AMERICAN SOCIETY OF CIVIL ENGINEERS
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The Terzaghi Lecture

by

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revised after
Texas A&M Presentation
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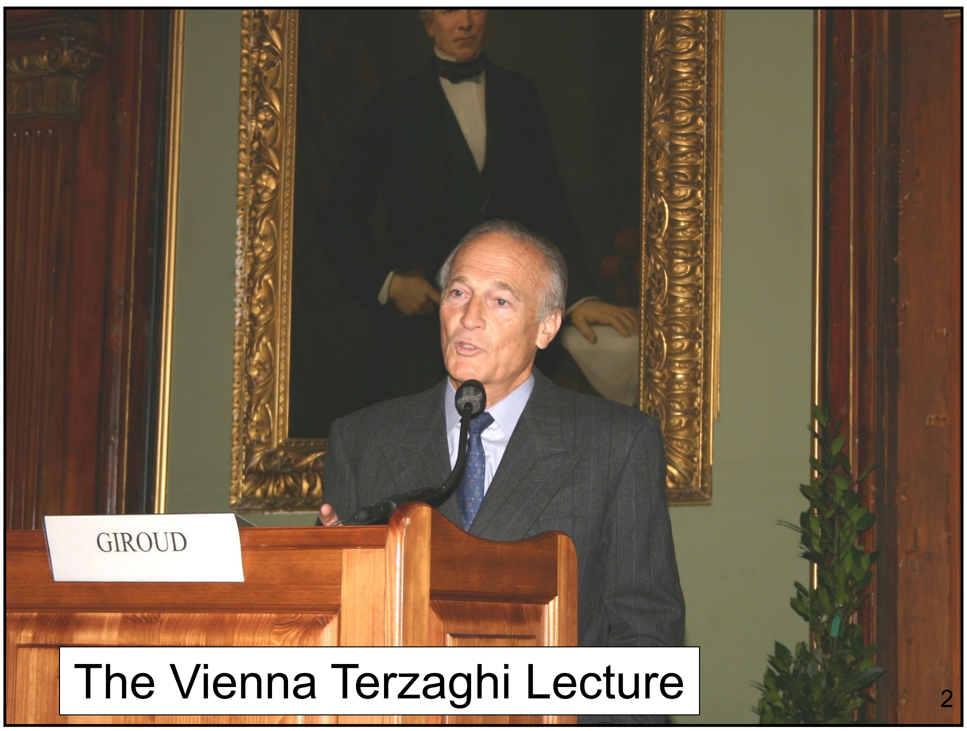

The Vienna Terzaghi Lecture

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JP GIROUD THE TERZAGHI LECTURE 3

The Terzaghi Lecture

FILTER CRITERIA

JP GIROUD THE TERZAGHI LECTURE 4

- Work on filter criteria has been published by many authors.
- It is not possible to present all of this work in a lecture.
- I will only present the work I have done.
- This does not mean I ignore work done by others, but I had to limit the scope.

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- The work I have done on filter criteria is **essentially theoretical**.
- This does not mean I ignore experimental work.
- In fact, I use experimental data.
- But, by just doing rational analyses, it was possible to build a **coherent system** of filter criteria.

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- I want to present the development of this **coherent system**, because this provides an opportunity to better understand the mechanisms of filtration.
- This **coherent system** of filter criteria has many practical applications, and I want to make geotechnical engineers aware of these possibilities.

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- I did this work to improve criteria for **geotextile filters**, but this work is applicable to **granular filters** as well.
- In fact, the first steps of the development of criteria for geotextile filters were inspired by granular filter criteria.
- As a result, the lecture often refers to **Terzaghi's filter criteria**.

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Terzaghi's criteria for granular filters are well known:

$d_{15F} \geq$ 4 or 5 d_{15S} — The d_{15} of the filter must not be too **small**.

This is the permeability criterion.

$d_{15F} \leq$ 4 or 5 d_{85S} — The d_{15} of the filter must not be too **large**.

This is the retention criterion.

The difference between the factors 4 and 5 is not significant.
I will use the factor **5** in the discussions.

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Both Terzaghi's criteria are expressed using the $\mathbf{d_{15}}$ of the granular filter.

This is possible because the $\mathbf{d_{15}}$ of a granular material is related to the size of its openings.

The relationship is :

OPENING SIZE ≈ $\mathbf{d_{15} / 5}$

(based on theoretical and experimental work on arrangements of particles by Silveira, Wittmann, Witt, Kenney, etc.)

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The **opening size** of a filter (any type of filter) is defined as the diameter of the largest sphere that can pass through the filter.

In the 1970s, several criteria for "filter fabrics" were used, some of them inspired by Terzaghi's criteria.

This is an example of a set of criteria used in the early 1970s:

$$k_F > k_S$$

$$0.150 \text{ mm} < O_F < d_{85S}$$

$$4\% < \text{Open area} < 36\%$$

Early on, it was explicitly mentioned that **nonwoven** "filter fabrics" **should not be used**.

In any case,
many nonwoven fabrics
were eliminated
by the requirement: $O_F > 0.150$ mm
(which was even $O_F > 0.250$ mm
in an early stage)
and **all** nonwoven fabrics were eliminated
by the requirement: Open area < 36%.

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Progressively, the anti-nonwoven clauses disappeared.

However, the remaining criteria for **"filter fabrics"**:

$$k_F > k_S$$

$$O_F < d_{85S}$$

Open area > 4%

were not satisfactory, as we will discuss.

The terminology **"geotextile"** appeared in 1977, and it will be used in the rest of this lecture.

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In this lecture, I will:

- discuss problems related to the old criteria I just mentioned,
- present the development of proposed filter criteria, and
- discuss the application of the proposed criteria to geotextile filters and granular filters.

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Granular filters are well known.
Let's see examples of geotextiles filters.

EXAMPLES OF GEOTEXTILE FILTERS

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A geotextile filter
in a drainage trench
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A geotextile filter in landfill
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A geotextile filter in a dam

DEVELOPMENT
OF A
PERMEABILITY CRITERION
FOR
GEOTEXTILE FILTERS

AND APPLICATIONS
TO GRANULAR FILTERS

The presence of a filter
disturbs the flow of water
in the soil upstream of the filter.

The selected filter must be such
that the disturbance is small
and acceptable.

The disturbance can affect
the pore pressure and the flow rate.

Therefore, the permeability criterion includes two requirements:

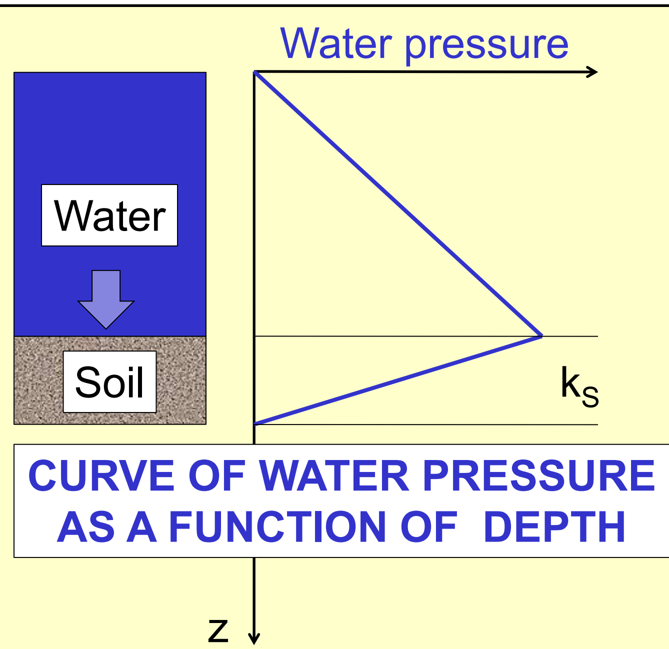
- a pore pressure requirement; and
- a flow rate requirement.

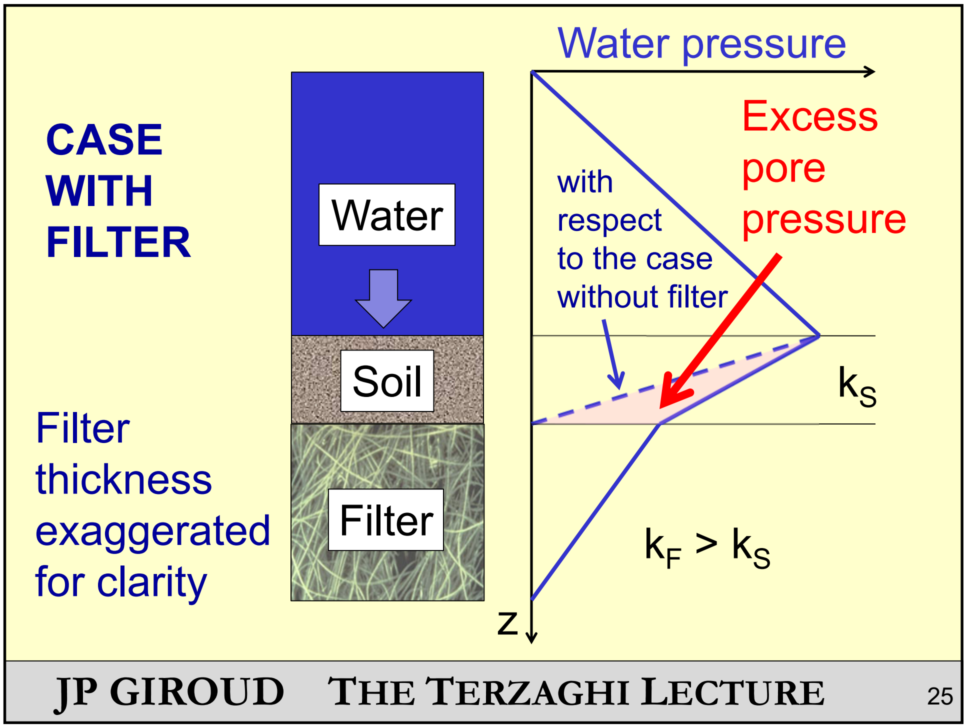
First, the pore pressure requirement:

The presence of a filter potentially increases the pore pressure in the soil upstream of the filter.

The selected filter should be such that the pore pressure increase is as small as possible, ideally zero.

CASE OF WATER FLOWING THROUGH A SOIL LAYER WITHOUT FILTER




CASE
WITH
FILTER
Filter
thickness
exaggerated
for clarity
Water
Soil
Filter
Water pressure
Excess
pore
pressure
with
respect
to the case
without filter
k_S
$k_F > k_S$
z
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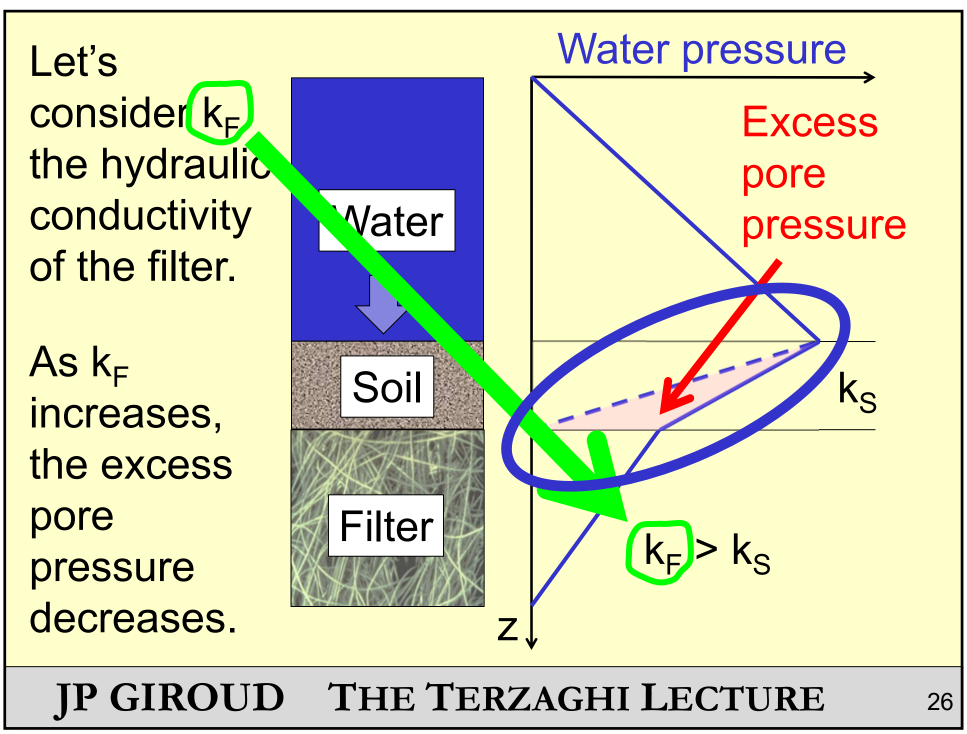
Let's
consider k_F
the hydraulic
conductivity
of the filter.
As k_F
increases,
the excess
pore
pressure
decreases.
Water
Soil
Filter
Water pressure
Excess
pore
pressure
k_S
$k_F > k_S$
z
JP GIROUD THE TERZAGHI LECTURE
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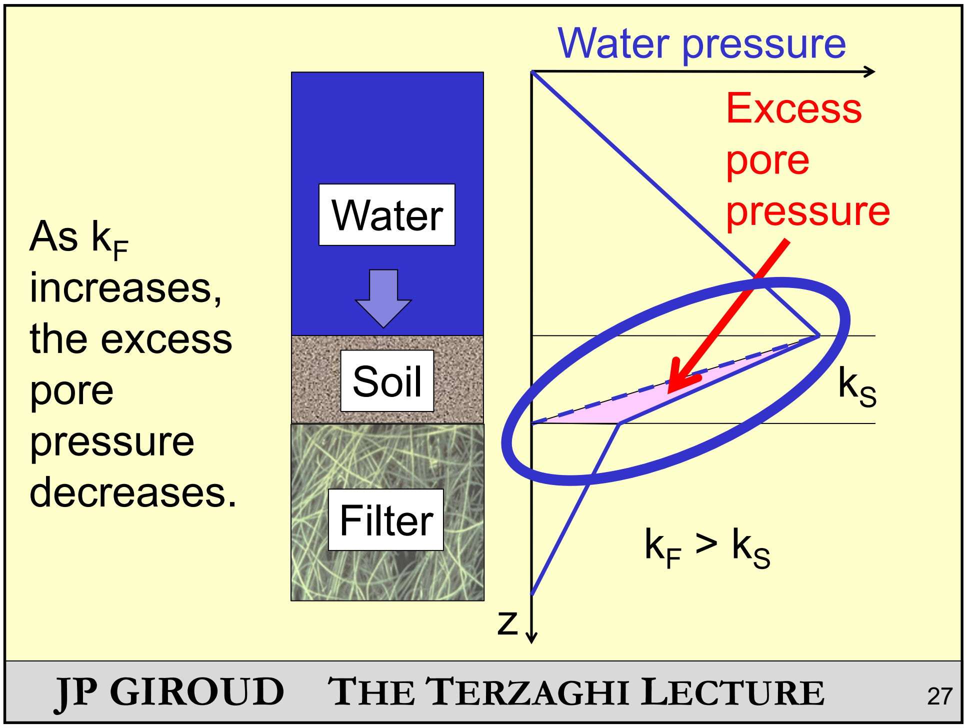
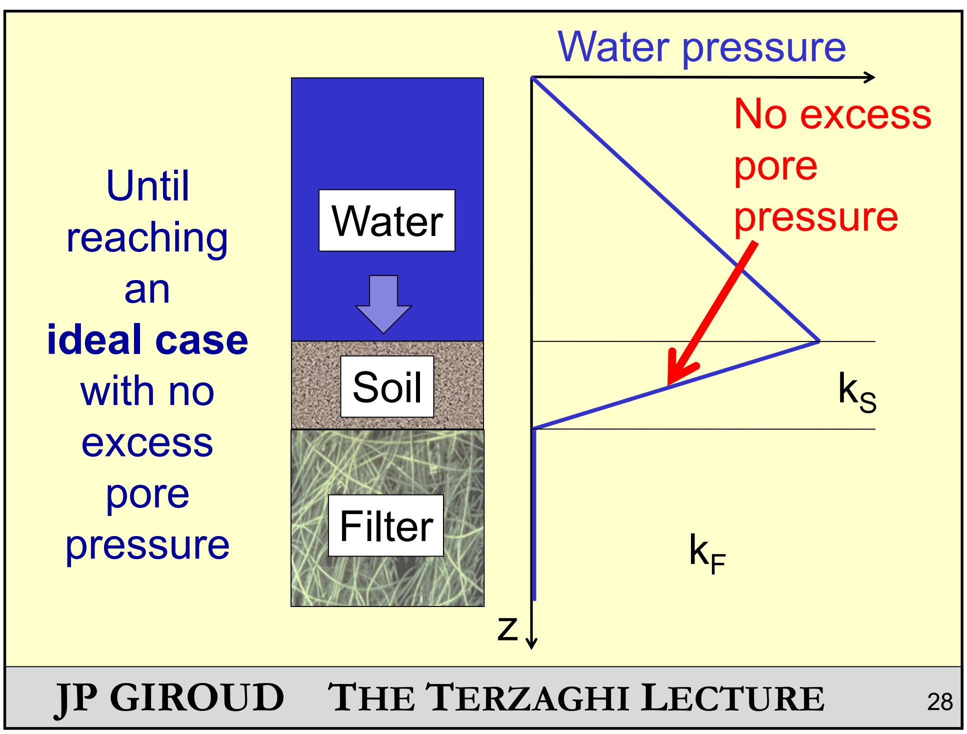

As k_F increases, the excess pore pressure decreases.
Water pressure
Excess pore pressure
Water
Soil
Filter
k_S
$k_F > k_S$
z
JP GIROUD THE TERZAGHI LECTURE
27


Until reaching an **ideal case** with no excess pore pressure
Water pressure
No excess pore pressure
Water
Soil
Filter
k_S
k_F
z
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PORE PRESSURE REQUIREMENT

The analysis of the pore pressure diagram shows that the presence of the filter causes no pore pressure increase if :

$$k_F \geq i_S\, k_S$$

where:
k_F = permeability of filter material
k_S = permeability of soil
i_S = hydraulic gradient in soil next to filter

TYPICAL HYDRAULIC GRADIENTS IN SOIL NEXT TO FILTERS

Application	Hydraulic gradient
Dewatering trench	≤ 1.0
Vertical wall drainage	1.5
Road edge drain	≤ 1.0
Inland waterway protection	≤ 1.0
Landfill drainage layer	1.5
Dam toe drain	2.0
Drain behind dam clay core	3 to >10
Liquid impoundment with clay liner	> 10

TYPICAL HYDRAULIC GRADIENTS IN SOIL NEXT TO FILTERS

Application	Hydraulic gradient
Dewat[illegible]	≤ 1.0
[illegible]	1.5
[illegible]	≤ 1.0
[illegible]	≤ 1.0
Landfi[illegible]	1.5
Dam to[illegible]	2.0
D[illegible]	3 to >10
Liquid impoundment with clay liner	> 10

Values are typically less than 2, with the exception of filters behind thin clay layers.

and rarely exceed 20.

The permeability criterion includes two requirements :

- a pore pressure requirement; and
- a flow rate requirement.

FLOW RATE REQUIREMENT

The presence of a filter, even very permeable, decreases the liquid flow rate compared with the case without filter.

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FLOW RATE REQUIREMENT

Calculations done with Darcy's equation show that the **flow rate decrease** is **less than 10% of the flow rate without filter if the following conditions are met:**

$k_F \geq k_S$ for a filter thickness 1 to 10 mm

$k_F \geq 25\ k_S$ for a filter thickness 250 to 2500 mm

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The 1 to 10 mm thickness applies to geotextile filters.

Therefore, the first condition:

$k_F \geq k_S$ for a filter thickness 1 to 10 mm

becomes: $k_F \geq k_S$ for geotextile filters

The 250 to 2500 mm thickness applies to granular filters.

Therefore, the second condition:

$k_F \geq 25\ k_S$ for a filter thickness 250 to 2500 mm

becomes: $k_F \geq 25\ k_S$ for granular filters

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DISCUSSION OF THE TWO REQUIREMENTS

PORE PRESSURE REQUIREMENT AND FLOW RATE REQUIREMENT

For GEOTEXTILE FILTERS

$k_F \geq k_S$ (flow rate requirement)
is **more stringent** or **less stringent** than
$k_F \geq i_S\ k_S$ (pore pressure requirement)
depending on hydraulic gradient.

For GRANULAR FILTERS

$k_F \geq 25\ k_S$ (flow rate requirement)
is generally **more stringent** than
$k_F \geq i_S\ k_S$ (pore pressure requirement)
because i_S *is generally less than* 25.

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It is important to note that
the flow rate requirement for granular filters
($k_F \geq 25\ k_S$)
can be expressed in terms of particle size.

Indeed, it is well known that
the permeability of a granular material
is **proportional to the square** of
a small particle size such as d_{10} or d_{15} :

$$k_F \approx \kappa\ (d_{15F})^2 \qquad k_S \approx \kappa\ (d_{15S})^2$$

[from the classical Hazen's equation, which is
a special case of Kozeny-Carman's equation.]

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Combining the three equations:

$$k_F \geq 25\ k_S \qquad k_F \approx \kappa\ (d_{15F})^2 \quad \text{and} \quad k_S \approx \kappa\ (d_{15S})^2$$

shows that

$k_F \geq 25\ k_S$ is equivalent to: $d_{15F} \geq 5\ d_{15S}$

This is the classical permeability criterion for granular filters.

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This discussion shows that the **classical permeability criterion** for granular filters, is only the **flow rate requirement**.

In other words, it does not include the **pore pressure requirement** (but it is generally **more stringent**).

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Therefore, there is a difference between geotextile filters and granular filters regarding the permeability criterion:

- In the case of **geotextile filters,** the **pore pressure** requirement or the **flow rate** requirement governs (*depending on hydraulic gradient*)**;**

  whereas

- In the case of **granular filters**, the **flow rate** requirement **(Terzaghi's criterion)** generally governs.

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Clearly, to develop
an appropriate permeability criterion
for geotextile filters,

it would have been
incorrect to simply imitate
Terzaghi's permeability criterion
for granular filters.

It is true that
Terzaghi's permeability criterion
provided a **starting point**
for the derivation
of a permeability criterion
for geotextile filters.

However, to extend to geotextile filters the work of Terzaghi on granular filters,

it was necessary to **thoroughly understand** the requirements related to water flow through a filter.

Now, the second criterion

DEVELOPMENT OF A RETENTION CRITERION FOR GEOTEXTILE FILTERS

AND APPLICATIONS TO GRANULAR FILTERS

RETENTION CRITERION FOR GEOTEXTILE FILTERS

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

A simple answer consists in adapting to geotextiles Terzaghi's retention criterion for granular filters:

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

It is known that $O_{FILTER} \approx d_{15FILTER} / 5$

Combining these two equations gives:

$$O_{FILTER} \leq d_{85\ SOIL}$$

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$$O_{FILTER} \leq d_{85\ SOIL}$$

- **This equation means that a filter should only retain large soil particles.**
- **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.

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Thus,
Terzaghi's retention criterion
is **incomplete**
because it does not take into account
the internal stability
of the soil retained by the filter.

However,
Terzaghi's retention criterion
has been **successfully used**
during decades for **granular filters**.

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There are two reasons for the success
of Terzaghi's retention criterion
in granular filter design.

The first reason is that,
to a certain degree,
granular filters function,
even if the soil lacks
internal stability,
because they are thick.

JP GIROUD THE TERZAGHI LECTURE 48

The mechanism is the following:

Particles that are not retained may accumulate in the filter, thereby decreasing the filter opening size, until the filter functions.

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

But, filter thickness alone does not explain the success of Terzaghi's retention criterion with granular filters.

The **second**, and most important, **reason** for the success of Terzaghi's retention criterion is that **its use has been limited to the most stable soils**,

i.e. soils with a maximum particle size less than a certain value, typically 4.75 mm.

hence, the practice of truncation of the particle size distribution curve, which will be discussed later.

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.

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In **internally stable** soils,
there are particles of a certain size
that form a **continuous skeleton**.

This continuous skeleton
entraps particles
that are a **little smaller**
than the skeleton particles.

In turn, these particles
entrap particles
that are a **little smaller**, and so on.

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Therefore, if a filter has openings such that the skeleton is retained, then all **particles smaller** than the skeleton particles **are retained**.

Also, particles **larger** than the skeleton particles **will be retained** because, if a filter retains certain particles, it will retain coarser particles.

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But, if a filter has **openings too large** to retain the skeleton, the soil is **not** retained because the particles retained in this case **do not form a continuous skeleton**.

In conclusion, a **filter** must have **openings** such that the skeleton is retained.

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This leads to two questions:

- What is the size of the skeleton particles?
- What is the maximum filter opening size that can retain a given skeleton?

JP GIROUD THE TERZAGHI LECTURE 55

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- What is the size of the skeleton particles?
- What is the maximum filter opening size that can retain a given skeleton?

JP GIROUD THE TERZAGHI LECTURE 56

**As mentioned earlier,
retention of the skeleton
is essential
for the retention
of an internally stable soil.**

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

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Geometric considerations show that,
in a soil
with a **coefficient of uniformity**
of approximately **3,**
particles are tightly interlocked.

**In other words, such a soil
has maximum internal stability.**

This is illustrated in the following slides.

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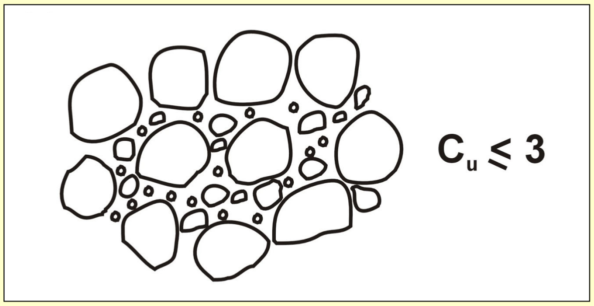
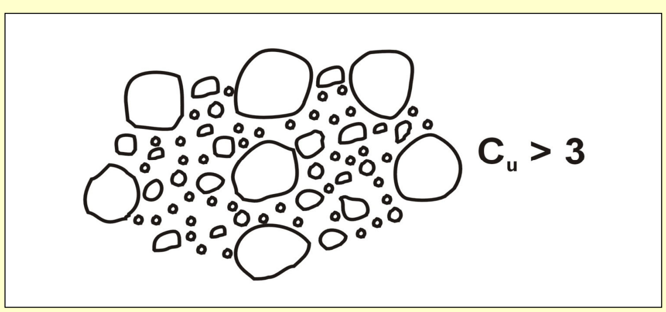
When a soil has a coefficient of uniformity **equal to or less than 3**, the coarsest particles form a **continuous skeleton** that entraps all other particles.



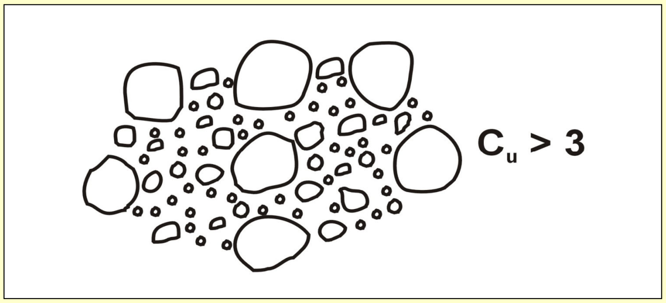
When a soil has a coefficient of uniformity **greater than 3**, the coarsest particles are **not in contact**.

As a result, they do not form a continuous skeleton that entraps other particles.

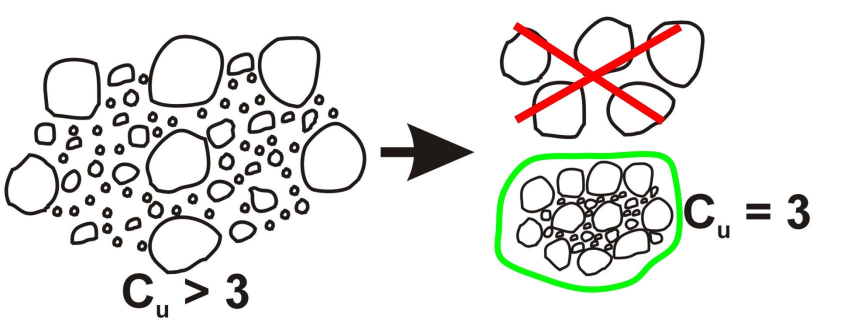


In other words, when a soil has
a coefficient of uniformity **greater than 3**,
the coarsest particles "**float**"
in the matrix formed by the other particles.

In this case, the coarsest particles
do not contribute to internal stability.

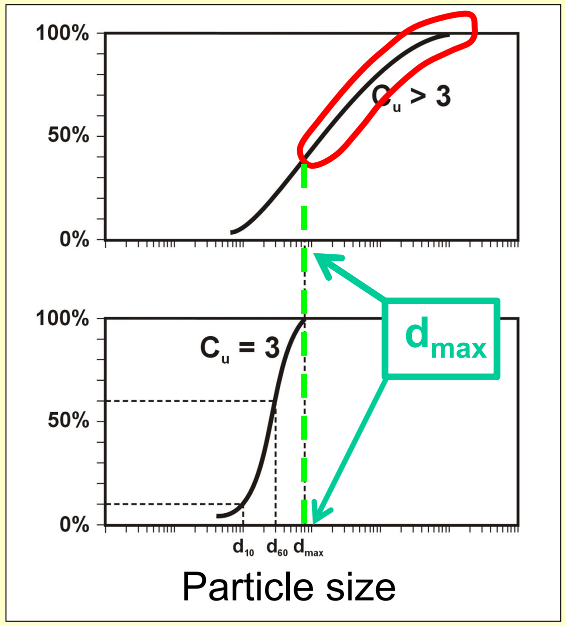


To develop a retention criterion for soils
having a coefficient of uniformity greater than 3,
we **only consider the fraction** of this soil
that has a coefficient of uniformity equal to 3.



In other words, we ignore the coarse fraction.

This means that we **truncate** the particle size distribution curve and consider only the particles smaller than d_{max} .



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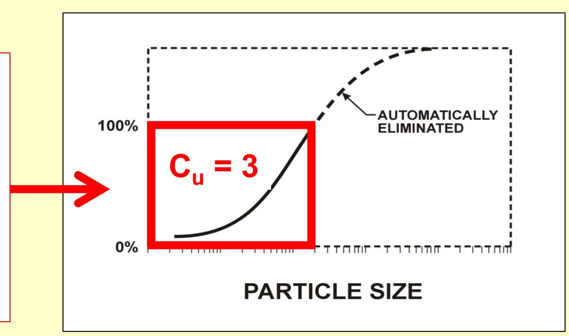
The user of the proposed retention criterion does not have to do the truncation.

The **truncation is done automatically** (it is included in the equations that express the retention criterion).

Only this fraction of the curve (with $C_u = 3$) is used in the criterion.



JP GIROUD THE TERZAGHI LECTURE 64

We answered the first of the two questions:

- **What is the size of the skeleton particles?**
- What is the maximum filter opening size that can retain a given skeleton?

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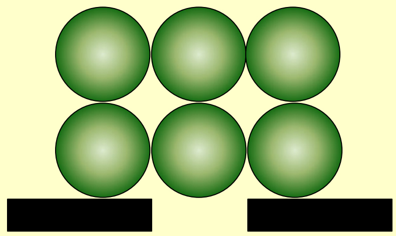
Let's answer the second of the two questions:

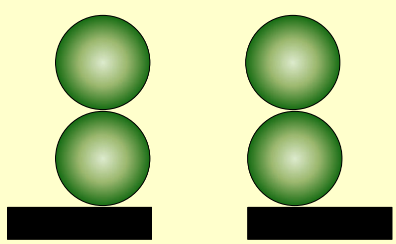
- What is the size of the skeleton particles?
- **What is the maximum filter opening size that can retain a given skeleton?**

JP GIROUD THE TERZAGHI LECTURE 66

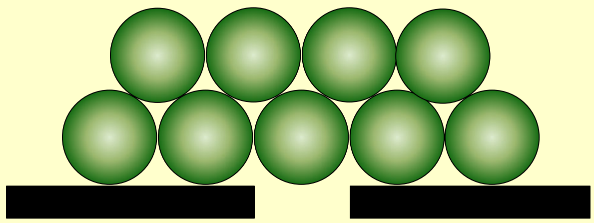
If the soil is in a **loose** state (represented by a cubic arrangement), particles pass if the opening size is **just larger** than particle size.



If the soil is in a **loose** state (represented by a cubic arrangement), particles pass if the opening size is **just larger** than particle size.



If the soil is in a **dense** state
(represented by an hexagonal arrangement),
particles do not pass if the opening size
is **as large** as particle size.



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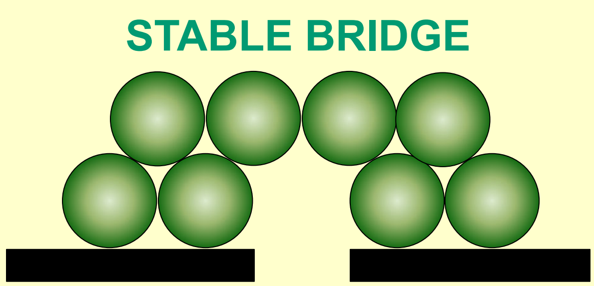
If the soil is in a **dense** state
(represented by an hexagonal arrangement),
particles do not pass if the opening size
is **as large** as particle size.



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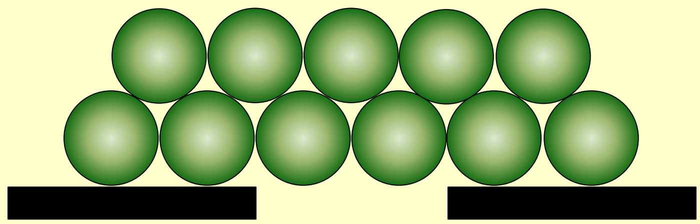
If the soil is in a dense state, particles pass if the opening size is twice as large as particle size.



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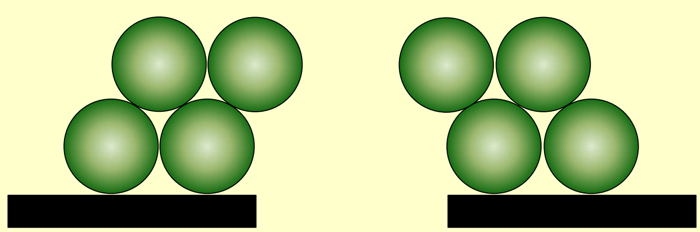
If the soil is in a dense state, particles pass if the opening size is twice as large as particle size.



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Based on this demonstration, the internal stability of a soil depends not only on its **coefficient of uniformity**, but also on its **density**.

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So far, in this lecture, the presentation of the retention criterion has been mostly qualitative,

but I have done a mathematical analysis of the role of the **coefficient of uniformity** and the **density** of soil.

Calculations, not presented here**, lead to the following equations.**

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RETENTION CRITERION EQUATIONS

Soil density (Relative density)	Linear coefficient of uniformity of the soil C'_u	
	$1 \le C'_u \le 3$	$C'_u \ge 3$
loose ($I_D \le 35\%$)	$O_F \le (C'_u)^{0.3} d_{85S}$	$O_F \le \frac{9}{(C'_u)^{1.7}} d_{85S}$
medium dense ($35\% < I_D \le 65\%$)	$O_F \le 1.5 (C'_u)^{0.3} d_{85S}$	$O_F \le \frac{13.5}{(C'_u)^{1.7}} d_{85S}$
dense ($I_D > 65\%$)	$O_F \le 2 (C'_u)^{0.3} d_{85S}$	$O_F \le \frac{18}{(C'_u)^{1.7}} d_{85S}$

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Here, the role of soil density

Soil density (Relative density)	Linear coefficient of uniformity of the soil C'_u	
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and here, the role of uniformity

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JP GIROUD THE TERZAGHI LECTURE 77

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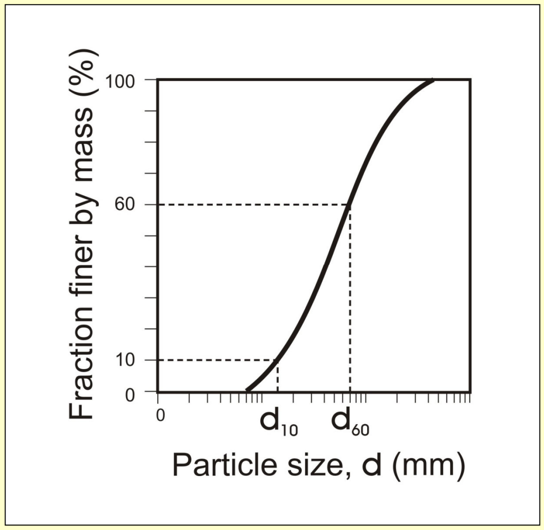
	$1 \le C'_u \le 3$	$C'_u \ge 3$
loose ($I_D \le 35\%$)	$O_F \le (C'_u)^{0.3} d_{85S}$	$O_F \le \frac{9}{(C'_u)^{1.7}} d_{85S}$
medium dense ($35\% < I_D \le 65\%$)	$O_F \le 1.5 (C'_u)^{0.3} d_{85S}$	$O_F \le \frac{13.5}{(C'_u)^{1.7}} d_{85S}$
dense ($I_D > 65\%$)	$O_F \le 2 (C'_u)^{0.3} d_{85S}$	$O_F \le \frac{18}{(C'_u)^{1.7}} d_{85S}$

In these equations, we use the linear coefficient of uniformity rather than the coefficient of uniformity to obtain simple equations.

JP GIROUD THE TERZAGHI LECTURE 78

All geotechnical engineers know the definition of the coefficient of uniformity.

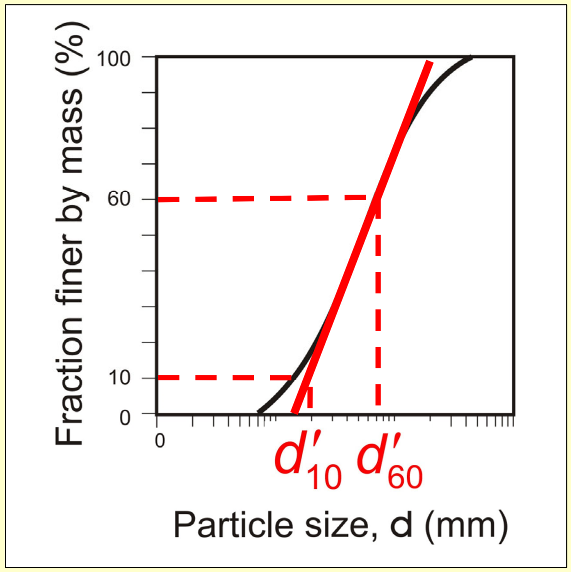
$$C_u = \frac{d_{60}}{d_{10}}$$



The linear coefficient of uniformity is defined using a straight line that closely follows the central part of the actual particle size distribution curve.

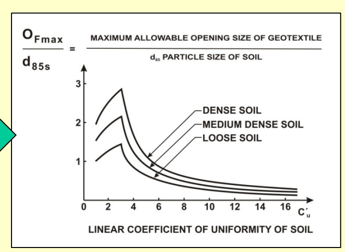
The linear coefficient of uniformity

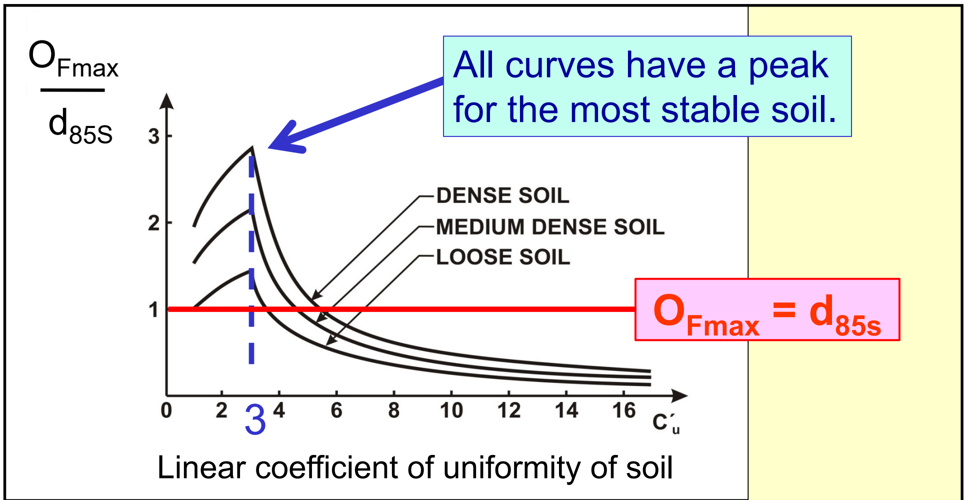
$$C'_u = \frac{d'_{60}}{d'_{10}}$$



The equations for the proposed retention criterion can be represented graphically.

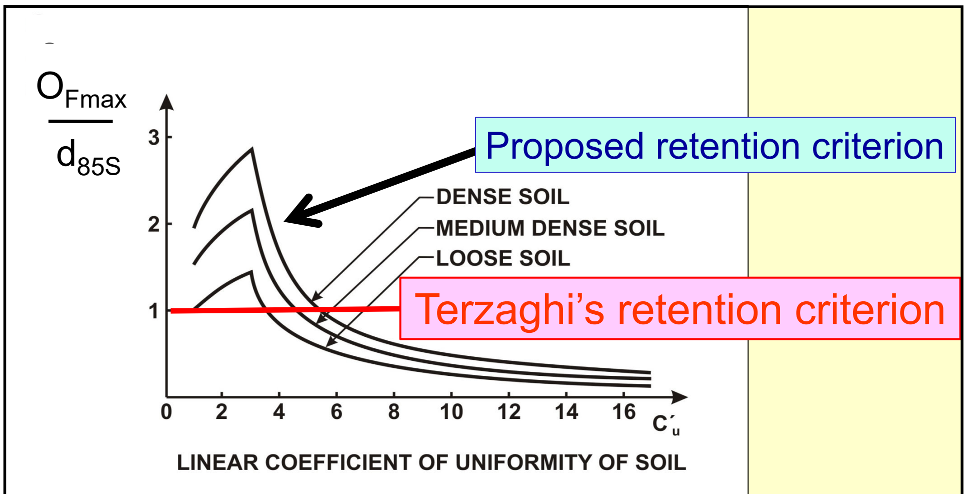
Soil density (Relative density)	Linear coefficient of uniformity of the soil C'_u: $1 \le C'_u \le 3$	$C'_u \ge 3$
loose ($I_D \le 35\%$)	$O_F \le (C'_u)^{0.3} d_{85S}$	$O_F \le \frac{9}{(C'_u)^{1.7}} d_{85S}$
medium dense ($35\% < I_D \le 65\%$)	$O_F \le 1.5 (C'_u)^{0.3} d_{85S}$	$O_F \le \frac{13.5}{(C'_u)^{1.7}} d_{85S}$
dense ($I_D > 65\%$)	$O_F \le 2 (C'_u)^{0.3} d_{85S}$	$O_F \le \frac{18}{(C'_u)^{1.7}} d_{85S}$





THE RED HORIZONTAL LINE REPRESENTS TERZAGHI'S RETENTION CRITERION, EXPRESSED IN TERMS OF OPENING SIZE.

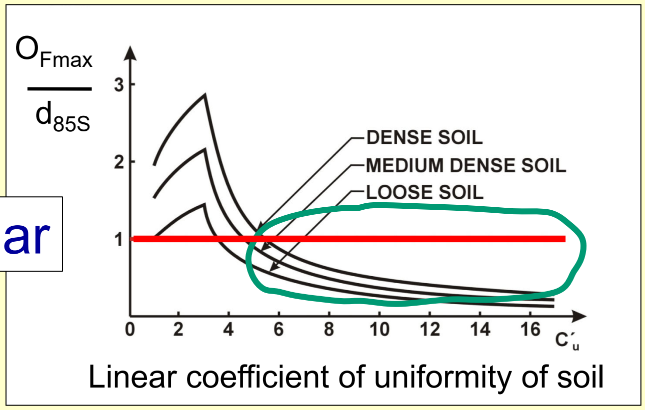
JP GIROUD THE TERZAGHI LECTURE 83



There is a significant difference between the two retention criteria.

JP GIROUD THE TERZAGHI LECTURE 84

In particular

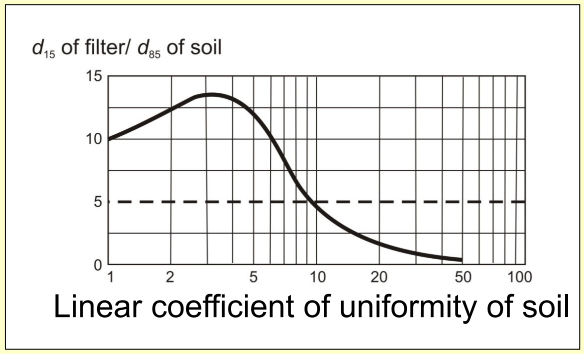


Using $O_{Fmax} = d_{85S}$ (the red line)
for soils having a **high coefficient of uniformity**,
allows filter openings that are too large,
hence a **risk of piping**.

**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.**

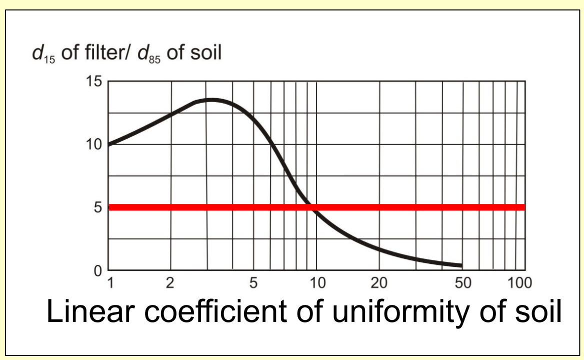
The retention criterion developed for geotextile filters has been extended for granular filters.



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

JP GIROUD THE TERZAGHI LECTURE 87

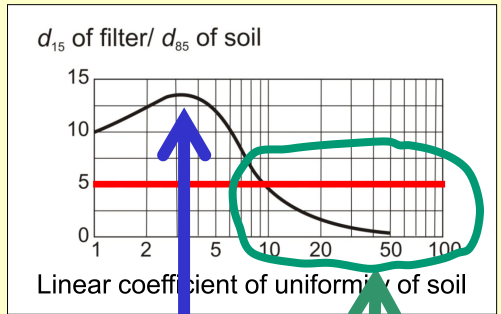
The retention criterion developed for geotextile filters has been extended for granular filters.



The Terzaghi's retention criterion is represented here by the horizontal line d_{15F} / d_{85S} = 5.

JP GIROUD THE TERZAGHI LECTURE 88

RETENTION CRITERION FOR GRANULAR FILTERS

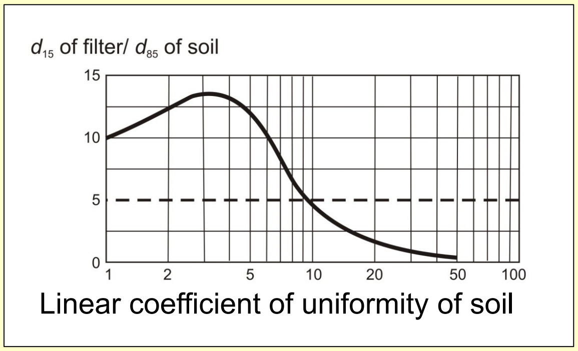


The values of d_{15F} / d_{85S} greater than 5
for uniform soils
are consistent with experimental data
by Bertram, Sherard and others.

And, for large coefficients of uniformity,
Terzaghi' criterion is unconservative.

It is for this reason that **truncation**
of the particle size distribution curve
is used for of granular filters.

Truncation artificially decreases
the coefficient of uniformity of the soil
to compensate for the fact that
Terzaghi's retention criterion
is unconservative
for large coefficients of uniformity.

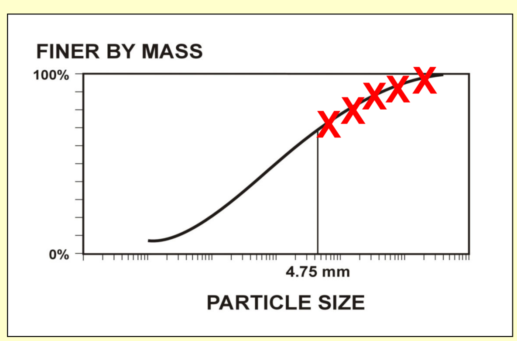


RETENTION CRITERION FOR GRANULAR FILTERS

- This retention criterion is applicable regardless of maximum particle size.
- In other words, it is not limited to particles smaller than 4.75 mm.

JP GIROUD THE TERZAGHI LECTURE 91

Therefore, the need for the potentially inaccurate operation of truncating particle size distribution curves at 4.75 mm is eliminated.



JP GIROUD THE TERZAGHI LECTURE 92

In fact, with
the proposed retention criterion,
truncation is done automatically
(in other words
it is included in the equations).

More importantly,
the automatic truncation
takes place
at the appropriate location,
which is generally not 4.75 mm.

JP GIROUD THE TERZAGHI LECTURE 93

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.

JP GIROUD THE TERZAGHI LECTURE 94

So far we have discussed the use for geotextile filters of the two criteria used for granular filters:

- **the permeability criterion; and**
- **the retention criterion.**

But, two additional criteria are needed for geotextile filters.

Indeed, since there are almost unlimited possibilities in geosynthetic manufacturing, it is possible to imagine **extreme geosynthetics materials** that would be unlikely to perform properly as filters, such as:

- geosynthetics with very few openings,
- some extremely thin nonwoven geotextiles.

Criteria are needed to prevent the use as filters of such extreme materials.

Therefore, for geotextile filters, two additional criteria are needed:

- **a criterion to ensure that the number of openings is sufficient;**
- **a criterion to ensure that the filter thickness is sufficient.**

First, let's discuss the criterion for number of openings.

We will see that the criterion that ensures that *"the number of filter openings is sufficient"* **results in a porosity criterion.**

DEVELOPMENT OF A POROSITY CRITERION FOR GEOTEXTILE FILTERS

Flow of liquids
through porous media,
such as granular or fibrous filters,
takes place in **tortuous channels**.

These channels
are called **flow channels**.

It is possible to demonstrate that
the number of flow channels
per unit area
is **greater in the soil** than in a filter
that meets the retention criterion
for that soil.

As a result, the flow of liquid is **disturbed**
at the soil-filter interface
due to **flow concentration**
into a smaller number of flow channels.

JP GIROUD THE TERZAGHI LECTURE 101

Disturbance of the flow
at the soil-filter interface
could cause displacement
of fine soil particles
in the vicinity of the filter,

which could result in
accumulation of fine soil particles
at the surface of the filter
or inside the filter.

JP GIROUD THE TERZAGHI LECTURE 102

This **accumulation** of fine particles could cause clogging of the soil-filter system.

Therefore, the number of flow channels in the filter per unit area should be **as large as possible** in order to **minimize disturbance** of the flow of liquid from the soil (retained by the filter) to the filter.

JP GIROUD THE TERZAGHI LECTURE 103

There is an additional reason for the number of flow channels in the filter per unit area to be **as large as possible**.

JP GIROUD THE TERZAGHI LECTURE 104

In spite of the presence
of a properly designed filter,
there is **always the possibility**
that some fine soil particles will move.

If such fine particles
clog some flow channels in the filter,
their **impact** on flow rate
will be reduced
if the **number of flow channels**
in the filter per unit area is **larger**.

JP GIROUD THE TERZAGHI LECTURE 105

Depending on the filter structure,
the number of **flow channels**
is equal, or proportional,
to the number of **filter openings**.

Therefore, to achieve
a large number of flow channels,
a filter should have
as many openings as possible
per unit area.

JP GIROUD THE TERZAGHI LECTURE 106

It should be noted that many **geotextiles are so permeable** that, even if a geotextile has a small number of openings per unit area, it may still meet the permeability criterion.

Clearly, the **permeability criterion is not sufficient** to eliminate geotextile filters that do not have enough openings.

Therefore, **a criterion specific to the number of openings per unit area** is needed.

JP GIROUD THE TERZAGHI LECTURE 107

I do not know a rational analysis of the required number of filter openings.

The only guidance is that we know that granular filters work.

JP GIROUD THE TERZAGHI LECTURE 108

Thus, it may be assumed that **if**
the **number of filter openings**
in a **geotextile** filter
is equal to, or greater than,
the **number of filter openings**
in a typical **granular** filter
then the geotextile filter
should work, i.e. should have
a **sufficient number of openings**.

JP GIROUD   THE TERZAGHI LECTURE   109

Therefore,
the **first step** of the analysis
is to determine
the **number of filter openings**
in a typical **granular** filter.

The number of openings
depends on
the **geometric characteristics**
of the granular filter.

JP GIROUD   THE TERZAGHI LECTURE   110

Herein, we will express
the number of openings
as a function of
one of its geometric characteristics:
the **opening size**.

This will make it possible
to **objectively** compare
geotextile filters and granular filters
having the **same** opening size.

JP GIROUD THE TERZAGHI LECTURE 111

Calculations show that the number of openings per unit area is approximately:

$$N \approx \frac{0.1}{(O_F)^2}$$

for typical granular filters

where O_F = filter opening size

This will be used as a minimum value
for the number of openings per unit area
for geotextile filters.

JP GIROUD THE TERZAGHI LECTURE 112

Calculations show that the number of openings per unit area is:

$$N = \frac{A_R}{(O_F)^2}$$

for **woven geotextiles**

where A_R = relative open area (open area / total area)

Comparing with:

$$N = \frac{0.1}{(O_F)^2}$$

for granular filters

gives the **following condition** for woven geotextiles :

$$A_R = 0.1$$

Therefore,
the relative open area
of a woven geotextile filter
should be equal to or greater than 0.1

to ensure that
the **number of openings**
in the woven geotextile filter
is **at least equal**
to the **number of openings**
in a granular filter
having the same opening size.

In the case of
nonwoven geotextile filters,
the determination of
the number of openings per unit area
is difficult.

Only an **approximate calculation**
has been done, and only
lower and an upper boundaries
were obtained.

JP GIROUD THE TERZAGHI LECTURE 115

Here are the lower and upper boundaries, for the number of openings per unit area in nonwoven geotextile filters:

$$\frac{\left(1-\sqrt{1-n}\right)^2}{\left(O_F\right)^2} \leq N \leq \frac{4\left(1+0.4n-\sqrt{1-n}\right)^2}{\sqrt{3}\left(O_F\right)^2}$$

where n = porosity of the nonwoven geotextile

Comparing with:

$$N = \frac{0.1}{\left(O_F\right)^2}$$

for granular filters

and . . .

JP GIROUD THE TERZAGHI LECTURE 116

performing calculations for a wide range of values of the porosity, *n*,
give a **conservative criterion**,
which ensures that
the **number of openings**
in the nonwoven geotextile filter
is **at least equal**
to the **number of openings**
in a granular filter
having the same opening size.

The **conservative criterion** is that
the **porosity**
of a nonwoven geotextile filter
should be
equal to or greater than **0.55**.

In conclusion, the two criteria are:

$A_R \geq 0.1$ for woven geotextiles

and

$n \geq 0.55$ for nonwoven geotextiles

The relative open area of a woven geotextile (A_R) is the **two-dimensional equivalent of porosity** (n).

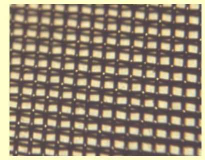
Therefore, the two criteria can be grouped under the terminology "**porosity criteria**".

JP GIROUD THE TERZAGHI LECTURE 119

Since the criteria
for the two types of geotextile filters
are of the **same** nature,
one may wonder why
the numerical values
are so **different**:
0.10 for **woven** geotextile filters
0.55 for **nonwoven** geotextile filters.

JP GIROUD THE TERZAGHI LECTURE 120

The reason is that,
in **woven** geotextile filters,
most of the pore space
is used for flow,



whereas in **nonwoven** geotextile filters,
a significant fraction
of the pore space
is not used for flow.

The case of **granular** filters is intermediate,
because **particles** occupy
a larger faction of the pore space
than **fibers** of a nonwoven geotextile.

JP GIROUD THE TERZAGHI LECTURE 121

As a result, among filters
having the same opening size,
the **same number of openings** per unit area
is achieved by:

- **Woven** geotextile filters with a relative open area (i.e. *two-dimensional porosity*) of **10%**
- **Granular** filters with a porosity of **20-30%**
- **Nonwoven** geotextile filters with a porosity of **55%**

JP GIROUD THE TERZAGHI LECTURE 122

The porosity criterion
has never been formulated
for **granular filters**
because all granular filters
have approximately the same porosity.

In contrast, the porosity criterion
is important for **geotextile filters**,
because there is
a **wide range** of porosities,
from 0.01 for some **woven** geotextiles
to 0.92 for some **nonwoven** geotextiles.

JP GIROUD THE TERZAGHI LECTURE 123

Based on the analysis,
woven geotextiles with
a **relative open area less than 0.1**
should not be used as filters.

However,
many **woven geotextiles** have
a relative open area less than 0.1;
and some of them are used as filters
. . . with a high risk of clogging.

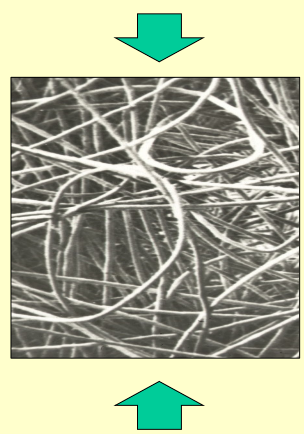
JP GIROUD THE TERZAGHI LECTURE 124

All **nonwoven geotextiles** (even subjected to compressive stress) **meet the porosity criterion** ($n \geq 0.55$), because their porosity is typically 0.7-0.9 (uncompressed) and 0.6-0.8 (compressed).

In fact, in the case of nonwoven geotextile filters, the porosity criterion should be applied to **uncompressed** geotextiles.

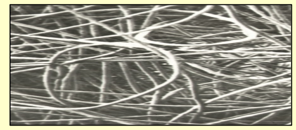
JP GIROUD THE TERZAGHI LECTURE 125

Indeed, a compressive stress normal to the plane of a nonwoven geotextile **does not change the number of openings**,



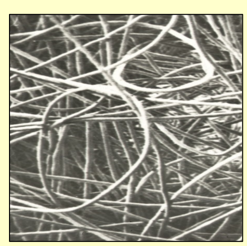
JP GIROUD THE TERZAGHI LECTURE 126

Indeed, a compressive stress
normal to the plane
of a nonwoven geotextile
does not change
the number of openings,



Indeed, a compressive stress
normal to the plane
of a nonwoven geotextile
does not change
the number of openings,

and the calculations
presented earlier in this lecture
were performed
for a **quasi isotropic** geotextile,
which is representative of the
uncompressed state
of a nonwoven geotextile.



Remember that, for geotextiles, two additional criteria are needed:

- **a criterion to ensure that the number of openings is sufficient;**
- **a criterion to ensure that the filter thickness is sufficient.**

The discussion of filter thickness will address nonwoven geotextile filters and granular filters.
(*Woven geotextile filters will not be considered because thickness is not relevant in their case*.)

DEVELOPMENT OF A THICKNESS CRITERION FOR GEOTEXTILE FILTERS

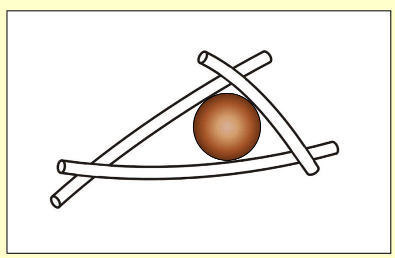
(NONWOVEN GEOTEXTILES ONLY)

To understand the role of filter **thickness**, it is necessary to understand how a soil particle travels through a filter.

A soil particle that travels through a filter (any filter, granular or geotextile) must go through **narrow passages** called **constrictions**.

(*A terminology proposed by Kenney*.)

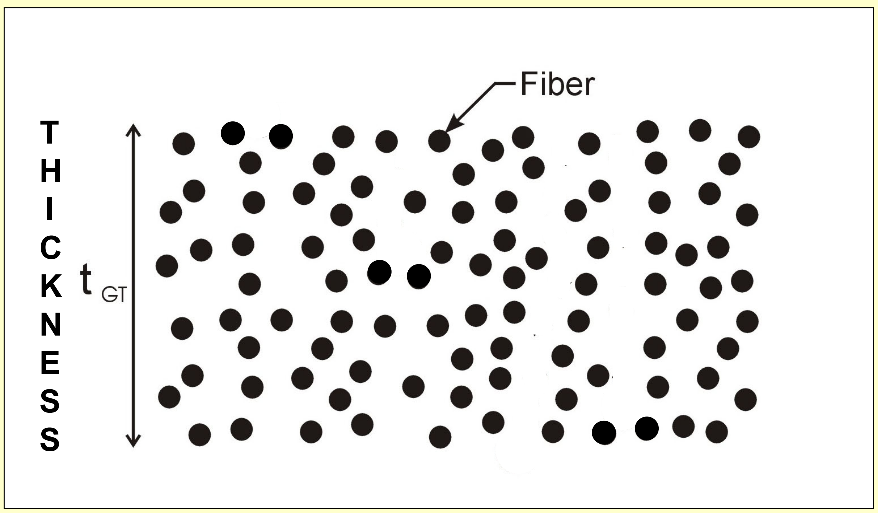
In the case of a geotextile filter, a constriction is a passage between fibers.



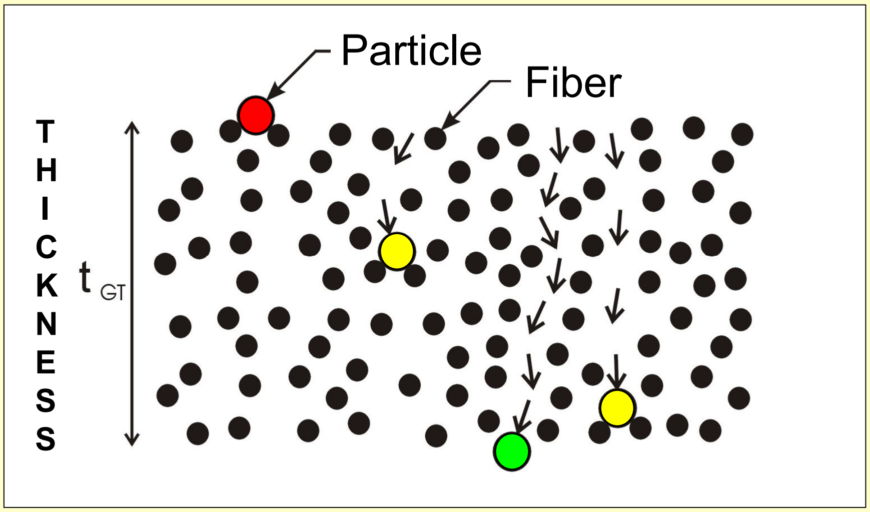
The **size of a constriction** is the **diameter** of the **largest spherical particle** that passes through the constriction.

A **soil particle**
that travels through a filter
moves from one constriction
to another,
thereby following a **filtration path**
(*which is identical to a flow channel*).

The particle will be stopped
or will pass
depending on the size of constrictions
along the filtration path.



SCHEMATIC CROSS SECTION OF A NONWOVEN GEOTEXTILE FILTER



Particles can be stopped on top (RED), stopped inside (YELLOW) or pass (GREEN).

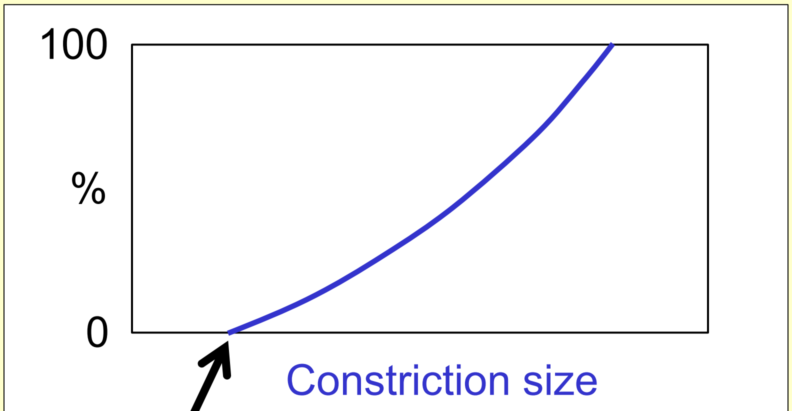
JP GIROUD THE TERZAGHI LECTURE 135

Consider the **nonwoven material** used to make a nonwoven geotextile.

This **material** is characterized by a constriction size distribution curve.

JP GIROUD THE TERZAGHI LECTURE 136

CONSTRICTION SIZE DISTRIBUTION CURVE



An important point on the curve is the smallest constriction size.

JP GIROUD THE TERZAGHI LECTURE 137

The **constriction size distribution curve** is a characteristic of the **material** from which the geotextile is made.

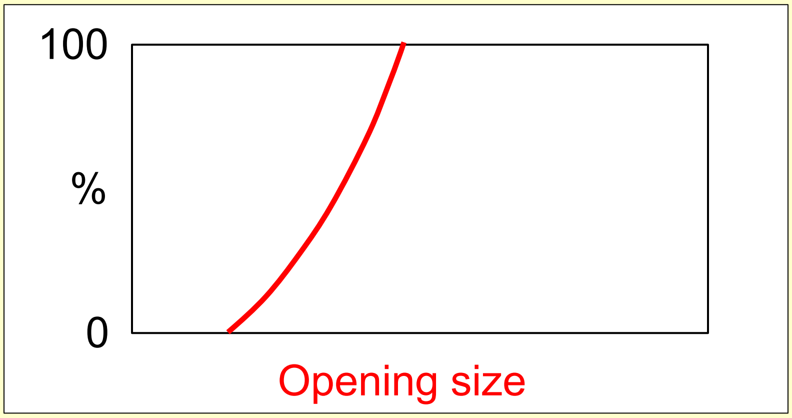
The **constriction size distribution curve** **is not** a characteristic of the geotextile.

A geotextile filter, i.e. a nonwoven material **with a given thickness**, is characterized by another curve.

A geotextile filter is characterized by an **opening size distribution curve**.

JP GIROUD THE TERZAGHI LECTURE 138

OPENING SIZE DISTRIBUTION CURVE



Why is there a curve and not a **single value** of the opening size (as for granular filters)?

This is a legitimate question because, so far in this lecture, each geotextile filter has been characterized by a **unique opening size**.

To answer this question,
a long demonstration is needed.

Each filtration path contains
a number of constrictions.

A soil particle can go through the filter
if it is smaller than
the **smallest constriction** in a path.

Therefore,
each filtration path is characterized
by the **smallest constriction**
that exists in that path.

JP GIROUD THE TERZAGHI LECTURE 141

Thus, the **smallest constriction**
in a **given filtration path**
is the **opening size** of that filtration path.

In general, the smallest constriction
is **different** in each filtration path.

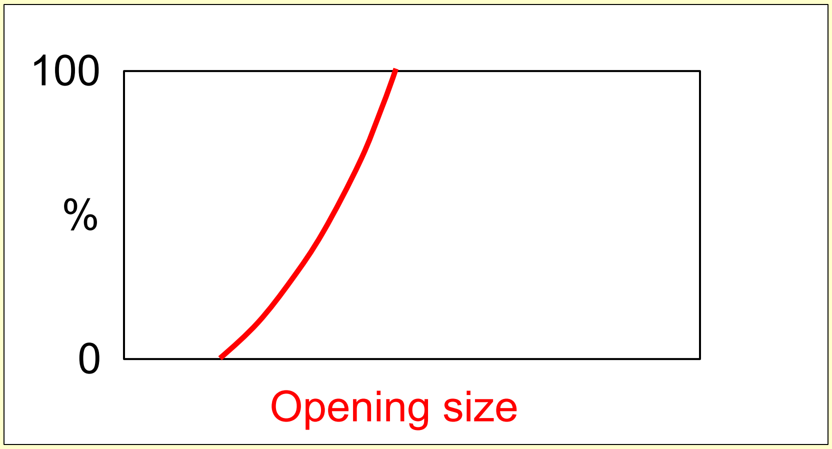
Therefore, each filtration path
has a **different** opening size.

As a result, a filter is characterized by
an **opening size distribution curve**.

JP GIROUD THE TERZAGHI LECTURE 142

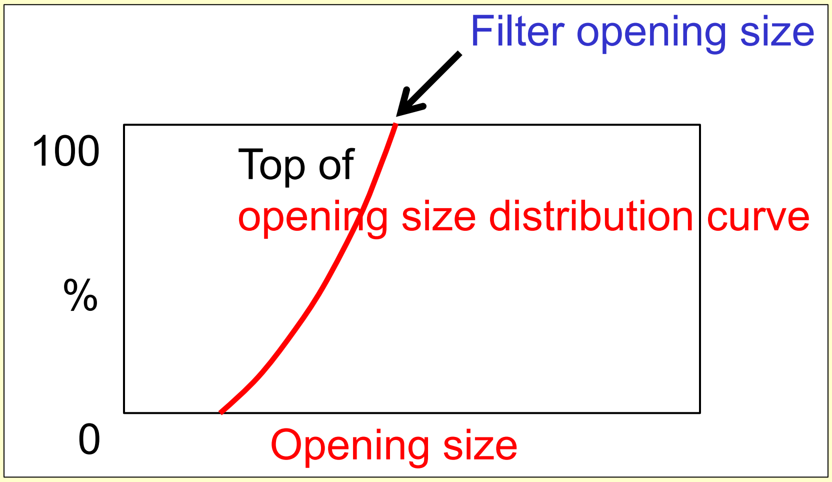
Here again is the

OPENING SIZE DISTRIBUTION CURVE OF A FILTER



Knowing that
the **opening size of a filter**
is defined as the diameter
of the largest sphere
that can pass through the filter,
it is possible to **visualize**
the opening size of the filter
on the
opening size distribution curve.

The **opening size of the filter** is naturally the largest opening size of the filtration paths.



JP GIROUD THE TERZAGHI LECTURE 145

What is the relationship between
the **opening size distribution curve**
(which characterizes a **filter**
with a given thickness)

and

the **constriction size distribution curve**
(which characterizes the filter **material**)?

Geometric considerations must be made.

JP GIROUD THE TERZAGHI LECTURE 146

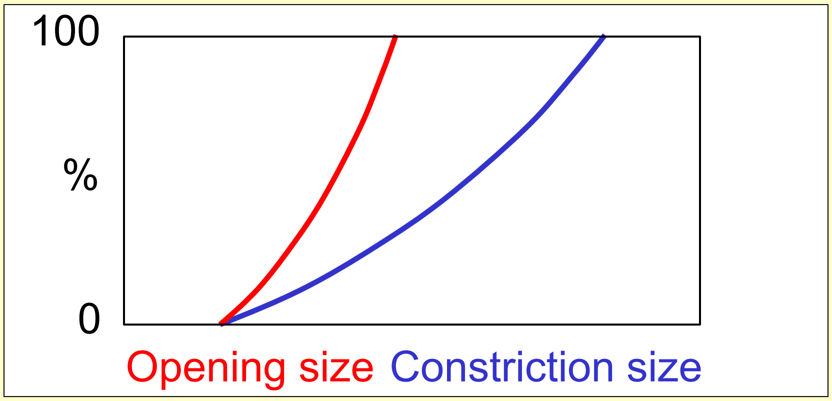
Geometric considerations:

- In a filter (granular or geotextile), there is a very large number of filtration paths (millions per m^2).
- In a nonwoven geotextile filter, due to the limited thickness, there are not many constrictions in each filtration path (10 to 100).

Statistically the conclusion is:

- The smallest
  filtration path opening size
  is
  the smallest constriction size.
- The largest
  filtration path opening size
  is not
  the largest constriction size.

Accordingly, the two curves have the same origin, but not the same top.



This demonstration may seem too quick,
but it is easier to understand using limit cases.

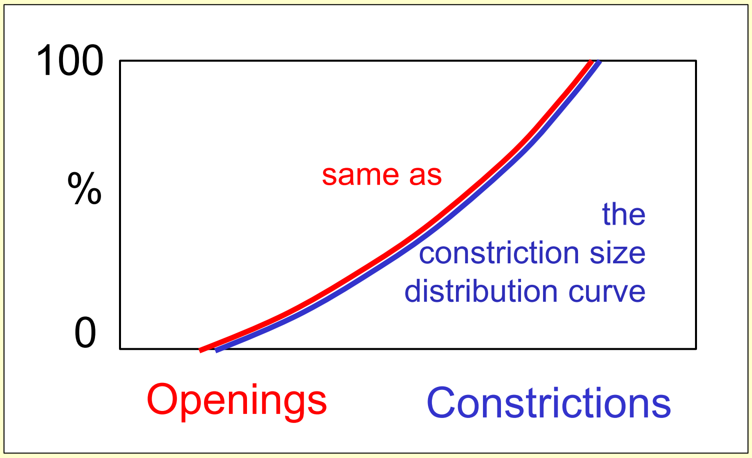
FIRST LIMIT CASE

If a filter has **quasi-zero thickness**,
there is only
one constriction per filtration path.

Therefore, in this case,
the opening size distribution curve
is the same as
the constriction size distribution curve.

FIRST LIMIT CASE

OPENING SIZE DISTRIBUTION CURVE FOR AN INFINITELY THIN GEOTEXTILE



SECOND LIMIT CASE

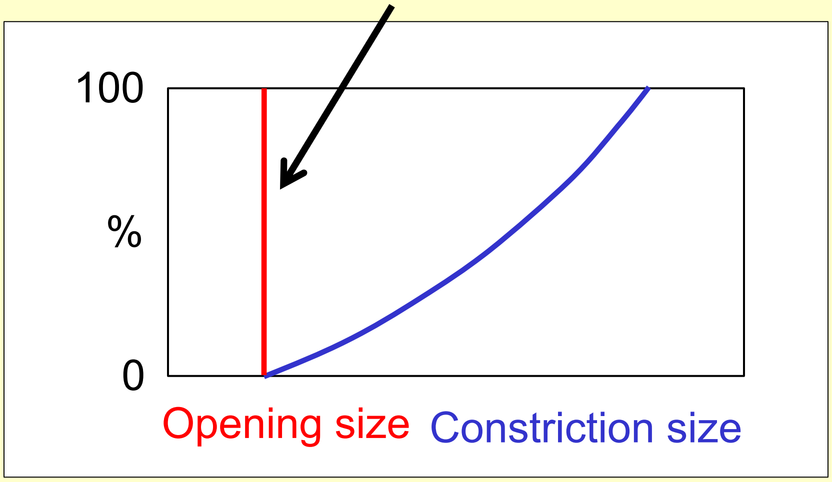
If a filter has **infinite thickness**, the probability for having the **smallest constriction** in every filtration path is 100%.

As a result, all the filtration paths have the **same opening size**, which is the smallest constriction size.

Therefore, in this case, the opening size distribution curve is a **vertical line**.

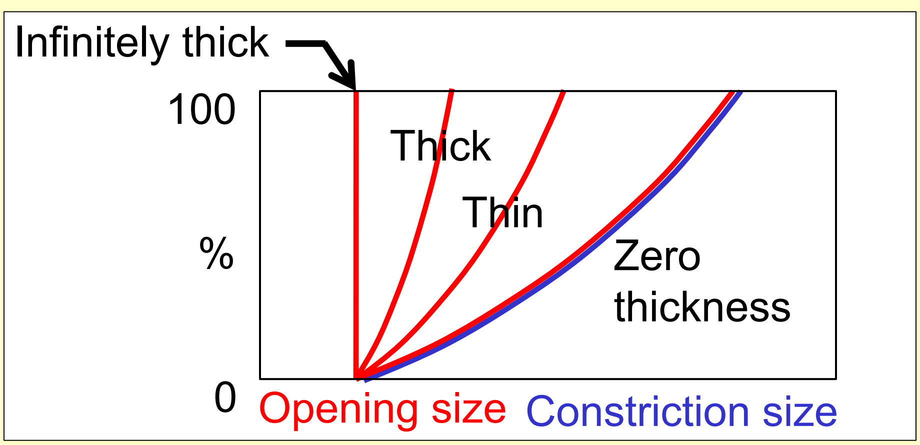
SECOND LIMIT CASE

OPENING SIZE DISTRIBUTION CURVE FOR INFINITELY THICK GEOTEXTILE



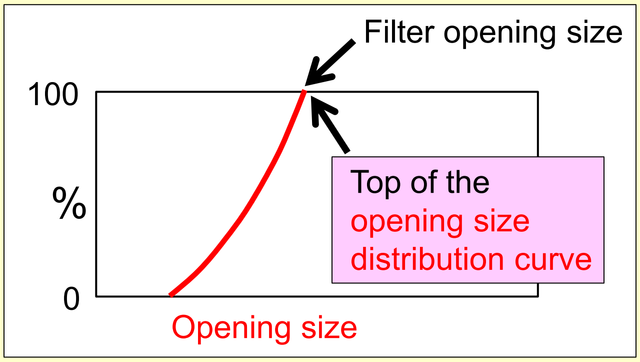
JP GIROUD THE TERZAGHI LECTURE 153

Consider nonwoven geotextile filters made of the same nonwoven material. These filters (which differ only by thickness) **are between the two limit cases.**



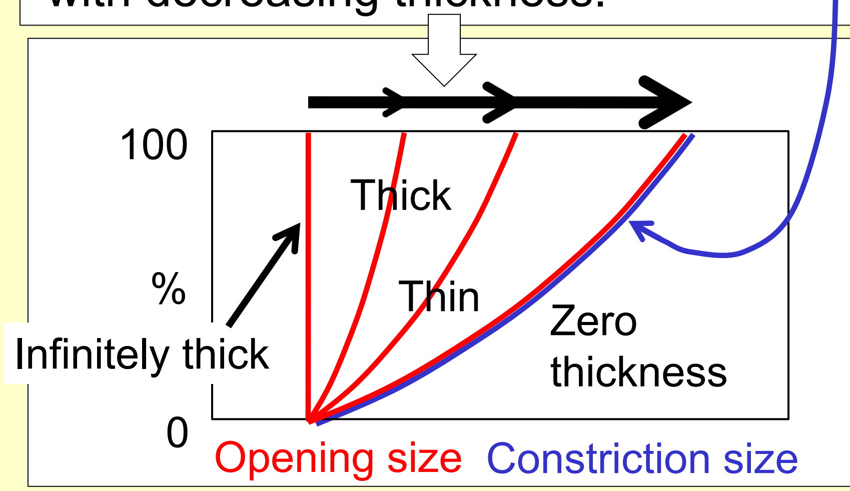
JP GIROUD THE TERZAGHI LECTURE 154

And, since the opening of a filter
is the **top** of
the opening size distribution curve . . .



it is possible to infer that . . .

For filters made of the **same material**,
the **opening size** increases
with decreasing thickness.



IMPORTANT CONCLUSION

For a given filter **material**
(characterized by a unique
constriction size distribution curve)**,**
the opening size of a filter depends on its thickness.

In fact, the opening size decreases for increasing values of the thickness of the filter.

This is true for all types of filters , but . . .

From a practical standpoint,
there is a major difference
between **nonwoven geotextile filters**
and **granular filters**.

Granular filters have
a **quasi-infinite thickness**.

Therefore **granular filters**
made from the same granular material
have an **opening size**
that does not depend on thickness.

From a practical standpoint,
there is a major difference
between **nonwoven geotextile filters**
and **granular filters**.

Whereas
nonwoven geotextile filters
made from the same nonwoven material
have an opening size
that depends on thickness.

So far, in this lecture, the impact
of **geotextile thickness**
on filter opening size
has been discussed qualitatively.

However, this impact
can be evaluated quantitatively.

I have proposed this relationship between nonwoven geotextile **opening size** and nonwoven geotextile **thickness.**

$$\frac{O_F}{d_f} \approx \frac{1}{\sqrt{1-n}} - 1 + \frac{10n}{(1-n)\,t_{GT}/d_f}$$

O_F = opening size; t_{GT} = geotextile thickness;
n = porosity of the geotextile; d_f = fiber diameter

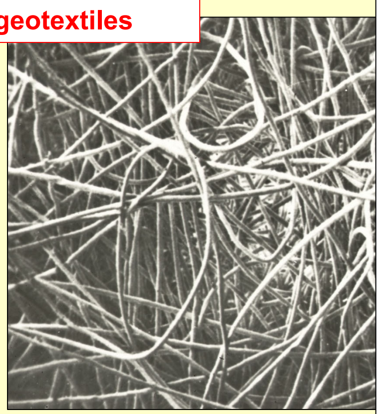
Equation developed theoretically and checked using experimental data

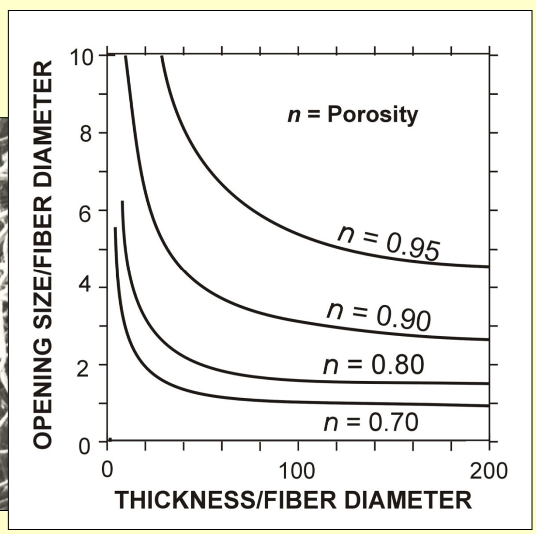
JP GIROUD THE TERZAGHI LECTURE 161

The relationship is a **family of curves** that give

Opening size/Fiber diameter vs. Geotextile thickness/Fiber diameter

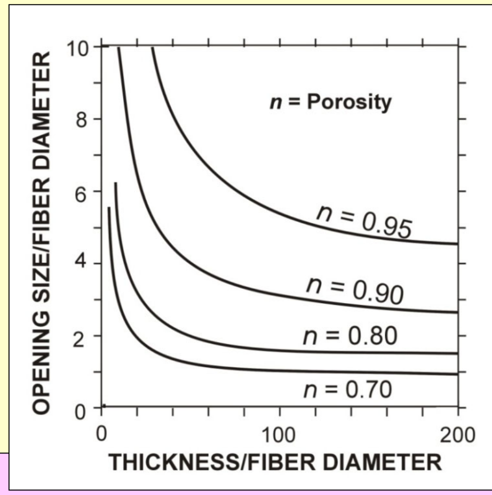
For nonwoven geotextiles





JP GIROUD THE TERZAGHI LECTURE 162

Consistent with what we have just discussed, we see on the graph that:



For a given porosity
(i.e. for a given nonwoven material under a given normal stress),
the geotextile filter **opening size decreases**
for increasing values of the geotextile **thickness**.

JP GIROUD THE TERZAGHI LECTURE 163

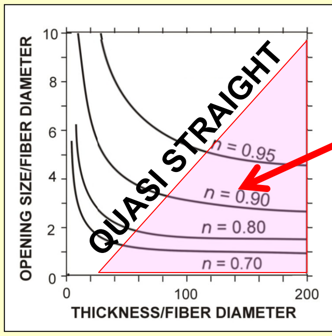
Based on the same analysis:

The **number of constrictions** through a nonwoven geotextile filter can be calculated using:

$$N_{constrictions} = \frac{\mu_{GT}}{\rho_f \, d_f \sqrt{1-n}}$$

where:
μ_{GT} = mass per unit area of geotextile
n = porosity of geotextile
ρ_f = fiber density
d_f = fiber diameter

JP GIROUD THE TERZAGHI LECTURE 164



Zone of the graph with more than 25 constrictions

In this zone, the curves are relatively flat (close to the asymptote).

A parametric study of the curves has shown that, beyond a geotextile thickness containing approximately **25 constrictions**, the opening size is not significantly affected by changes in geotextile thickness.

JP GIROUD THE TERZAGHI LECTURE 165

Therefore, to be reliable, a nonwoven geotextile filter should have a thickness that corresponds to at least 25 constrictions.

This is the thickness criterion.

It is **convenient to express the thickness in terms of numbers of constrictions**, so the criterion is independent of geotextile porosity and fiber diameter.

The ASTM standard D 7178 on filters uses this work.

JP GIROUD THE TERZAGHI LECTURE 166

In summary, **four filter criteria** have been established for geotextile filters:

- Permeability criterion
- Retention criterion
- Porosity criterion
- Thickness criterion

A last question is . . .

JP GIROUD THE TERZAGHI LECTURE 167

Do the four criteria form a complete set of filter criteria?

- Filtration is governed by filter openings.
- The characteristics of filter openings are the **size**, **shape**, **density** (number per unit area) and **distribution**.
- The four criteria address three of these four characteristics: the **size**, **density** and **distribution**.

JP GIROUD THE TERZAGHI LECTURE 168

Do the four criteria form a complete set of filter criteria?

- The **shape** of filter openings is not addressed in the four criteria.
- The shape of filter openings is likely to be a **minor consideration** in the case of materials with a **quasi-random structure** such as **granular** filters and **nonwoven geotextile** filters.

JP GIROUD THE TERZAGHI LECTURE 169

Do the four criteria form a complete set of filter criteria?

- In contrast, the shape of openings may be a relevant issue in the case of some **woven geotextiles** and some other types of man-made filters (such as perforated plates).

JP GIROUD THE TERZAGHI LECTURE 170

Do the four criteria form a complete set of filter criteria?

- Clearly, more work is needed on the impact of the shape of filter openings on the performance of filters.
- In the meantime, the set of four criteria discussed in this lecture can be considered complete, at least for granular and nonwoven filters.

JP GIROUD THE TERZAGHI LECTURE 171

Furthermore,
the set of four criteria
discussed in this lecture
is a **coherent set of criteria**,
because it addresses only
parameters that are **relevant**
to the filtration function.

JP GIROUD THE TERZAGHI LECTURE 172

Other types of requirements,
such as **strength** requirements
(called survivability requirements)
and **durability** requirements,
which are sometimes presented
as part of geotextile filter criteria,

are not filter criteria
because they are not intrinsic
to the filtration function.
(*They can be used for geotextiles performing other functions*.)

This is the end of the presentation
of research on filter criteria
conducted over thirty years.

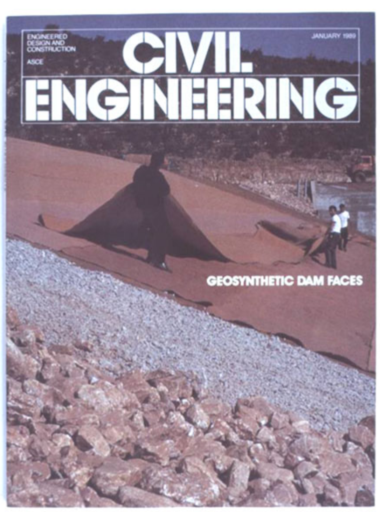
And, now a case history . . .

A case history
that has been cited
by various authors
in several publications.

THE FIRST GEOTEXTILE FILTER IN A DAM

JP GIROUD THE TERZAGHI LECTURE 175

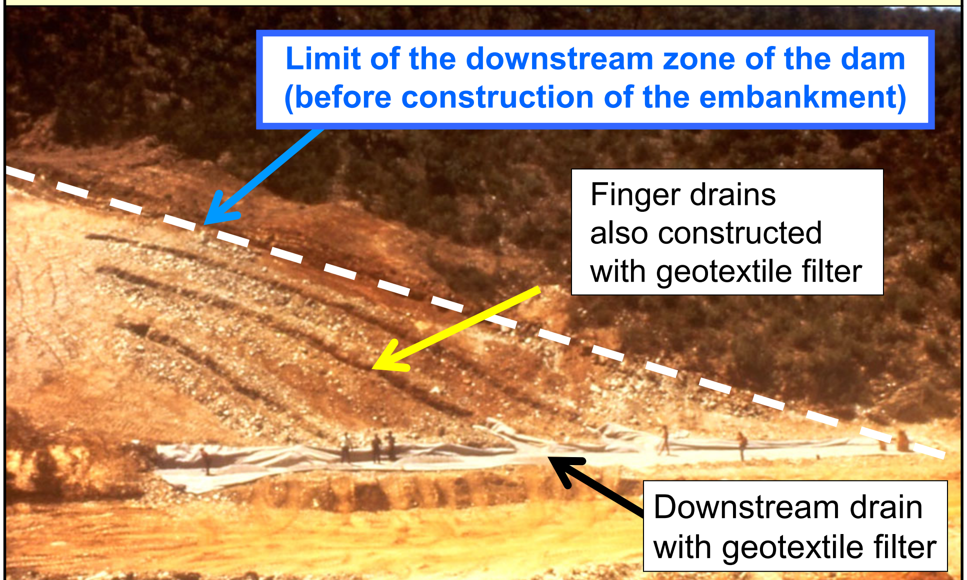
VALCROS DAM, FRANCE (1970)



In 1989, this dam
was on the cover of
CIVIL ENGINEERING.
Almost 20 years before,
it had been
the first dam constructed
with geotextiles:
on the upstream slope,
as we see here,
but, more importantly . . .

JP GIROUD THE TERZAGHI LECTURE 176

DOWNSTREAM DRAIN WITH GEOTEXTILE FILTER



JP GIROUD THE TERZAGHI LECTURE 177

- **17 m high homogeneous dam**
- **Silty sand, 30% < 0.075 mm**
- **I was the design engineer for the dam and I could not get adequate sand filter.**
- **I elected to use a nonwoven geotextile (never used before as a filter).**

JP GIROUD THE TERZAGHI LECTURE 178

The dam has been in service ever since 1970.

JP GIROUD THE TERZAGHI LECTURE 179

The performance has been satisfactory:

- **Constant trickle of clean water.**
- **Flow rate consistent with the hydraulic conductivity of the embankment soil.**
- **No seepage of water ever observed through the downstream slope.**
- **Geotextile filter in good condition and clogging absolutely negligible** (0.2% of the pore volume of the geotextile).

JP GIROUD THE TERZAGHI LECTURE 180

as demonstrated by tests on samples of geotextile removed from the actual filter, 6 years and 22 years after construction.

VALCROS DAM DOWNSTREAM SLOPE

JP GIROUD THE TERZAGHI LECTURE 181

VALCROS DAM

The outstanding performance of the geotextile filter can be explained.

FIRST COMMENT

Fortunately, the Valcros Dam filter was not designed using classical filter criteria.

JP GIROUD THE TERZAGHI LECTURE 182

In reality, I did not use filter criteria
to select the geotextile filter for Valcros Dam.

I selected the geotextile
on the basis of limited experimental data
available at that time (1970).

Therefore, some degree of luck was involved
in the success of the Valcros Dam filter.

Ten years later, in the 1980s,
I felt compelled to "repay" for that luck
and started working on filter criteria.

JP GIROUD THE TERZAGHI LECTURE 183

Today,
we can finally use
geotextile filter criteria
for Valcros Dam.

JP GIROUD THE TERZAGHI LECTURE 184

It is easy to check that:

- **the permeability criterion,**
- **the porosity criterion, and**
- **the thickness criterion**

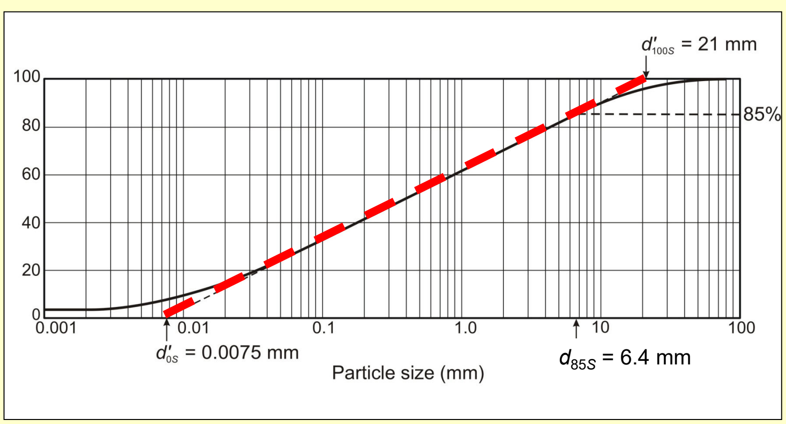
are met.

Only the retention criterion will be discussed.

JP GIROUD THE TERZAGHI LECTURE 185

VALCROS DAM

PARTICLE SIZE DISTRIBUTION CURVE

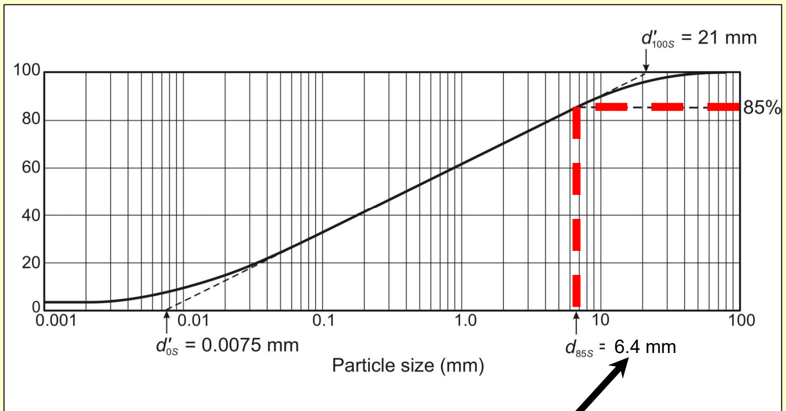


COEFFICIENT OF UNIFORMITY $C_u = 90$

LINEAR COEFFICIENT OF UNIFORMITY $C'_u = 53$

JP GIROUD THE TERZAGHI LECTURE 186

VALCROS DAM



TERZAGHI's RETENTION CRITERION
DIRECTLY ADAPTED TO GEOTEXTILE FILTERS

$O_F < d_{85S}$

JP GIROUD THE TERZAGHI LECTURE 187

An opening size of 6.4 mm
is very large.

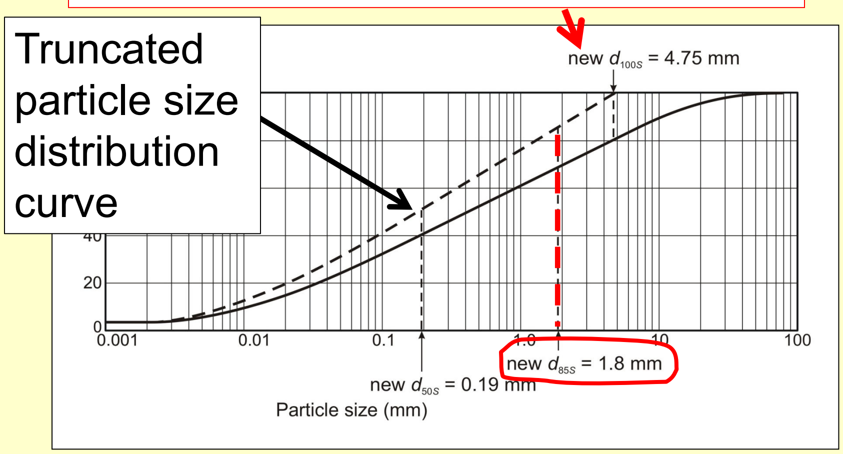
Such an opening size
does not seem adequate
to retain a silty sand.

The problem is caused by
the **large coefficient of uniformity**
of the silty sand.

JP GIROUD THE TERZAGHI LECTURE 188

This problem with large coefficient of uniformity is known by geotechnical engineers.

Traditional solution: TRUNCATION



JP GIROUD THE TERZAGHI LECTURE 189

An opening size of 1.8 mm
is still very large
and does not seem adequate
to retain a silty sand.

JP GIROUD THE TERZAGHI LECTURE 190

One may object that, so far, I used the retention criterion for **cohesionless soils**, whereas the soil in Valcros Dam has 30% particles smaller than 0.075 mm, which may generate some cohesion.

Sherard proposed a retention criterion depending on the percentage of particles smaller than 0.075 mm.

I used Sherard's criterion and obtained: **2.67 mm**.

This is very large.

Then, I used Sherard's criterion with the **truncated** particle size distribution curve.

I obtained: 0.83 mm.

This is still very large.

The soil in Valcros Dam seems to defy all retention criteria.

Use of the proposed retention criterion

Soil density (Relative density)	Linear coefficient of uniformity of the soil C'_u	
	$1 \le C'_u \le 3$	$C'_u \ge 3$
loose ($I_D \le 35\%$)	$O_F \le (C'_u)^{0.3} d_{85S}$	$O_F \le \frac{[illegible]}{(C'_u)^{1.7}} d_{85S}$
medium dense ($35\% < I_D \le 65\%$)	$O_F \le 1.5 (C'_u)^{0.3} d_{85S}$	$O_F \le \frac{[illegible].5}{(C'_u)^{1.7}} d_{85S}$
dense ($I_D > 65\%$)	[illegible]	$O_F \le \frac{18}{(C'_u)^{1.7}} d_{85S}$

USE OF THE PROPOSED RETENTION CRITERION

$$O_F \le \frac{18\, d_{85S}}{(C'_u)^{1.7}}$$

Equation for dense soil and coefficient of uniformity ≥ 3

Application to the Valcros Dam soil

with $d_{85s} = 6.4$ mm and $C'_u = 53$

$$O_F \le \frac{(18)(6.4)}{(53)^{1.7}} = 0.135 \text{ mm}$$

Application to the truncated particle size distribution curve

with $d_{85S} = 1.8$ mm and $C'_u = 25$

$$O_F \le \frac{(18)(1.8)}{(25)^{1.7}} = 0.135 \text{ mm}$$

Same result with or without truncation.

This remarkable result confirms the validity of the proposed retention criterion.

Clearly, the potentially inaccurate operation of **truncation** of the particle size distribution curve is **not needed** with the proposed retention criterion.

This has just been shown in the case of a **geotextile filter**; it could be shown in the case of a **granular filter**.

In conclusion,
the required value
of the Valcros Dam
geotextile filter opening size
is 0.135 mm.

This seems more reasonable,
for a silty sand,
than the values obtained
with other criteria:
6.4 mm, 2.7 mm, 1.8 mm and 0.8 mm.

The opening size of the geotextile filter measured on samples taken from the dam is **0.1 mm**.

Therefore, the retention criterion ($O_F \leq$ **0.135 mm**) is met.

The **opening size** of the Valcros Dam filter can be **calculated**

knowing the physical characteristics of the filter

μ_{GT} = 0.3 kg/m^2, ρ_f = 1380 kg/m^3, d_f = 0.027 mm, n = 0.92

using an equation presented earlier in this lecture:

$$\frac{O_F}{d_f} \approx \frac{1}{\sqrt{1-n}} - 1 + \frac{10 n \rho_f d_f}{\mu_{GT}}$$

which gives: 0.099 mm

This is in good agreement with the measured value of 0.1 mm.

It is useful to be able to **calculate** the **opening size of a nonwoven** geotextile filter knowing that its measurement is often inaccurate.

More importantly the calculation makes it possible to **predict the opening size** of a nonwoven geotextile filter in its **compressed state** inside a dam,

which is quasi impossible to measure in the laboratory.

CONCLUSION OF THE VALCROS DAM CASE HISTORY

The geotextile filter has performed well since 1970.

The **four filter criteria are met**, which is consistent with the good performance.

SUMMARY

- We have reviewed
  the two classical filter criteria,
  the **permeability** criterion and
  the **retention** criterion,
  for both granular and geotextile filters.
- We have added two criteria
  for geotextile filters:
  the **porosity** criterion and
  the **thickness** criterion.

JP GIROUD THE TERZAGHI LECTURE 201

CONCLUSION
FOR
GEOTEXTILE FILTERS

The four proposed criteria
for geotextile filters
form a **coherent set of criteria**
that allow
safe design of geotextile filters.

JP GIROUD THE TERZAGHI LECTURE 202

CONCLUSION
FOR
GRANULAR FILTERS

The retention criterion
for **granular** filters
can be improved
based on developments
made for the retention criterion
of **geotextile** filters.

JP GIROUD THE TERZAGHI LECTURE 203

Therefore,

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

has resulted in **technology transfer from geosynthetics engineering to geotechnical engineering.**

JP GIROUD THE TERZAGHI LECTURE 204

I am sure that Terzaghi
would have agreed that
his famous filter criteria
were not frozen forever,
but, rather,
could lead
to new developments.

JP GIROUD THE TERZAGHI LECTURE 205

I am sure that Terzaghi
would have agreed that,
with a new filter material,
the geotextile,
it was not sufficient
to simply adapt his criteria,
but it was necessary to review
the fundamentals of filtration,
and develop new criteria.

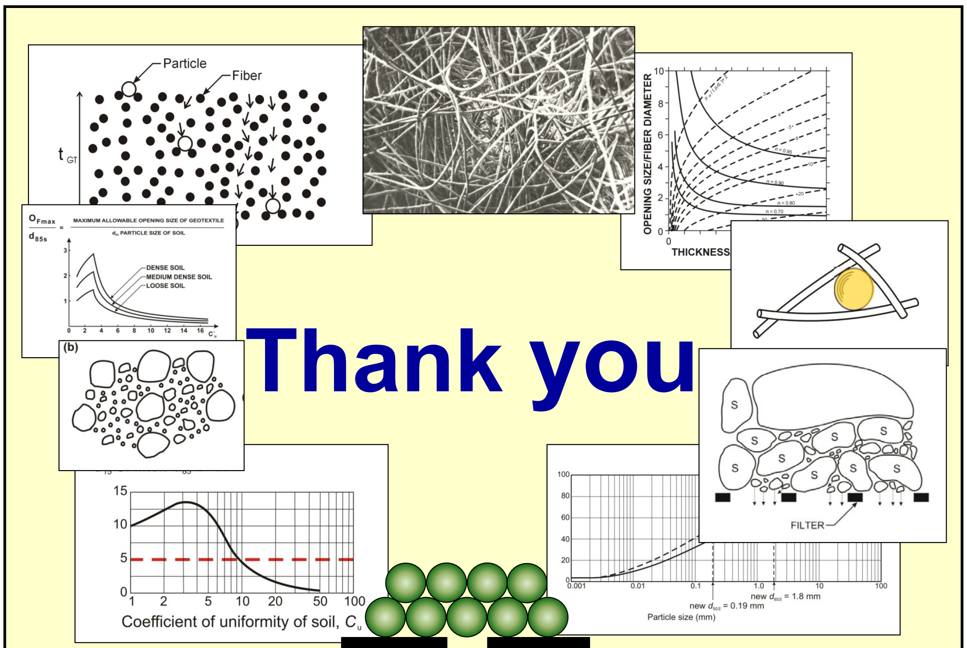
JP GIROUD THE TERZAGHI LECTURE 206

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.

JP GIROUD THE TERZAGHI LECTURE 207



JP GIROUD THE TERZAGHI LECTURE 208