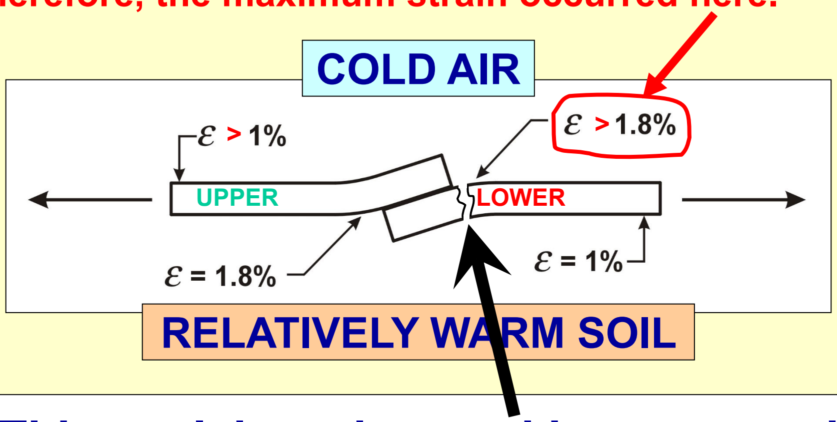


In the **winter**, when cracking occurred,
air was colder above the geomembrane than below.

As a result, the **upper face** of the geomembrane **contracted more** than the lower face, which caused **additional strain** in the geomembrane upper face.

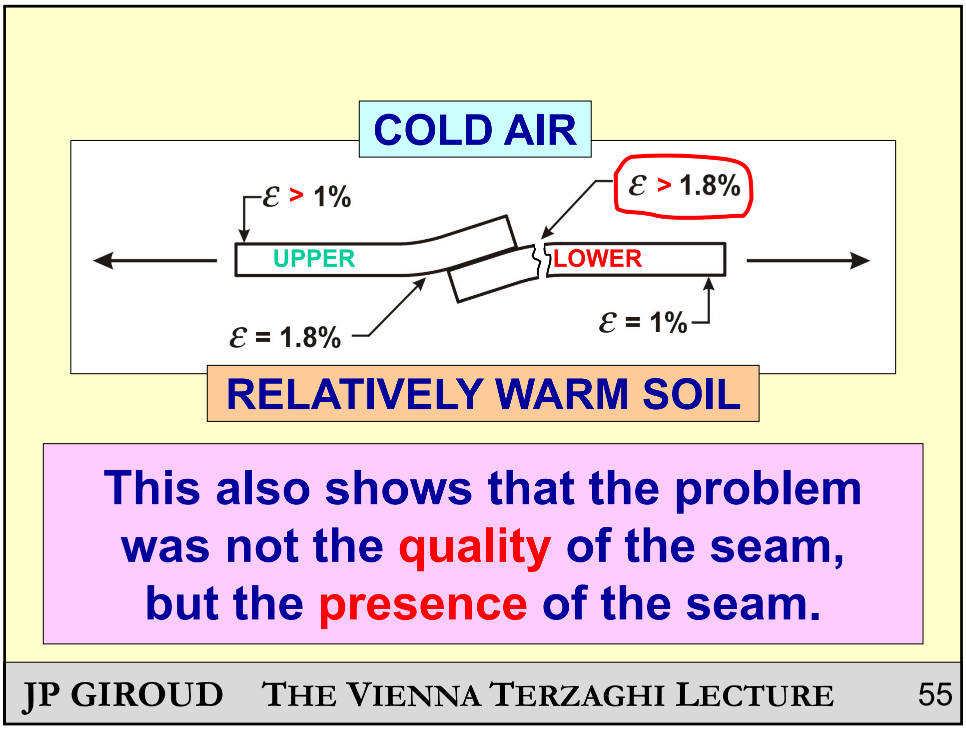
JP GIROUD THE VIENNA TERZAGHI LECTURE 53

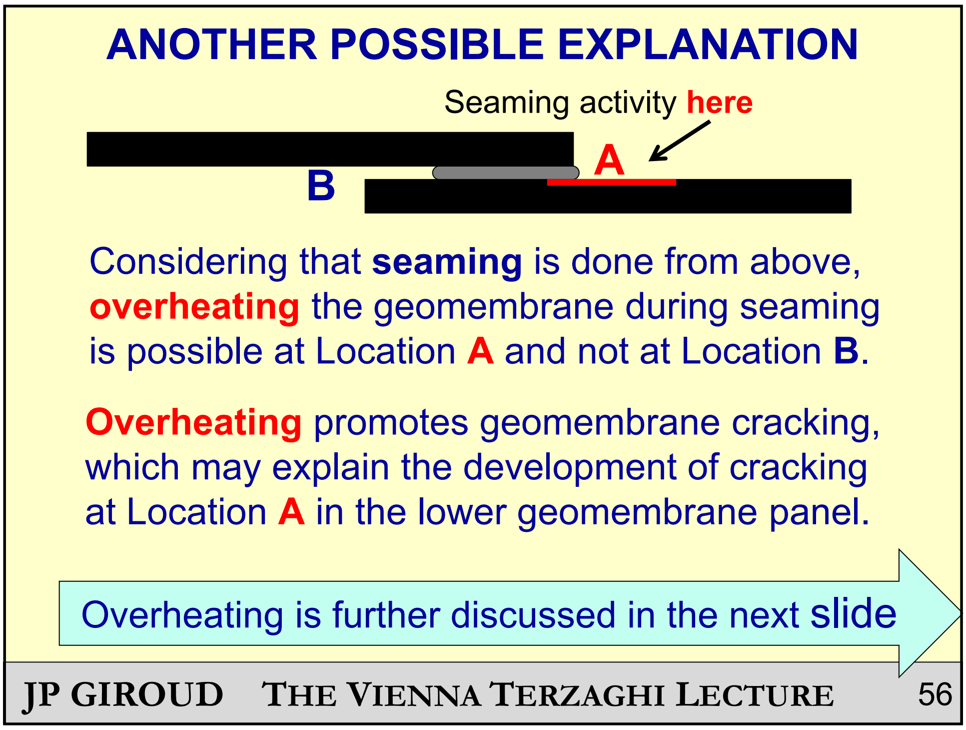
Therefore, the maximum strain occurred here.



This explains why cracking occurred in the lower panel and not in the upper panel.

JP GIROUD THE VIENNA TERZAGHI LECTURE 54

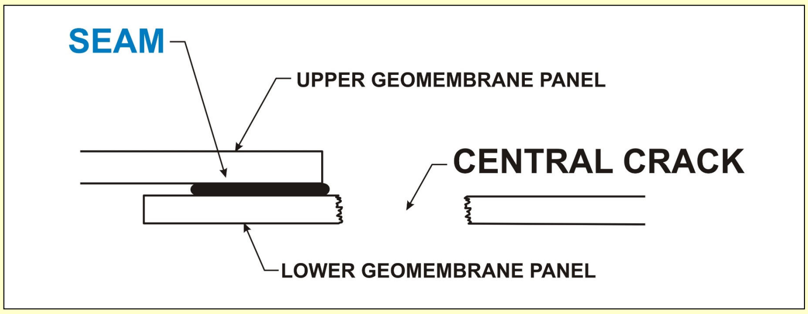

COLD AIR
ε > 1%
ε > 1.8%
UPPER
LOWER
ε = 1.8%
ε = 1%
RELATIVELY WARM SOIL
This also shows that the problem was not the quality of the seam, but the presence of the seam.
JP GIROUD THE VIENNA TERZAGHI LECTURE 55


ANOTHER POSSIBLE EXPLANATION
Seaming activity here
A
B
Considering that seaming is done from above, overheating the geomembrane during seaming is possible at Location A and not at Location B.
Overheating promotes geomembrane cracking, which may explain the development of cracking at Location A in the lower geomembrane panel.
Overheating is further discussed in the next slide
JP GIROUD THE VIENNA TERZAGHI LECTURE 56

Overheating makes an HDPE geomembrane more prone to cracking through **increased brittleness** and **stress concentration**:

- **increased brittleness** of the HDPE compound due to crystallinity increase, microstructural changes, and consumption of antioxidants additives;
- **stress concentration** due to deformed geometry and zones of different mechanical behavior.

At this point, **we had an explanation** (*in fact, two possible explanations*) for the development of the **central crack next to the seam**, in the **lower panel**.

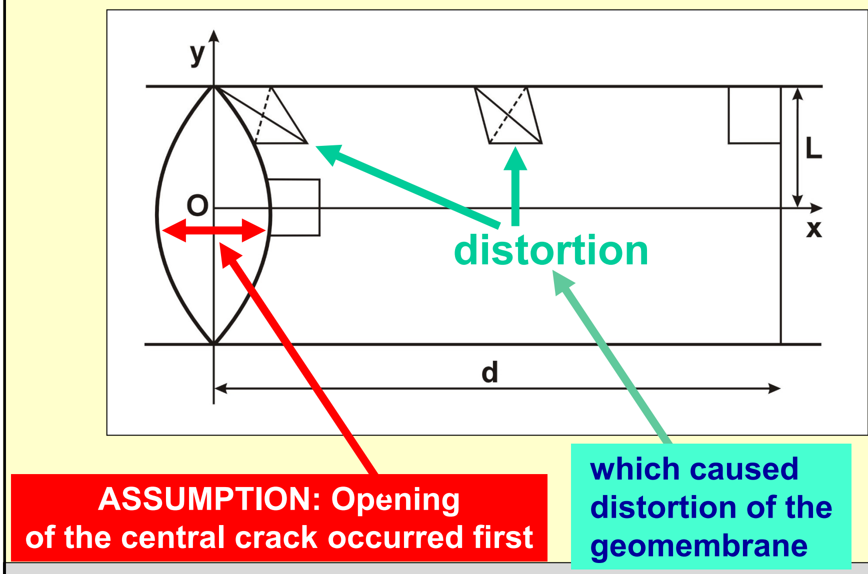


But . . . we had not demonstrated if the central crack had **triggered the shattering cracks.**

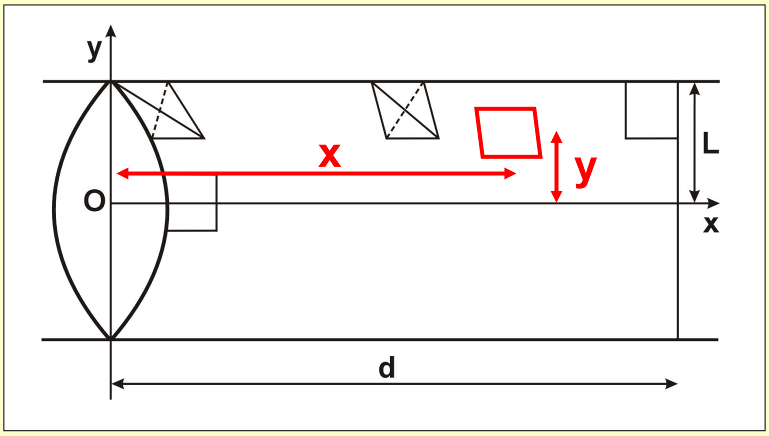
To be convincing, the demonstration had to be based on engineering principles.

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

MODEL USED FOR THE DEMONSTRATION



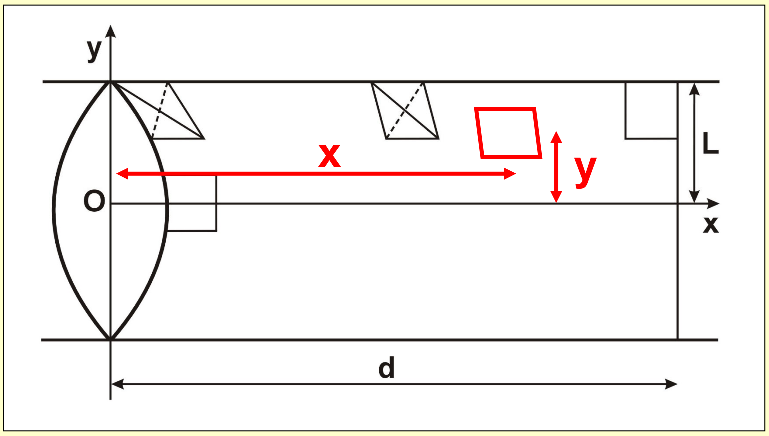
The distortion depends on x and y.



The distortion decreases for increasing x.
The distortion increases for increasing y.

JP GIROUD THE VIENNA TERZAGHI LECTURE 61

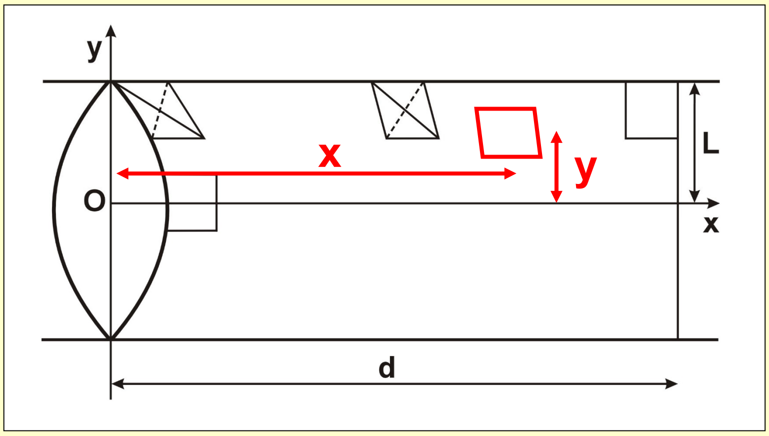
The distortion depends on x and y.



There is no distortion for x = d and for y = 0 and maximum distortion for x = 0 and y = L.

JP GIROUD THE VIENNA TERZAGHI LECTURE 62

The distortion depends on x and y.

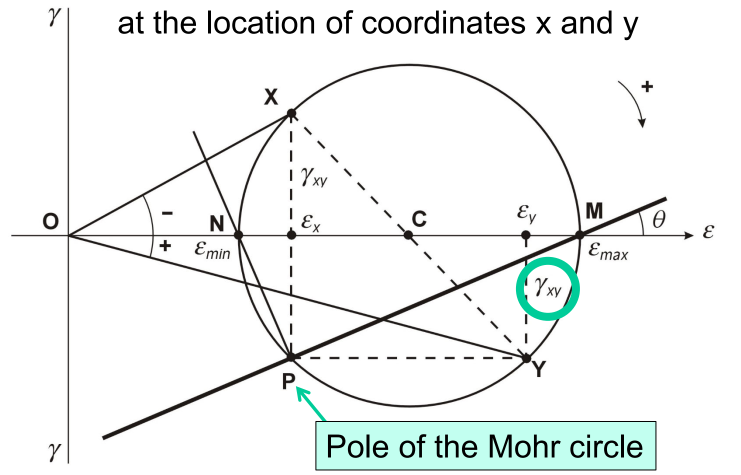


The Mohr's circle for strains in the geomembrane will, therefore, depend on x and y.

JP GIROUD THE VIENNA TERZAGHI LECTURE 63

MOHR'S CIRCLE FOR STRAINS

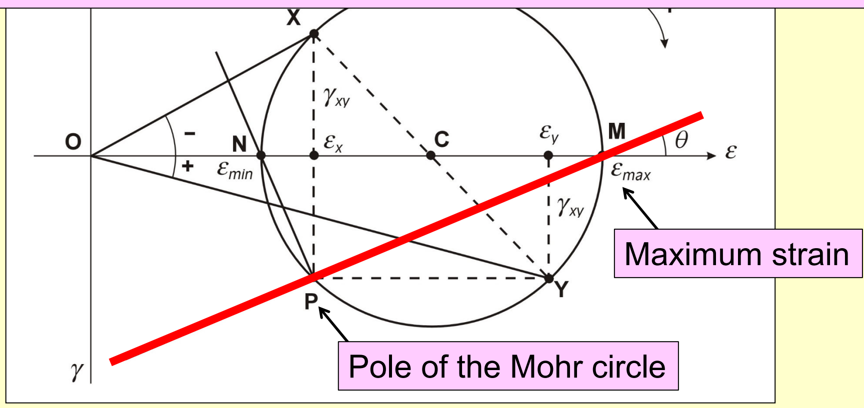
at the location of coordinates x and y



The pole, **P**, is obtained from the distortion, γ_{xy}, at the considered location of coordinates x and y.

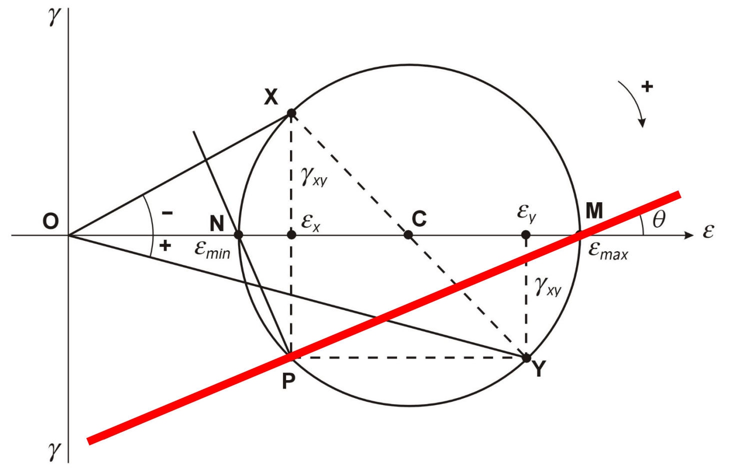
JP GIROUD THE VIENNA TERZAGHI LECTURE 64

A property of the Mohr's circle is that the straight line from the pole to the maximum strain, **PM**, is **perpendicular** to the **maximum strain direction**.



JP GIROUD THE VIENNA TERZAGHI LECTURE 65

MOHR'S CIRCLE FOR STRAINS



PM is perpendicular to the maximum strain.
Therefore, it is the crack direction.

JP GIROUD THE VIENNA TERZAGHI LECTURE 66

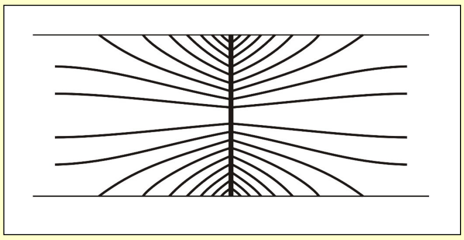
The Mohr's circle depends on x and y. Therefore, the direction of cracks depends on x and y.

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

[Giroud 1994]

This family of curves is the theoretical pattern of cracks.

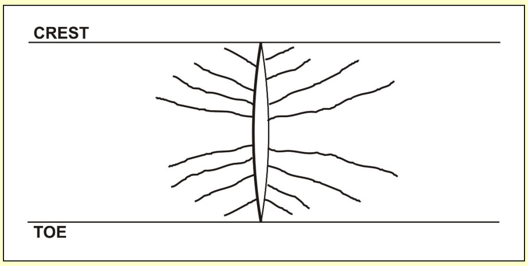
JP GIROUD THE VIENNA TERZAGHI LECTURE 67



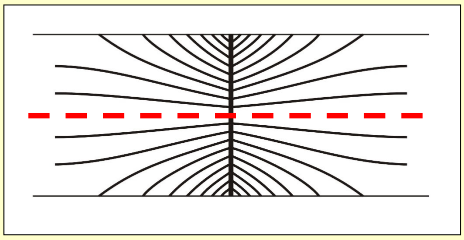
Here is the theoretical pattern of cracks,

which is similar to

the observed pattern of cracks.



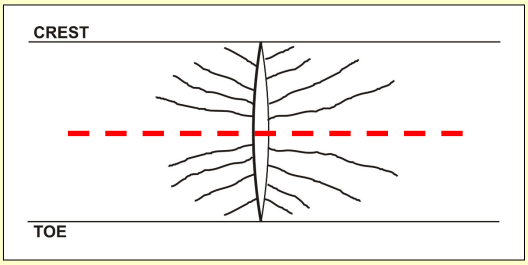
JP GIROUD THE VIENNA TERZAGHI LECTURE 68



THEORETICAL PATTERN OF CRACKS

In both the **theoretical** pattern of cracks and the **observed** pattern of cracks, there is **no crack on the mid-slope axis**.

OBSERVED PATTERN OF CRACKS



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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.**

JP GIROUD THE VIENNA TERZAGHI LECTURE 70

Clearly, a **theoretical** analysis
led to a **practical** solution.

This is consistent with Terzaghi's leitmotif:
"From theory to practice".

The practical solution
is described in the following slides.

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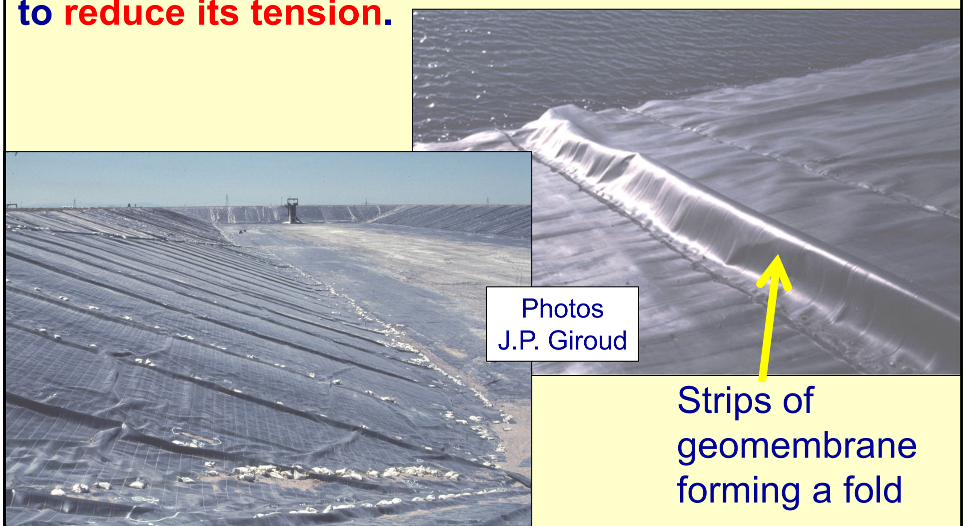
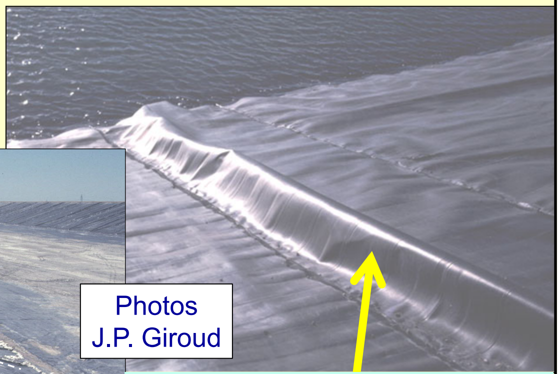
"Compensation panels" (kinds of huge intentional wrinkles)
were added to the geomembrane
to reduce its tension.



JP GIROUD THE VIENNA TERZAGHI LECTURE 72

“Compensation panels” were added to reduce tension in the geomembrane.

Compensation panels were added at regular intervals



Photos
J.P. Giroud

Compensation panels are folded strips of geomembrane.

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There were **ten quasi-identical reservoirs** at the site.

Extensive stress cracking occurred in the reservoirs where the geomembrane liner had been **installed in the summer**.

No or limited stress cracking occurred in the reservoirs where the geomembrane liner had been **installed in the fall**.

Cracking occurred where **geomembrane tension was high** due to **contraction** caused by large difference between temperatures **at installation** and **in service**.

These observations confirm the **role of tension** considered in the theoretical analysis.

JP GIROUD THE VIENNA TERZAGHI LECTURE 74

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.

JP GIROUD THE VIENNA TERZAGHI LECTURE 75

LESSON LEARNED BY THE INDUSTRY

The case of geomembrane cracking presented in the preceding slides happened in 1989.

This type of geomembrane **cracking** would be **less likely** to happen **today** because geomembrane manufacturing has made significant progress.

As a result, **modern geomembranes** are much **less susceptible to cracking** than the geomembrane discussed in preceding slides.

Manufacturing progress is described in the next slide.

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LESSON LEARNED BY THE INDUSTRY

Thanks to improvements
to the polymerization of the ethylene monomer,
such as the use of specially developed catalysts
and the addition of a small amount of “**comonomers**”
(*for example, hexene and octene*),
the resulting polyethylene polymer contains “**branches**”
between “chains” (i.e. the linear polyethylene molecules).

The **network** thus created makes it difficult
for the linear polyethylene molecules to move apart,
thereby making **cracking less likely**.

Clearly, the polymer **manufacturing industry has learned a lesson** from **cracking failures.**

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SECOND EXAMPLE

INSTABILITY OF GEOMEMBRANE/SOIL LAYERED SYSTEM ON SLOPE

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

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

JP GIROUD THE VIENNA TERZAGHI LECTURE 79

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

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INSTABILITY OF LINER SYSTEM ON LANDFILL SIDE SLOPE

JP GIROUD THE VIENNA TERZAGHI LECTURE 81

INSTABILITY OF TEMPORARY COVER

JP GIROUD THE VIENNA TERZAGHI LECTURE 82

INSTABILITY OF LANDFILL COVER

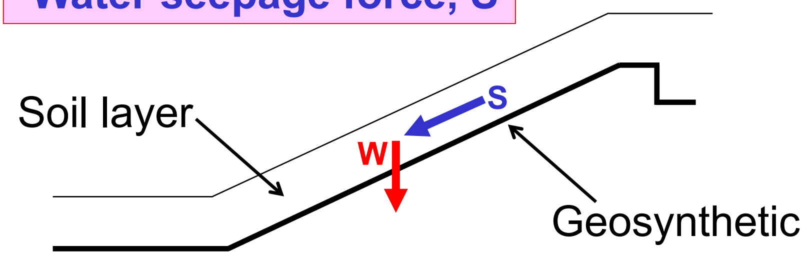
Courtesy
R.S. Thiel

JP GIROUD THE VIENNA TERZAGHI LECTURE 83

CAUSES OF INSTABILITY:

Weight of soil layer, W

Water seepage force, S



The seepage forces are due
to water flowing down slope.

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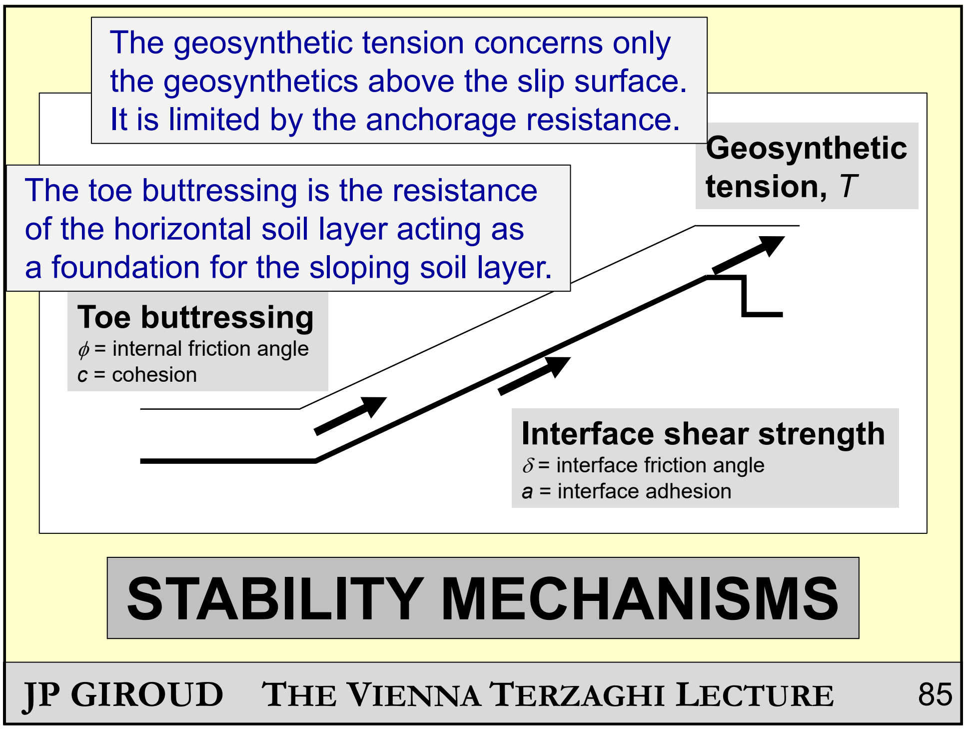
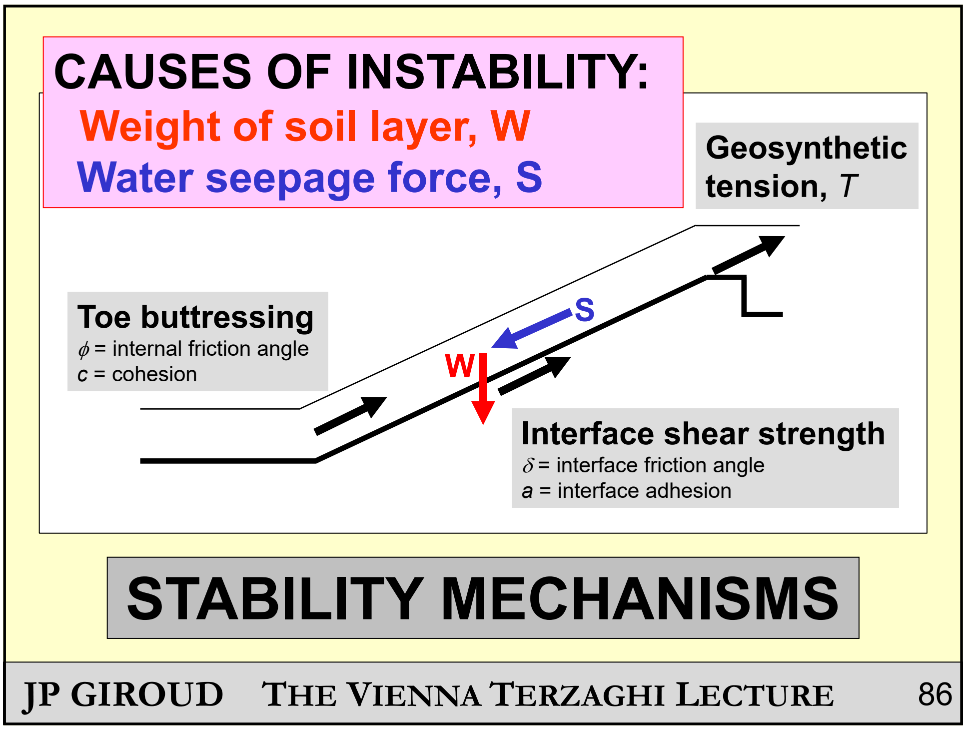
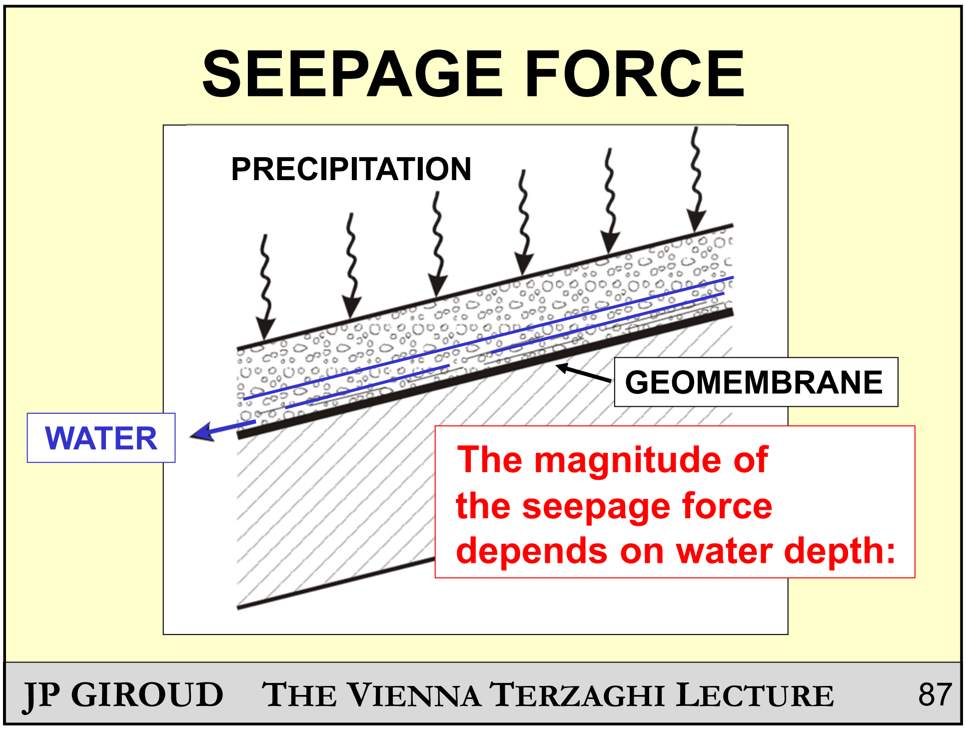
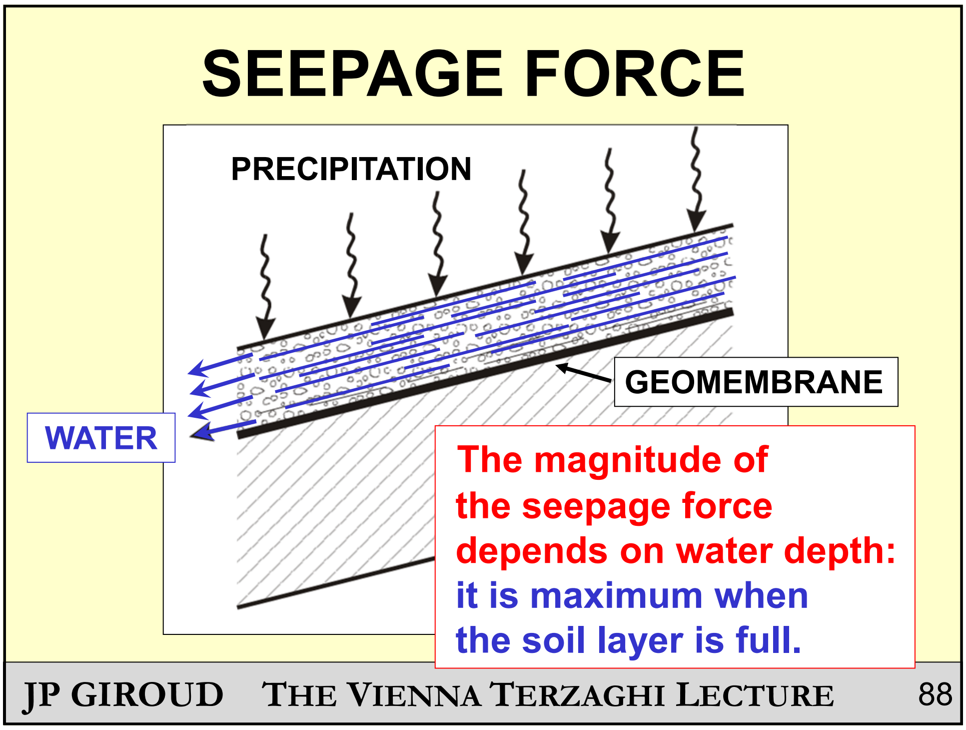

The geosynthetic tension concerns only the geosynthetics above the slip surface. It is limited by the anchorage resistance.
Geosynthetic tension, T
The toe buttressing is the resistance of the horizontal soil layer acting as a foundation for the sloping soil layer.
Toe buttressing
φ = internal friction angle
c = cohesion
Interface shear strength
δ = interface friction angle
a = interface adhesion
STABILITY MECHANISMS
JP GIROUD THE VIENNA TERZAGHI LECTURE 85


CAUSES OF INSTABILITY:
Weight of soil layer, W
Water seepage force, S
Geosynthetic tension, T
S
W
Toe buttressing
φ = internal friction angle
c = cohesion
Interface shear strength
δ = interface friction angle
a = interface adhesion
STABILITY MECHANISMS
JP GIROUD THE VIENNA TERZAGHI LECTURE 86


SEEPAGE FORCE
PRECIPITATION
GEOMEMBRANE
WATER
The magnitude of the seepage force depends on water depth:
JP GIROUD THE VIENNA TERZAGHI LECTURE 87


SEEPAGE FORCE
PRECIPITATION
GEOMEMBRANE
WATER
The magnitude of the seepage force depends on water depth:
it is maximum when the soil layer is full.
JP GIROUD THE VIENNA TERZAGHI LECTURE 88

SLOPE STABILITY EQUATIONS

NOTATION

δ = interface friction angle
a = interface adhesion
ϕ = soil internal friction angle
c = soil cohesion
β = slope angle
t = soil layer thickness
h = slope height
γ_{sat} = soil saturated unit weight
γ_b = soil buoyant unit weight

JP GIROUD THE VIENNA TERZAGHI LECTURE 89

The slope stability equations presented in the next slide take into account
the causes of **instability** (gravity and seepage forces) and the three **stability mechanisms**:

- interface friction and adhesion,
- toe buttressing effect, and
- anchorage at crest.

There are two equations,
one for each of the following two cases:

- Slip surface **above the geomembrane**; and
- Slip surface **below the geomembrane**.

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SLOPE STABILITY EQUATIONS
(full water depth)

Above

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

Below

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

[Giroud et al. 1995]

A = above geomembrane **B = below geomembrane**

The 3rd, 4th and 5th **terms** of both equations are **identical**.

This is not surprising because these three terms represent the **contribution to stability** of
the **toe buttressing** effect and
the **anchorage** at the crest of the slope,
two mechanisms **not influenced by flowing water**.

Furthermore, the **interface adhesion**, which governs the second term, is generally **neglected**.

Therefore, **only first terms need to be compared**.

Comparison of first terms **with** and **without** water is presented in subsequent slides.

Prior to proceeding with the comparison of **first terms with and without water**, it is necessary to note that the **first term** of the factor of safety equation **for a slope without water** is:

$$FS_{no\,water} = \frac{\tan\delta}{\tan\beta}$$

with $\delta = \delta_A$ for a slip surface above the geomembrane
and $\delta = \delta_B$ for a slip surface below the geomembrane

Comparison of first terms **with** and **without** water is presented in the next slide and subsequent slides.

COMPARISON OF SLOPE STABILITY with and without water for a slip surface above the geomembrane

WITH WATER	WITHOUT WATER
$FS_{A\,water} = \frac{\gamma_b}{\gamma_{sat}}\frac{\tan\delta_A}{\tan\beta}$	$FS_{A\,no\,water} = \frac{\tan\delta_A}{\tan\beta}$

Ratio of buoyant and saturated unit weights:

$$\frac{\gamma_b}{\gamma_{sat}} = 1 - \frac{1}{(1-n)G_s + n}$$

where: G_s = specific gravity of soil particles
n = porosity of soil

For typical values for soil of n = 0.3-0.4 and G_s = 2.65-2.70:

$$\frac{\gamma_b}{\gamma_{sat}} = 0.5 \text{ to } 0.55 \approx 0.525$$

COMPARISON OF SLOPE STABILITY
with and without water
for a slip surface above the geomembrane

From the equations in the preceding slide,
the relationship between the **factors of safety with** and **without water**,
for a slip surface above the geomembrane, is:

$$\frac{FS_{Awater}}{FS_{Anowater}} \approx 0.525$$

Therefore, the factor of safety is significantly reduced by water flowing downslope
if the slip surface is above the geomembrane.

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In contrast, in the case of
a **slip surface below the geomembrane**,
the first terms of the slope stability equations are:

WITH WATER

$$FS_{Bwater} = \frac{\tan \delta_B}{\tan \beta}$$

WITHOUT WATER

$$FS_{Bnowater} = \frac{\tan \delta_B}{\tan \beta}$$

The factor of safety is the same with and without water.

Considering that **interface adhesion** has been **neglected**,
it can be concluded that water flowing downslope
does not have significant influence on
the factor of safety in the case of
a **slip surface below the geomembrane**.

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THE COMMON SENSE APPROACH

Common sense suggests that the factor of safety is same above and below since the **same driving forces** are applied, i.e. weight and seepage forces.

But **common sense does not understand** the concept of **effective stress** and, therefore, cannot understand that the **shear strength** is **much lower** above the geomembrane than below due to **lower effective stress** above the geomembrane.

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Important lesson from the 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.

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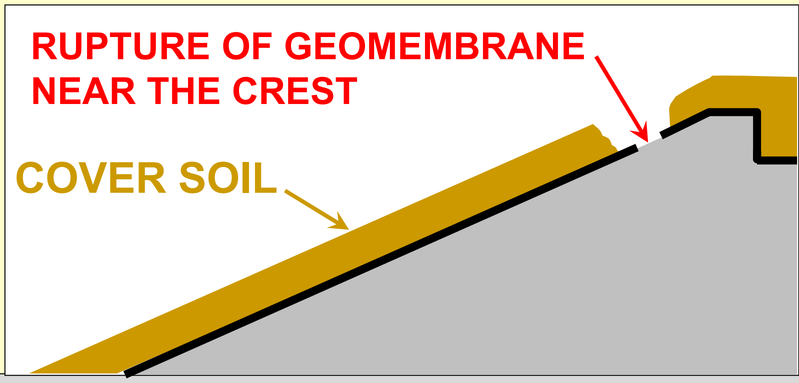
A landfill cover failed with geomembrane rupture near the crest of the slope, and large downward displacement.



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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.**

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

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

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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 !**

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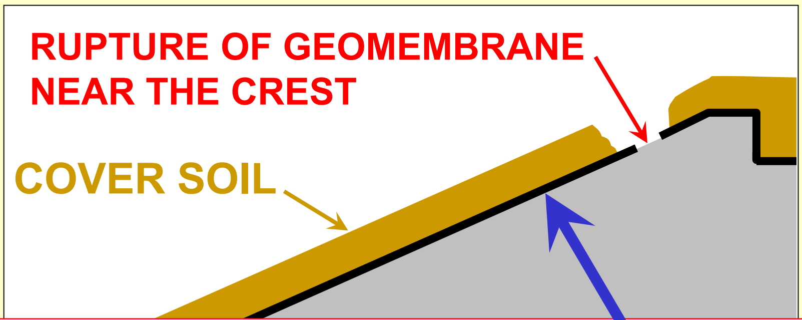
The real explanation was:

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

The real explanation was provided by a theoretical analysis.

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



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.

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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.**

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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 SUCCESSES IN PERSPECTIVE

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

Whereas, to date (2005), 20 billion m^2 of geosynthetics have been used successfully in several million projects.

a number of them significant and spectacular

The following slides will briefly illustrate the wide variety of applications of geosynthetics.

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DAMS

JP GIROUD THE VIENNA TERZAGHI LECTURE 114

RESERVOIRS

JP GIROUD THE VIENNA TERZAGHI LECTURE 115

WALLS

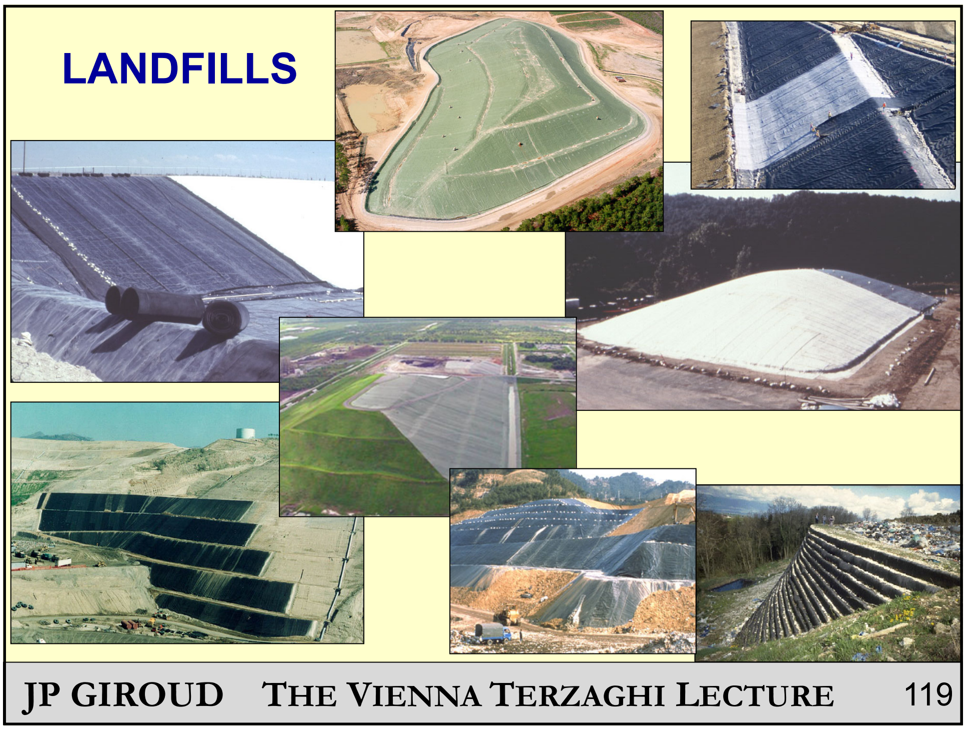
JP GIROUD THE VIENNA TERZAGHI LECTURE 116

SLOPES

JP GIROUD THE VIENNA TERZAGHI LECTURE 117

LANDSLIDE REPAIR

JP GIROUD THE VIENNA TERZAGHI LECTURE 118


LANDFILLS
JP GIROUD THE VIENNA TERZAGHI LECTURE 119


CANALS
JP GIROUD THE VIENNA TERZAGHI LECTURE 120

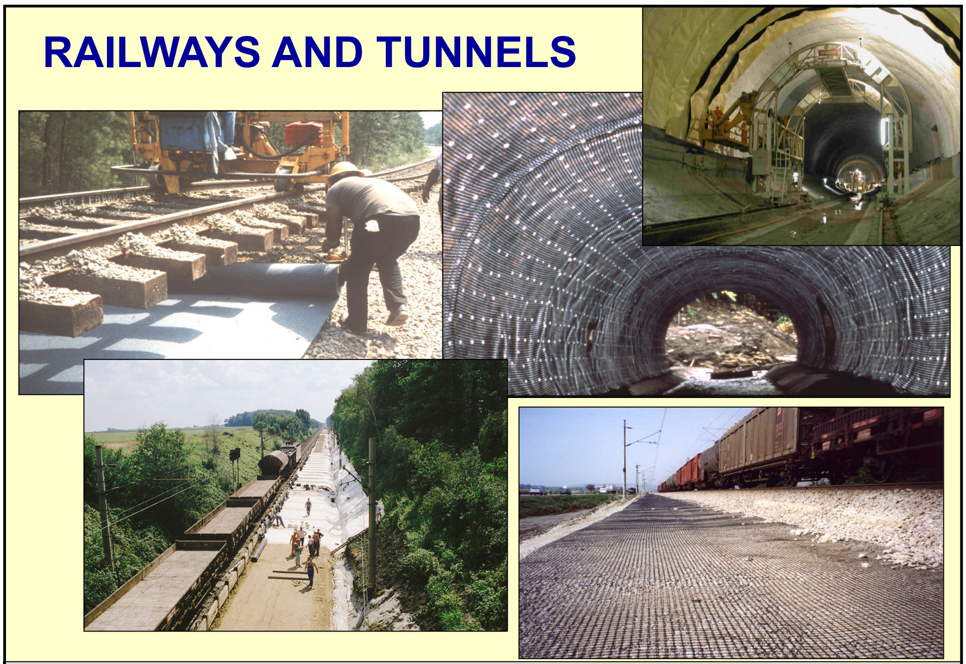

RIVERS
JP GIROUD THE VIENNA TERZAGHI LECTURE 121


MINING
JP GIROUD THE VIENNA TERZAGHI LECTURE 122

ROADS

JP GIROUD THE VIENNA TERZAGHI LECTURE 123

RAILWAYS AND TUNNELS



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DRAINAGE
JP GIROUD
THE VIENNA TERZAGHI LECTURE
125


COASTAL WORKS
JP GIROUD
THE VIENNA TERZAGHI LECTURE
126

EROSION CONTROL

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CONSTRUCTION ON SOFT SOILS

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ENVIRONMENTAL APPLICATIONS

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And not only large projects, but, also, a multitude of small applications

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

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

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FIRST EXAMPLE

USE OF GEOSYNTHETICS TO REHABILITATE OLD CONCRETE DAMS

JP GIROUD THE VIENNA TERZAGHI LECTURE 133

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

JP GIROUD THE VIENNA TERZAGHI LECTURE 134

Alkali-aggregate reaction is a mechanism of **concrete deterioration** due to a reaction between **hydroxide anions** (OH^-) and certain types of silica, which may be present in aggregate.

Therefore, alkali-aggregate reaction depends on the type of aggregate.

The hydroxide **anions** are contributed by cement and are **present** in the **concrete pore water**.

Therefore, the **presence of water** is essential for the development of alkali-aggregate reaction.

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

JP GIROUD THE VIENNA TERZAGHI LECTURE 136

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

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THE SAME DAM FACE AFTER REHABILITATION USING GEOSYNTHETICS

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REHABILITATION IN PROGRESS

Step 1
CONCRETE REPAIRED LOCALLY

Step 2
GEONET OR THICK GEOTEXTILE
for drainage

Step 3
GEOMEMBRANE
for water barrier

Courtesy Carpi

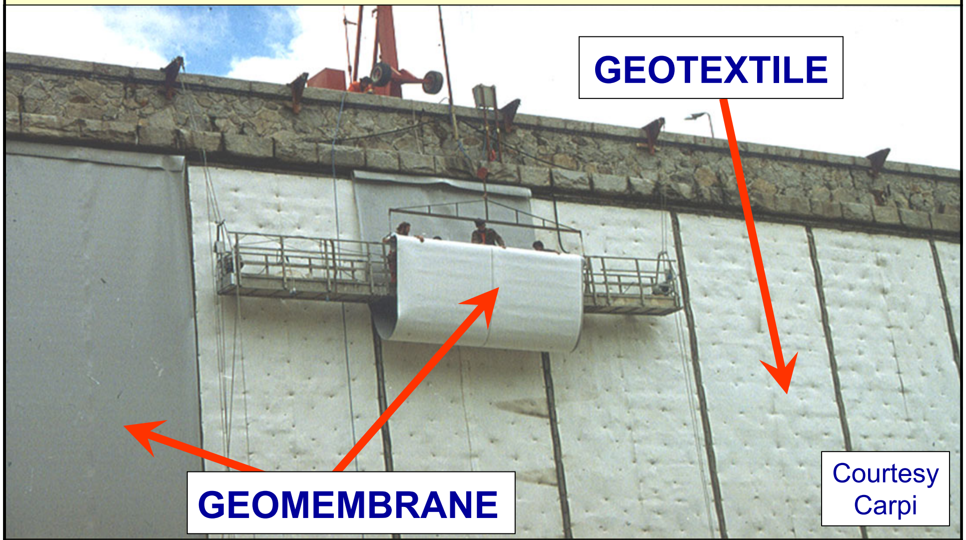
JP GIROUD THE VIENNA TERZAGHI LECTURE 139

Photo taken 10 years after rehabilitation

Courtesy Carpi

JP GIROUD THE VIENNA TERZAGHI LECTURE 140

REHABILITATION IN PROGRESS ON THE FACE OF A MASONRY DAM



JP GIROUD THE VIENNA TERZAGHI LECTURE 141

A thick nonwoven geotextile
is needed to cushion the geomembrane
in the case of some masonry dams.

Photos
Carpi

JP GIROUD THE VIENNA TERZAGHI LECTURE 142

THE SAME MASONRY DAM AFTER REHABILITATION USING GEOSYNTHETICS

JP GIROUD THE VIENNA TERZAGHI LECTURE 143

REHABILITATION CONCEPT

- The geomembrane provides a **barrier against leakage**.
- 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.

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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**, sometimes less.

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DURABILITY OF GEOSYNTHETICS

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

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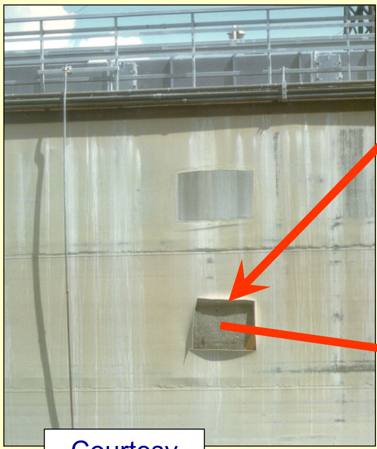
Samples taken periodically from the dam face



Courtesy
D. Cazzuffi

Laboratory testing

Based on 20 years of testing,
a durability of 40-50 years is predicted.

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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

JP GIROUD THE VIENNA TERZAGHI LECTURE 148

LESSONS LEARNED
from this successful application

In this application and some others,
the **durability** of **geosynthetics**
can be similar, even superior,
to the **durability**
of **traditional construction materials**
such as concrete.

Geosynthetics are **sufficiently durable**
to be used in **large dams**.

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Incidentally, it should be noted that geomembranes are extensively used in large dams.

- Geomembranes have been used as the **only waterproofing barrier** in more that **200 large dams** according to the ICOLD.
- The **first large dam** with a geomembrane was constructed in **1959** in Italy and is still in service in 2005.
- The highest dam with a geomembrane, as of 2005, is **174 m** high.

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SECOND EXAMPLE
OF
LEARNING FROM SUCCESS

DEVELOPMENT
OF A
RETENTION CRITERION
FOR
GEOTEXTILE FILTERS

JP GIROUD THE VIENNA TERZAGHI LECTURE 151

RETENTION CRITERION
FOR
GEOTEXTILE FILTERS

This is the last example presented in this lecture, and filter design is definitely a “Terzaghi subject”.

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

Today, **geotextiles**
are routinely used as filters.

Examples are shown in the following slides.

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Example of geotextile filter
between gravel drain and soil

JP GIROUD THE VIENNA TERZAGHI LECTURE 154

JP GIROUD THE VIENNA TERZAGHI LECTURE 155

Geotextile filters are even used in large dams.

JP GIROUD THE VIENNA TERZAGHI LECTURE 156

To develop a **retention criterion,**
we should answer the following question.

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

A simple answer consists in adapting

Terzaghi's retention criterion

for granular filters:

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

JP GIROUD THE VIENNA TERZAGHI LECTURE 157

RETENTION CRITERION

It is known that, in a **granular filter,**

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

where O_{FILTER} = filter opening size

Therefore, Terzaghi's retention criterion
which is: $d_{15\ FILTER} < 5\ d_{85\ SOIL}$

can be written: $O_{FILTER} < d_{85\ SOIL}$

This expression has the merit
of being applicable to **any type of filter**,
in particular a **geotextile filter**.

JP GIROUD THE VIENNA TERZAGHI LECTURE 158

$O_{FILTER} < d_{85\ SOIL}$ i.e. filter **opening size** smaller than one of the largest soil particles

- This equation means that **a filter** (of any type, granular or geotextile) **should only retain large soil particles.**
- (This is **against** common sense, as **common sense dictates** that a filter should retain all particles, not only the large particles.)
- Retaining **only** large soil particles works if the **large** particles **retain smaller** particles, and so on.

In other words, if the soil is internally stable

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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.

JP GIROUD THE VIENNA TERZAGHI LECTURE 160

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.

JP GIROUD THE VIENNA TERZAGHI LECTURE 161

In other words, **a granular filter**
may **adapt 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
(e.g. Terzaghi's retention criterion)
that does not take into account
the internal stability of the soil.

JP GIROUD THE VIENNA TERZAGHI LECTURE 162

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** of the soil particle size distribution curve.

JP GIROUD THE VIENNA TERZAGHI LECTURE 163

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

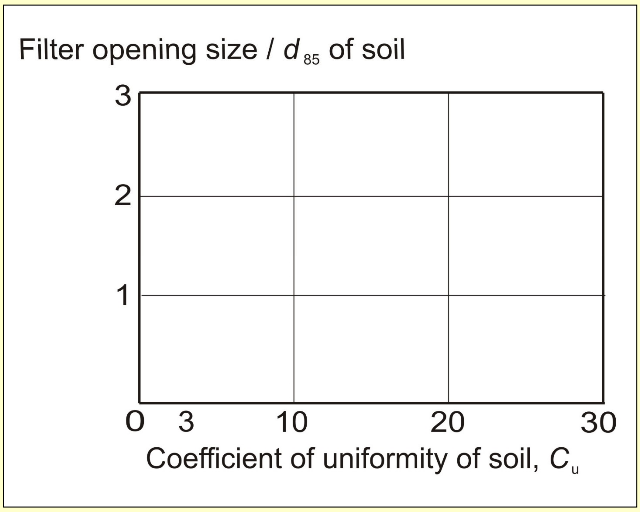
geotextile filters are thin,
which has created
an incentive for developing
a more accurate
retention criterion:

a criterion that takes into account the internal stability of the soil.

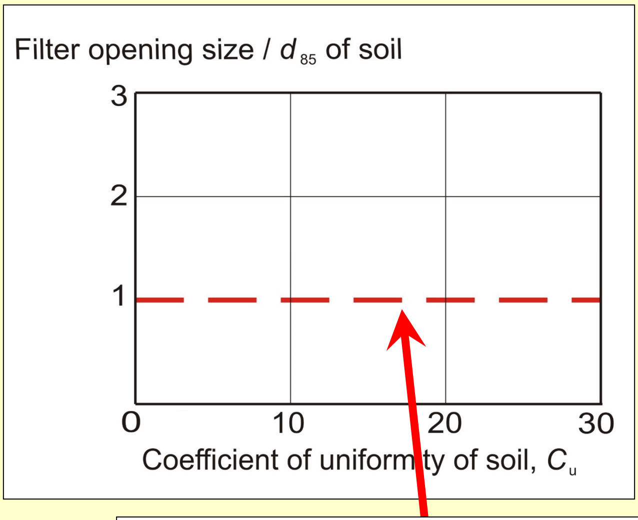
JP GIROUD THE VIENNA TERZAGHI LECTURE 164

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

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

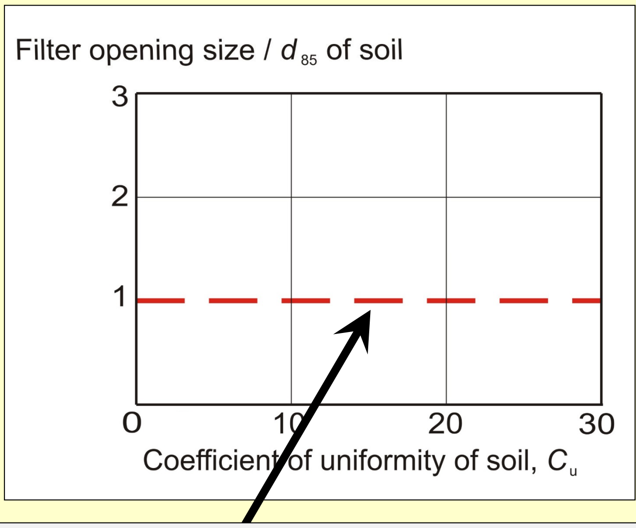


Graph of O_{FILTER}/d_{85} as a function of C_u



THE HORIZONTAL DASHED LINE REPRESENTS TERZAGHI's RETENTION CRITERION:
$O_{FILTER} = d_{85\ SOIL}$

JP GIROUD THE VIENNA TERZAGHI LECTURE 167



The **line is horizontal** because **Terzaghi's retention criterion does not depend on the particle size distribution of the soil.**

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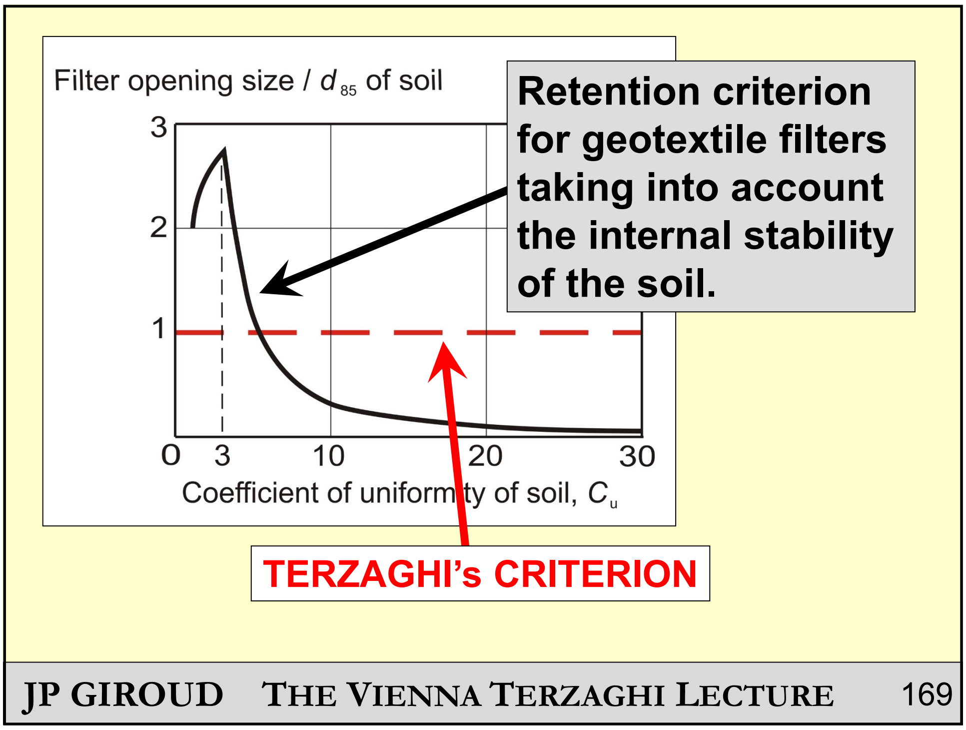
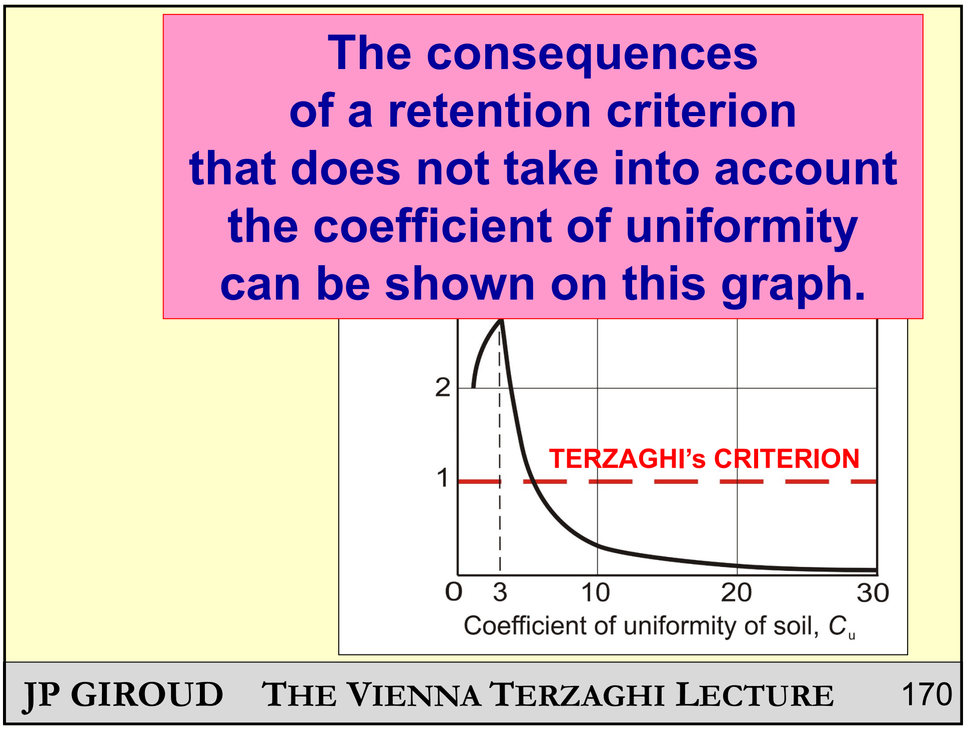
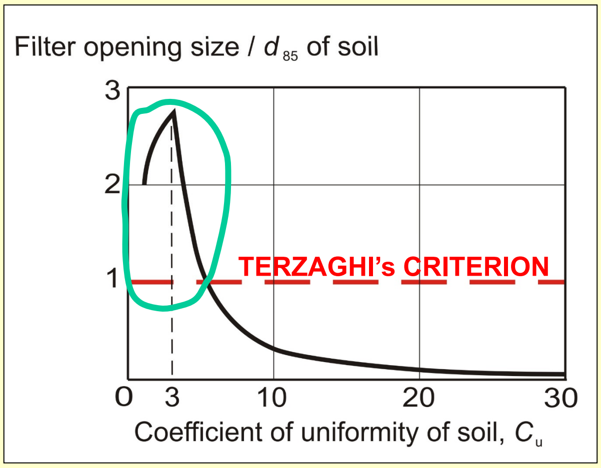

Filter opening size / d_{85} of soil
3
2
1
0
3
10
20
30
Coefficient of uniformity of soil, C_u
Retention criterion for geotextile filters taking into account the internal stability of the soil.
TERZAGHI's CRITERION
JP GIROUD
THE VIENNA TERZAGHI LECTURE
169


The consequences of a retention criterion that does not take into account the coefficient of uniformity can be shown on this graph.
2
1
TERZAGHI's CRITERION
0
3
10
20
30
Coefficient of uniformity of soil, C_u
JP GIROUD
THE VIENNA TERZAGHI LECTURE
170

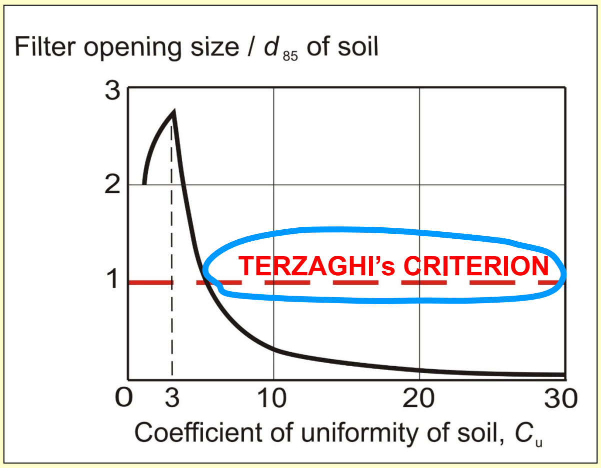
If the **coefficient of uniformity is small, the criterion represented by the red line** allows **filter openings** that are **too small.**

Hence a 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.

Hence a risk of soil piping

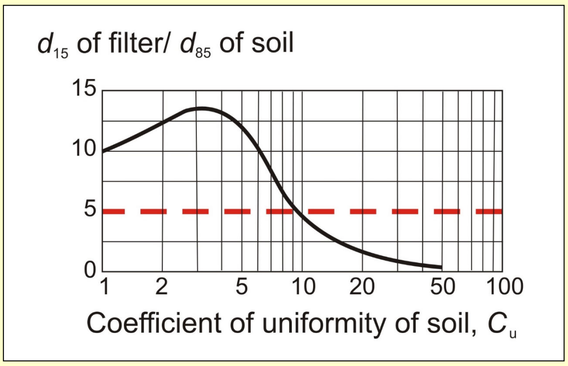


Therefore,
a **geotextile filter** is **safer**
if it is designed with
the **retention criterion**
that **takes into account**
the **internal stability**
of the soil.

The same can be done with granular filters.

JP GIROUD THE VIENNA TERZAGHI LECTURE 173

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



[Giroud 2003]

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

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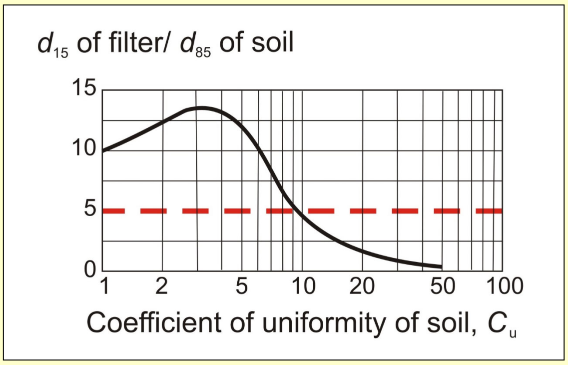
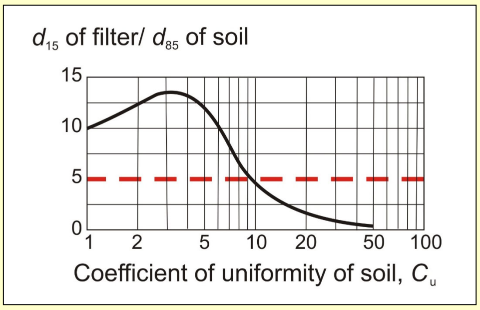
The retention criterion developed for geotextile filters has been extended for granular filters.



The black curve represents the proposed **criterion for granular filters**.

The **horizontal dashed line represents Terzaghi's retention criterion.**

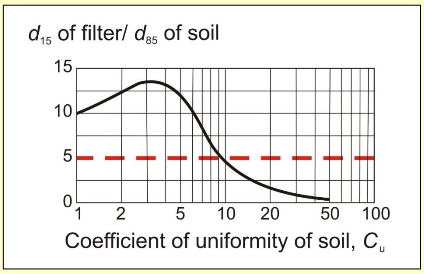
RETENTION CRITERION FOR GRANULAR FILTERS



For soils having a **low coefficient of uniformity**, the proposed retention criterion allows a d_{15} of the filter **higher** than the d_{15} allowed by **Terzaghi's criterion**.

This is **consistent with classical experiments** by Bertram (1940) and Sherard et al. (1984).

RETENTION CRITERION FOR GRANULAR FILTERS



- For soils having a **high coefficient of uniformity**, Terzaghi's criterion allows high values of d_{15} (*compared to the proposed criterion*) which means a filter with a large opening size, hence a **risk of internal erosion** ("piping").
- This is well known and has led to the practice of **truncating** the particle size distribution curve.

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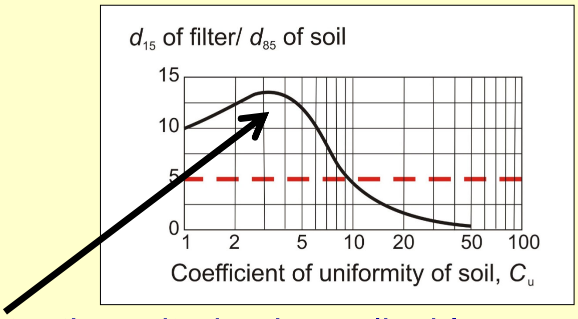
RETENTION CRITERION FOR GRANULAR FILTERS



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

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

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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.**

JP GIROUD THE VIENNA TERZAGHI LECTURE 180

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.

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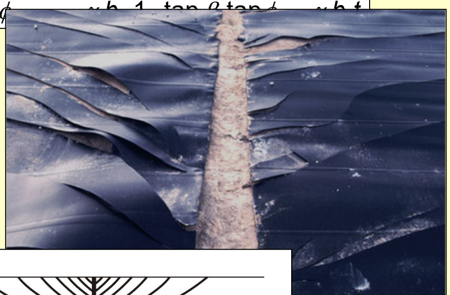
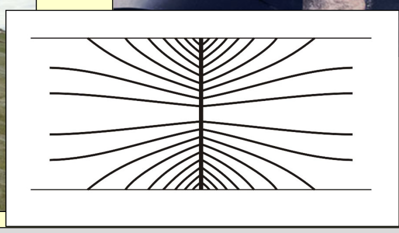
CONCLUSION

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

We learned from failures.





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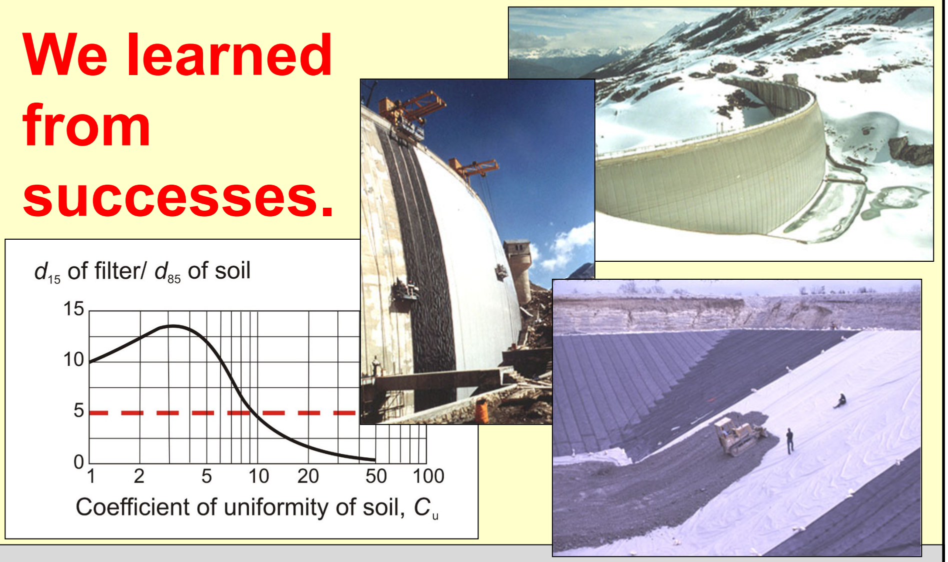
CONCLUSION

We learned from successes.



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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 approach "from theory to practice" advocated by Terzaghi.

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Thank you

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REFERENCES CITED IN THE LECTURE

Bertram, G.E., 1940, "An Experimental Investigation of Protective Filters", Soil Mechanics Series No. 7, Harvard University, Cambridge, Massachusetts, 21 p.

Giroud, J.P., 1994, "Determination of Geomembrane Shattering Cracks", Geosynthetics International, Vol. 1, No. 2, pp. 149-180.

Giroud, J.P., Bachus, R.C. & Bonaparte, R., 1995, "Influence of Water Flow on the Stability of Geosynthetic-Soil Layered Systems on Slopes", *Geosynthetics International*, Special Issue on Design of Geomembrane Applications, Vol. 2, No. 6, pp. 1149-1180. (Errata, 1997, Vol. 4, No. 2, pp. 209-210.)

Giroud, J.P., 2003, "Filter Criteria", pp. 221-259, in Jubilee Volume, 75th Anniversary of K. Terzaghi's "Erdbaumechanik" ("Soil Mechanics"), H. Brandl, Editor, Reports of the Institute for Soil Mechanics and Geotechnical Engineering, Technical University of Vienna, Austria, 378 p.

Sherard, J.L., Dunnigan, L.P. & Talbot, J.R., 1984, "Filters for Silt and Clays", ASCE Journal of Geotechnical Engineering, Vol. 110, No 6, June 1984, pp. 701-718.

REFERENCE OF THE PAPER PRESENTING THE LECTURE

Giroud, J.P., 2005, "Geosynthetics engineering: successes, failures and lessons learned", The Vienna Terzaghi Lecture, pp. 11-54 in Proceedings of 5. Osterreichische Geotechniktagung, Osterreichischer Ingenieur und Architekten Verein, Vienna, February 2005, 583 p.

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on 21 February 2005
at a special meeting of the
Österreichischer Ingenieur- und Architekten-Verein
in the Festivity Hall of Palais Eschenbach,
in Vienna, Austria.

The Vienna Terzaghi Lecture
has also been presented by JP Giroud in:

- Atlanta, USA, 15 November 2005
- Hong Kong, China, 11 April 2006
- Yokohama, Japan, 18 September 2006
- Bucharest, Romania, 7 June 2007

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