

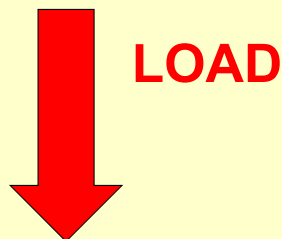
MECHANISMS OF ROAD IMPROVEMENT BY GEOSYNTHETICS

BY
J.P. GIROUD

Note: The slides presented herein should be viewed
in conjunction with Section 2 of the paper titled
“The Use of Geosynthetics in Roads”.

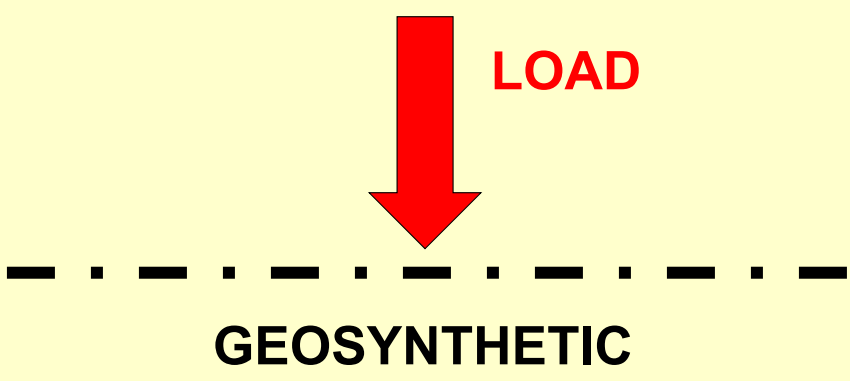
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.1

A load and a geosynthetic . . .



This sketch explains why
stabilizing a road is difficult.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.2



The **load** is in one direction
and the **geosynthetic** in the other direction.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.3

We will start with **unpaved roads**,
because
several improvement mechanisms
are involved in the case of **unpaved roads**,
whereas only **some** of them
are involved in **paved roads**.

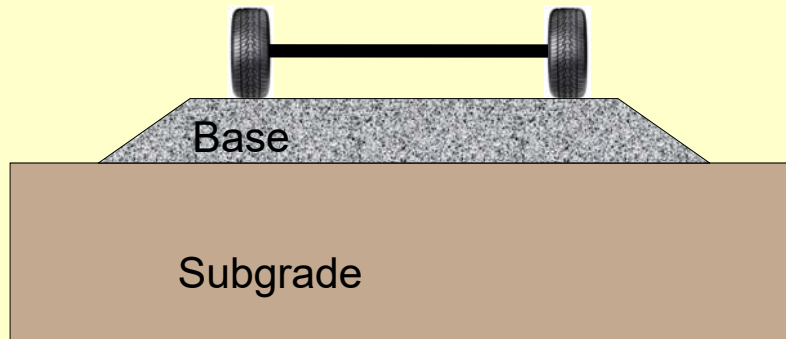
Therefore, **unpaved roads**
provide an opportunity
to develop a **complete understanding**
of the road improvement mechanisms.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.4

What is an unpaved road?

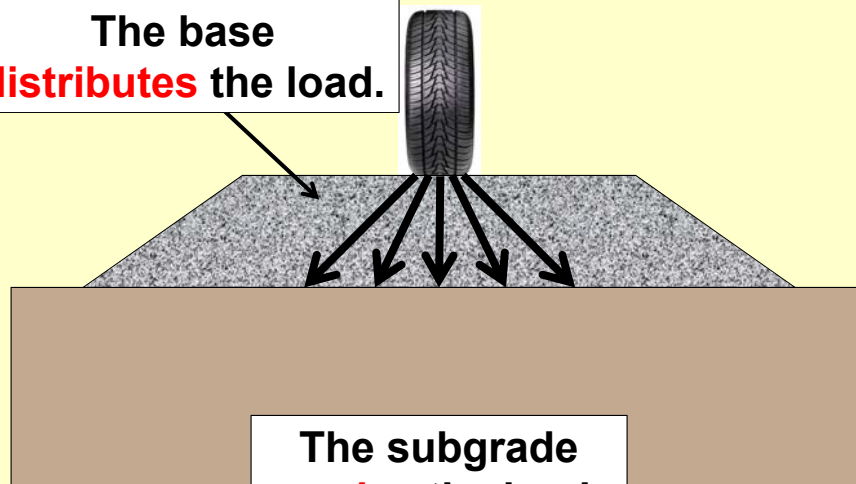
An unpaved road,
consists of a **base** (*typically an aggregate layer*)
resting on **subgrade** soil.

It is subjected to **traffic** by vehicles on wheels.



PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.5

The base
distributes the load.



The subgrade
carries the load.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.6

**Therefore,
improvement
of unpaved roads
consists in
improving load distribution
by the base
and
improving the subgrade
bearing capacity.**

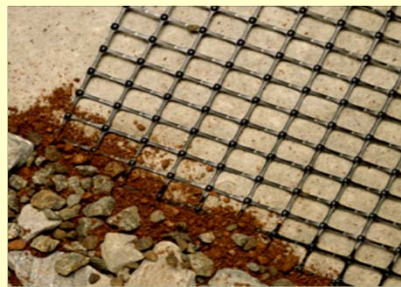
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.7

**We will discuss
unpaved road improvement
with geosynthetics.**

GEOTEXTILES



GEOGRIDS




PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.8

Among the geogrids, we consider **biaxial** geogrids

Characterized by ribs in two directions

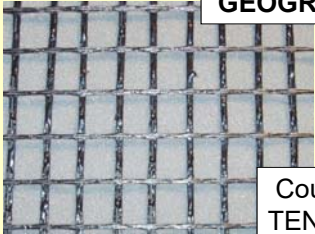
PUNCHED-AND-DRAWN GEOGRID



Courtesy TENSAR

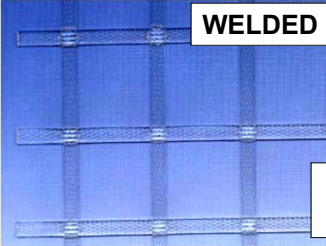
Also called "punched-and-stretched"

WOVEN GEOGRID



Courtesy TENCATE

WELDED GEOGRID




Courtesy NAUE

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.9

Here is a **triaxial** geogrid

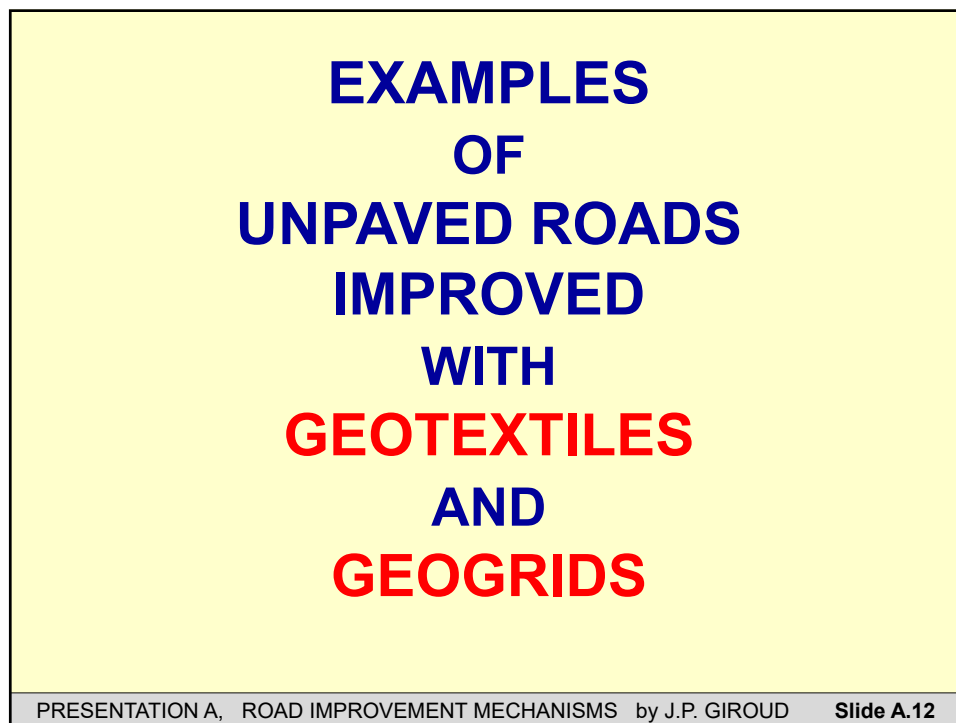
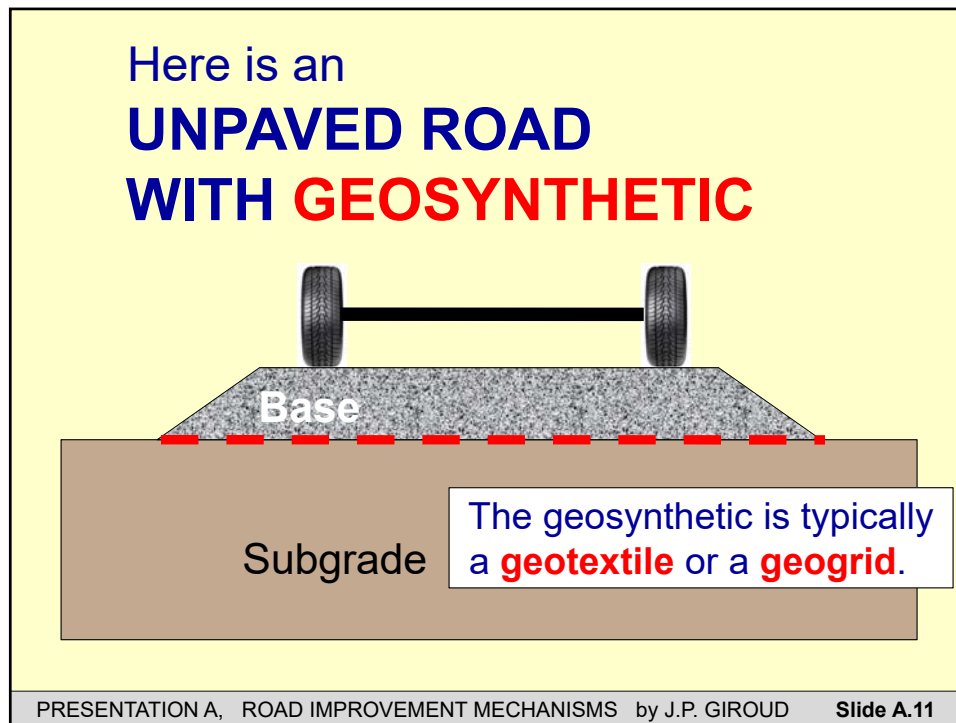
Characterized by ribs in three directions



Courtesy TENSAR

This is a punched-and-drawn geogrid.

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Mechanisms of Road Improvement by Geosynthetics
by J.P. Giroud

UNPAVED ROAD WITH GEOTEXTILE



Courtesy
TENCATE

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.13

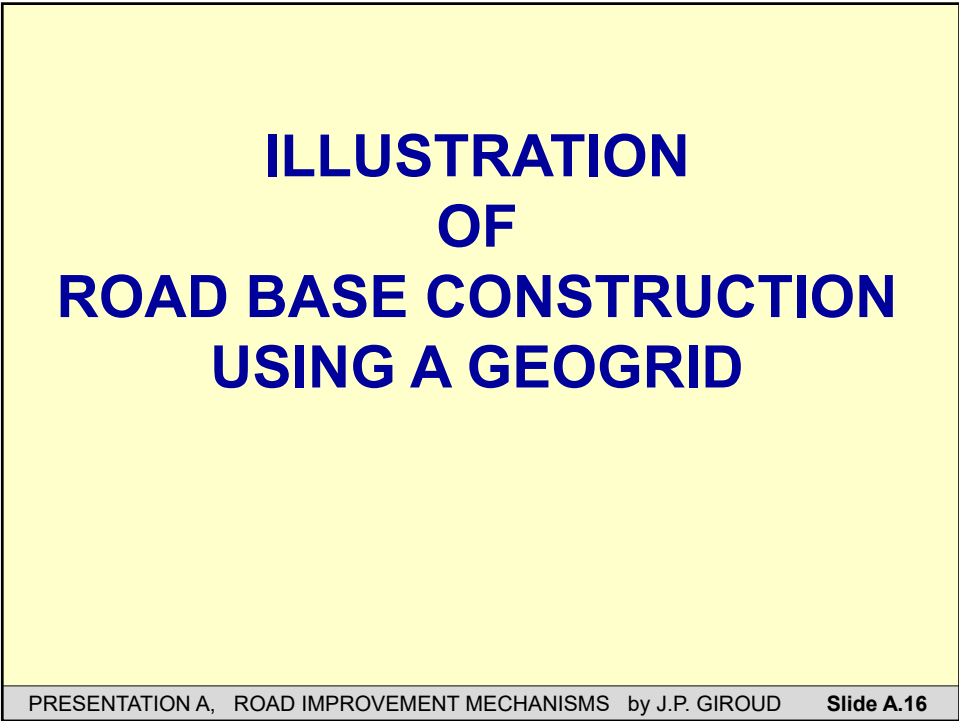
UNPAVED ROAD WITH BIAXIAL GEOGRID



Courtesy
TENSAR

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.14

Supplemental Material to the paper “The use of geosynthetics in roads”
by J.P. Giroud, J. Han, E. Tutumluer & M.J.D. Dobie,
published in *Geosynthetics International*, as jgein.21.00046.



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Mechanisms of Road Improvement by Geosynthetics
by J.P. Giroud

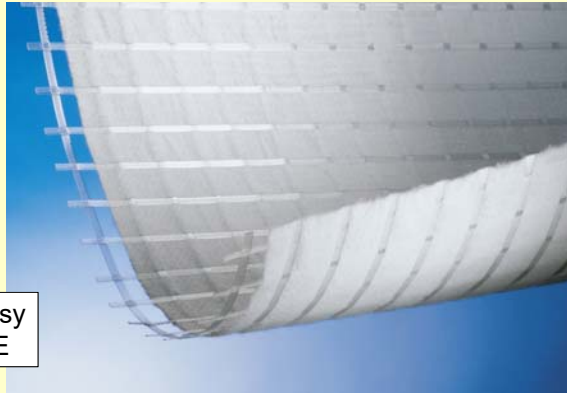


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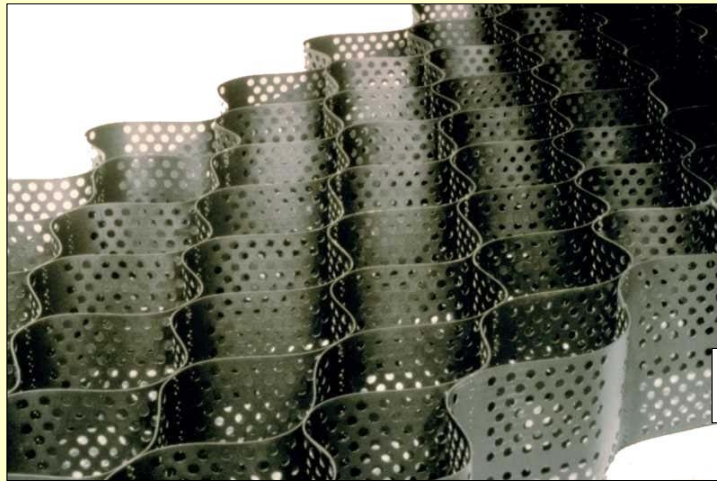
The geotextile and the geogrid can be installed independently, or they can be installed together if they are the components of a geogrid-geotextile composite manufactured by bonding a geogrid and a geotextile.



Courtesy
NAUE

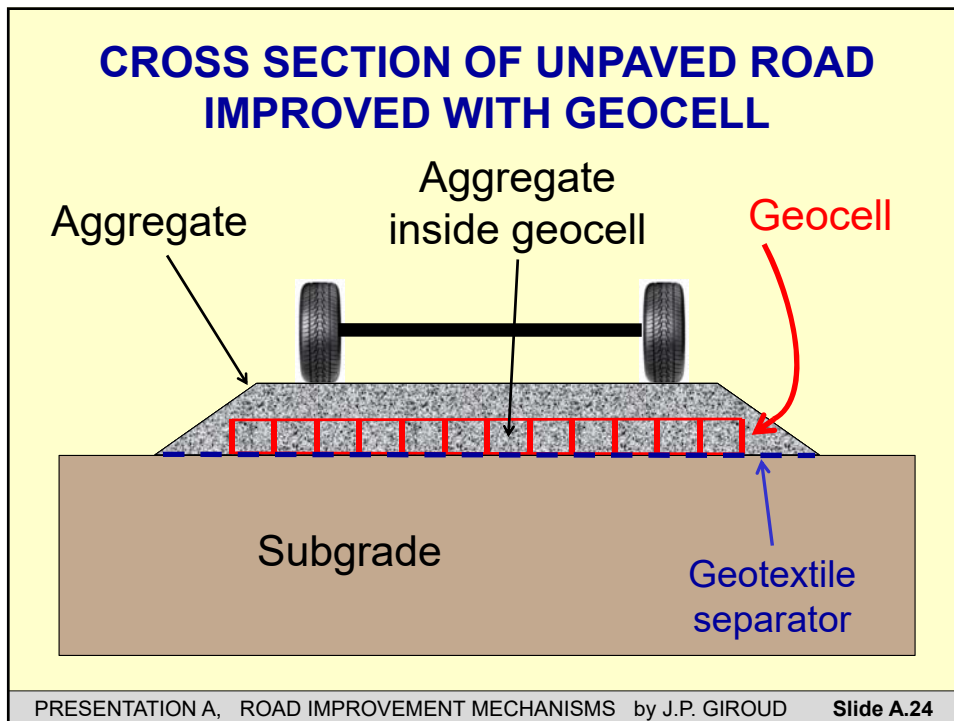
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.21

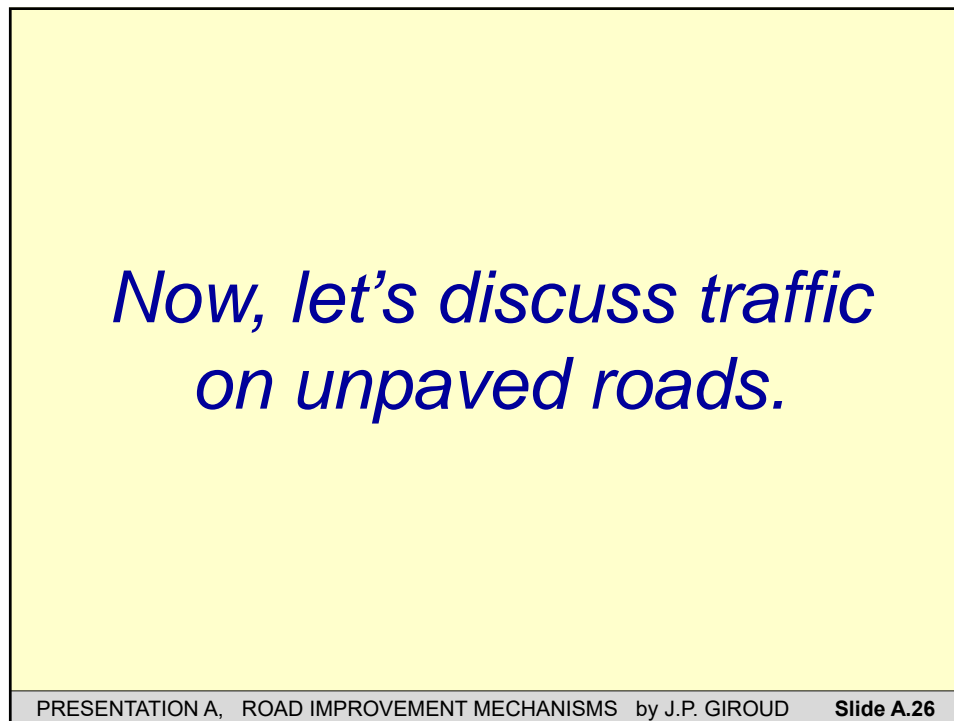
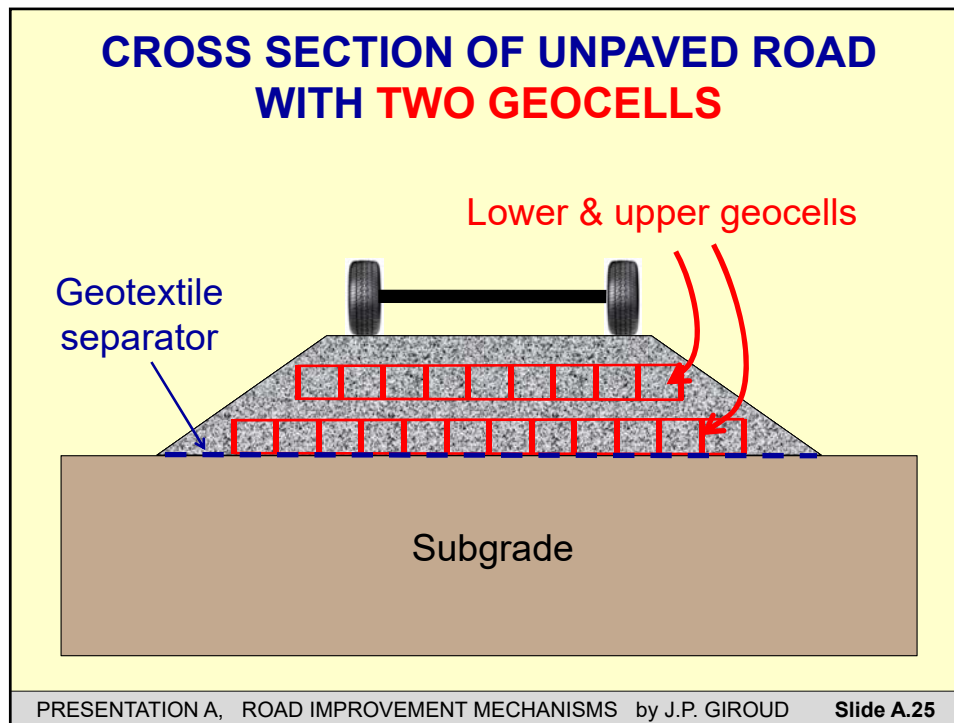
**Geocells are also used
in unpaved roads.**



Courtesy
PRESTO

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.22





**The traffic magnitude
is measured in number of passes
of vehicles or axles.**

It varies from a **few passes**
in temporary **access roads**
to **many thousand passes**
in permanent **low-volume roads**.

At construction sites,
several thousand passes are typical.

Therefore, the design of unpaved roads
is **not limited** to a small number of passes.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.27

In unpaved **roads**, the traffic
is generally assumed to be
channelized, as on this photo.



Courtesy
TENSAR

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.28

As a result of channelized traffic,
repeated loading (and service life)
can be quantified in terms of
number of passes
of vehicles or axles.

This is for
paved and unpaved **roads**.

Now, what about unpaved **areas** ?

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An unpaved area has the same
structure as an unpaved road,



PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.30

Therefore,
in the case of unpaved
areas,
it is **not clear** how
repeated loading
and service life
should be **quantified**.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.31

Some aspects of the design methods
for unpaved roads **may not be applicable**
to unpaved areas
because of the difference in traffic pattern:

channelized in unpaved roads
(at least approximately channelized)
and **erratic** in unpaved areas.

However, design methods for unpaved roads
are often used for unpaved areas.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.32

*From now on,
we will only address
unpaved roads.*

We will not discuss unpaved areas.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.33

In the following discussions it is assumed that the base course material is sufficiently strong to support the wheel load without shear failure.



PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.34

**As mentioned earlier,
an unpaved road
can be improved in two ways:**

- **by improving
load distribution by the base**
- **by improving
subgrade bearing capacity**

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.35

**First:
IMPROVEMENT OF
LOAD DISTRIBUTION**

The geosynthetic:

- **improves the ability of the base to
distribute loads; and**
- **contributes to load transfer through
the “tensioned membrane effect”.**

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.36

**First, we discuss
load distribution
by the base
(generally an aggregate layer).**

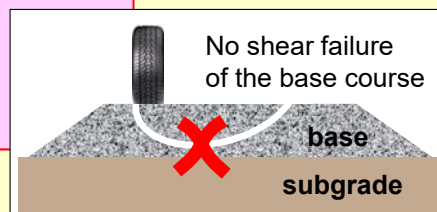
**The famous
“tensioned membrane effect”
will be discussed later.**

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.37

**A geosynthetic has two beneficial effects
on the base of an unpaved road:**

- **it minimizes deterioration of the base**
 - by **reducing lateral spreading** of base material
 - by preventing shear failure of the base,
but only in some cases

Remember: it has been assumed
that the base course material
is sufficiently strong
to support the wheel load
without shear failure.




PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.38

**A geosynthetic has two beneficial effects
on the base of an unpaved road:**

- **it minimizes deterioration of the base**
 - by **reducing lateral spreading** of base material
 - by preventing shear failure of the base,
but only in some cases
- **it imparts tensile stiffness to the base,**
thereby **increasing the modulus** of the base

FIRST: DISCUSSION OF BASE MODULUS

NEXT SLIDE 

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD

Slide A.39

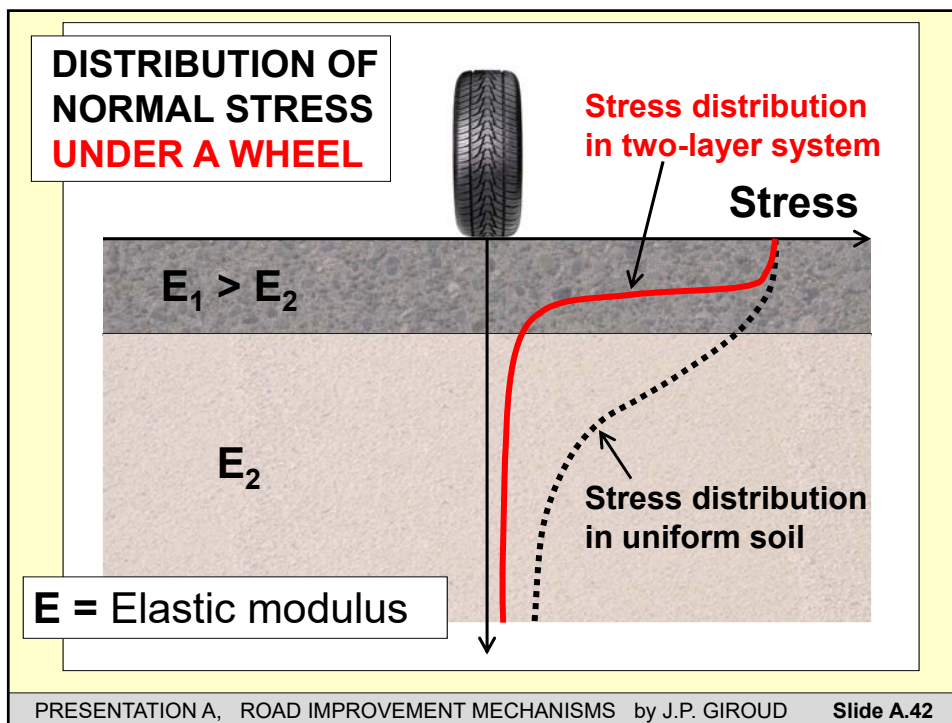
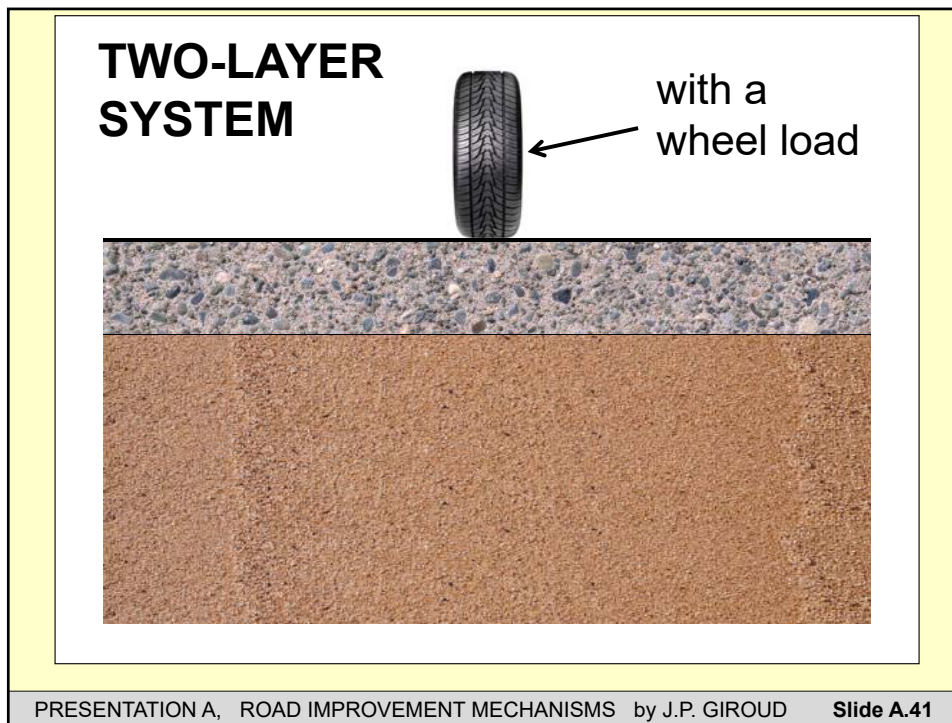
It is known from
the **theory of elasticity**
that, in a two-layer system,
the **stress distribution**
on the lower layer
depends on
the **modulus** of the upper layer
relative to
the modulus of the lower layer.

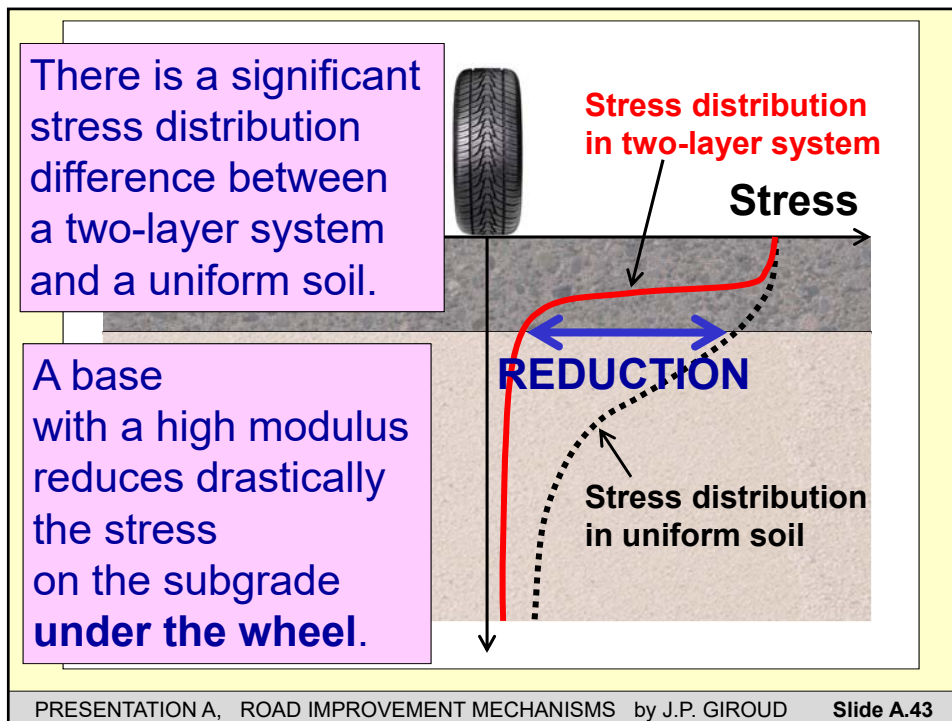
**TWO-LAYER
SYSTEM**



PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD

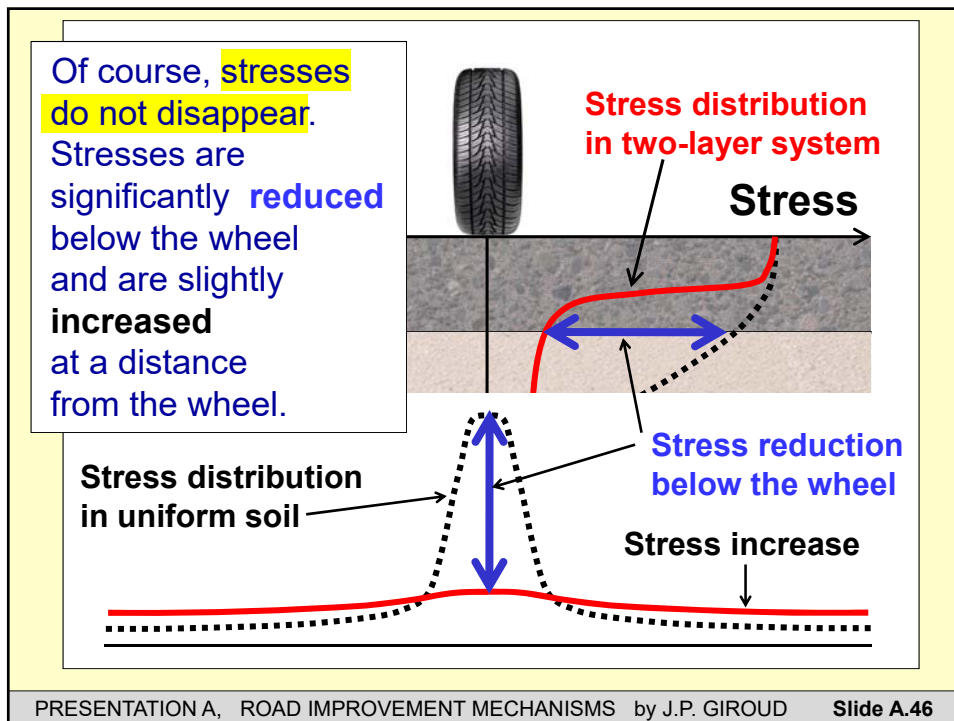
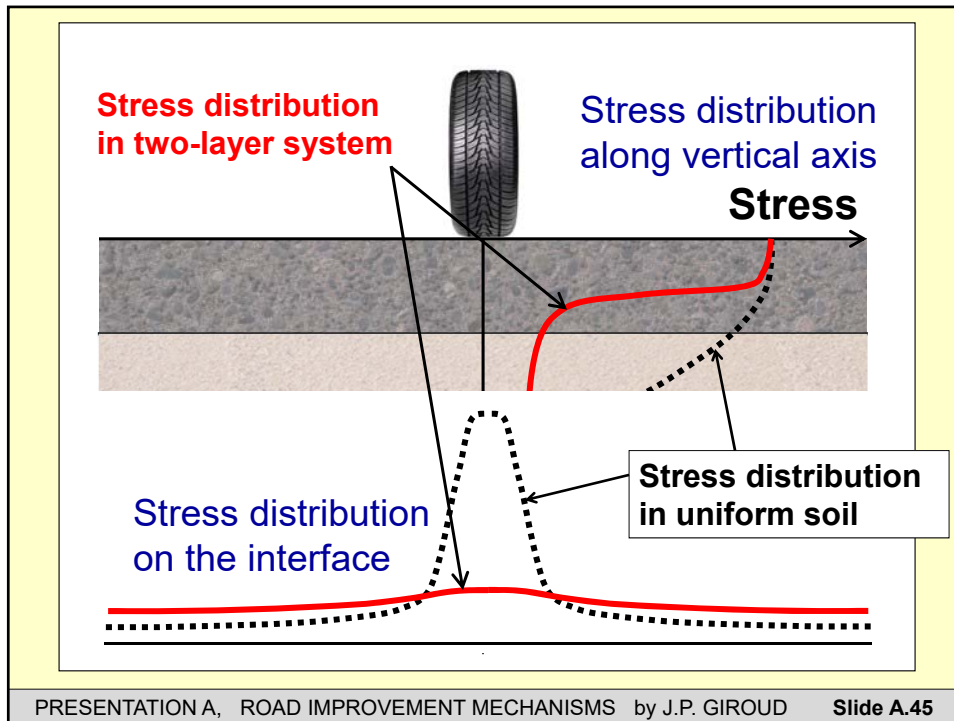
Slide A.40





*On the next slide,
we will also see
the stress distribution
on the **horizontal interface**
between
the base and the subgrade.*

Mechanisms of Road Improvement by Geosynthetics by J.P. Giroud



Stress distribution also called “**load** distribution”
is not **load** reduction
(*load* being the resultant of the stresses).

In other words, stress distribution by the base
does not result in
load reduction on the subgrade.

The load is constant at every level.

Stress distribution by the base
results in **reduction of the maximum stress**
on the subgrade,
which occurs below the wheel.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.47

Similarly, when base stabilization with geosynthetic
results in **improved stress distribution**,
it is not correct to say that the load is reduced.

The improved stress distribution is, in fact,
stress **redistribution** or load **redistribution**.

Improved stress distribution by the base
(i.e. “stress redistribution” or “load redistribution”)
results in further reduction of the maximum stress
on the subgrade.

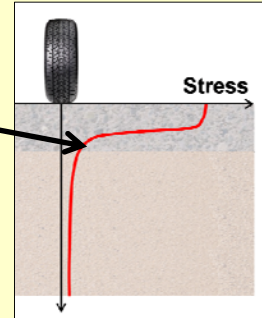
But again:

The load is constant at every level.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.48

QUANTIFICATION OF STRESS DISTRIBUTION

The **stress distribution**
in two-layer systems
from the theory of elasticity
is **too complex**
to be incorporated
in the equation
for base thickness.



PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.49

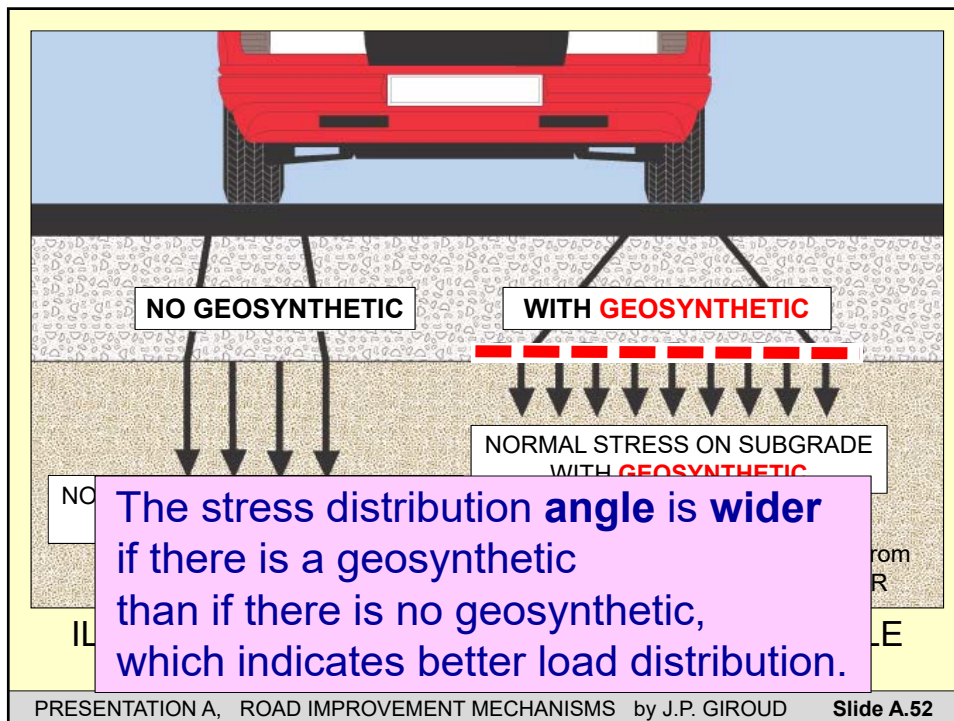
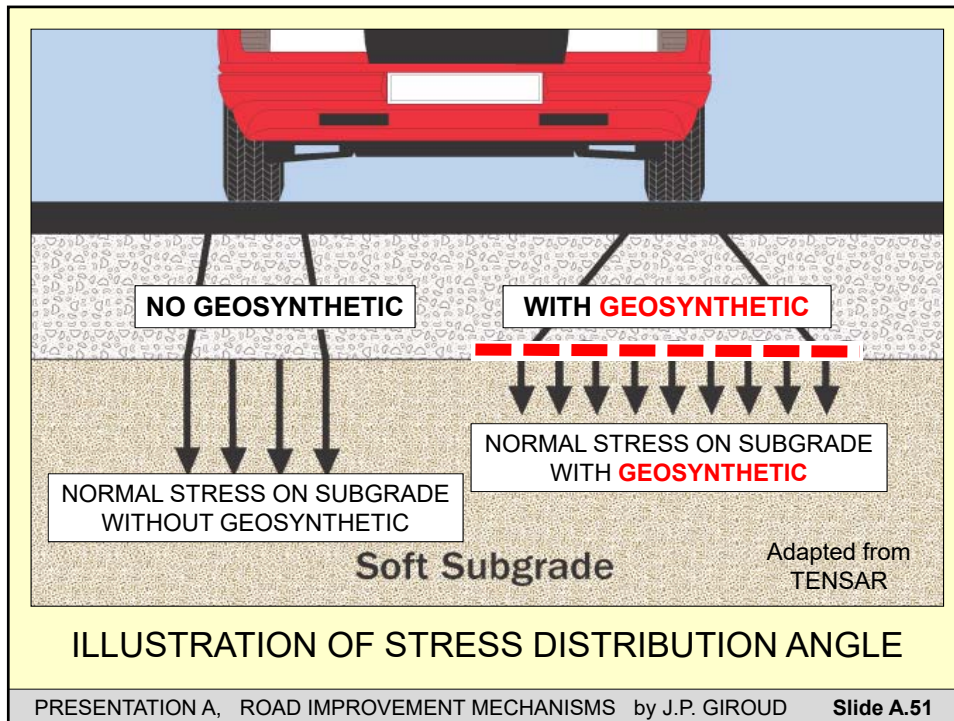
QUANTIFICATION OF STRESS DISTRIBUTION

It is generally accepted that
an **approximation**
of the **elastic** stress distribution
is provided by
a **stress distribution angle**.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.50

Mechanisms of Road Improvement by Geosynthetics

by J.P. Giroud



Selection of the stress distribution angle

- Clearly, the stress distribution angle is a **conventional way** to quantify what is more accurately quantified by the **theory of elasticity**.
- Therefore, ideally, the stress distribution angle should be **selected** to provide a stress distribution that approximates the elastic stress distribution.
- Practically, it can also be **quantified** experimentally by measuring stresses at base/subgrade interface.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.53

It is **simple** to use
a stress distribution angle,
but it is **difficult** to **select**
an appropriate **value**
for the **stress distribution angle**.

*Selection of the stress distribution angle
is discussed in detail
in Presentation B titled
**Design of Geosynthetic-Stabilized
Unpaved Roads and Case Histories** ,
by Jie Han.*

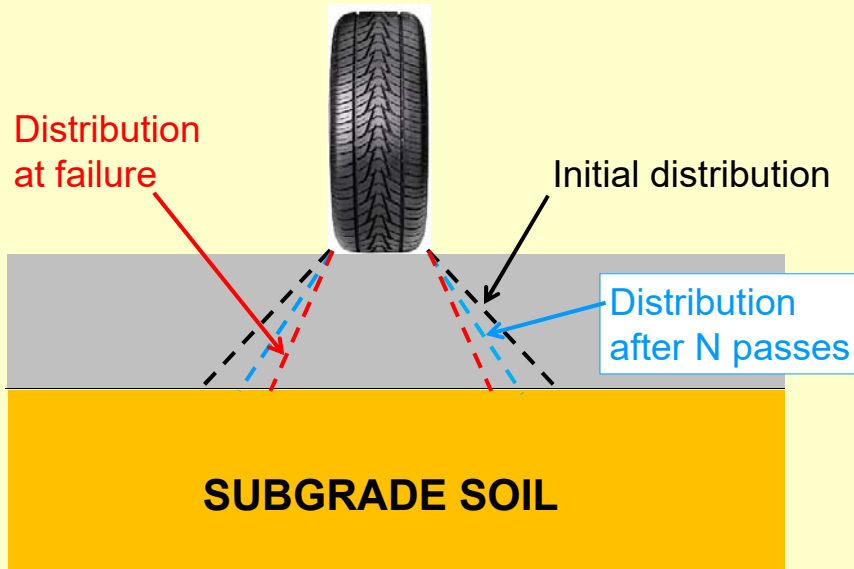
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.54

Among other parameters,
the **Giroud-Han design method**
for unpaved roads
takes into account the fact that
the **stress distribution angle decreases**
as the base modulus decreases
with the **increasing number**
of vehicle passages.

This is illustrated on the next slide.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.55

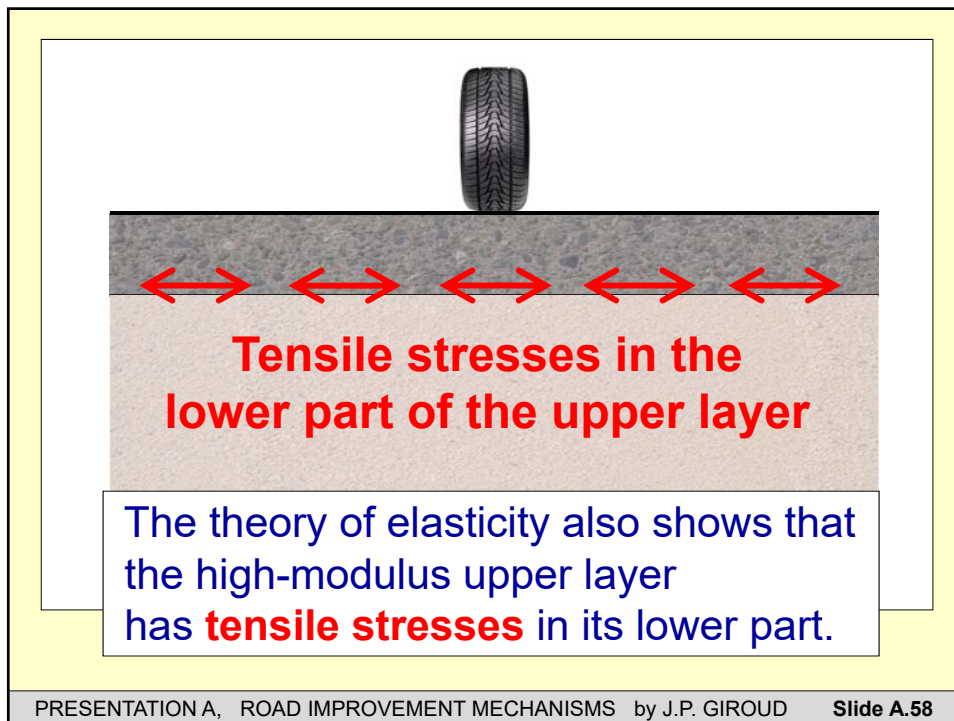
STRESS DISTRIBUTATION ANGLE



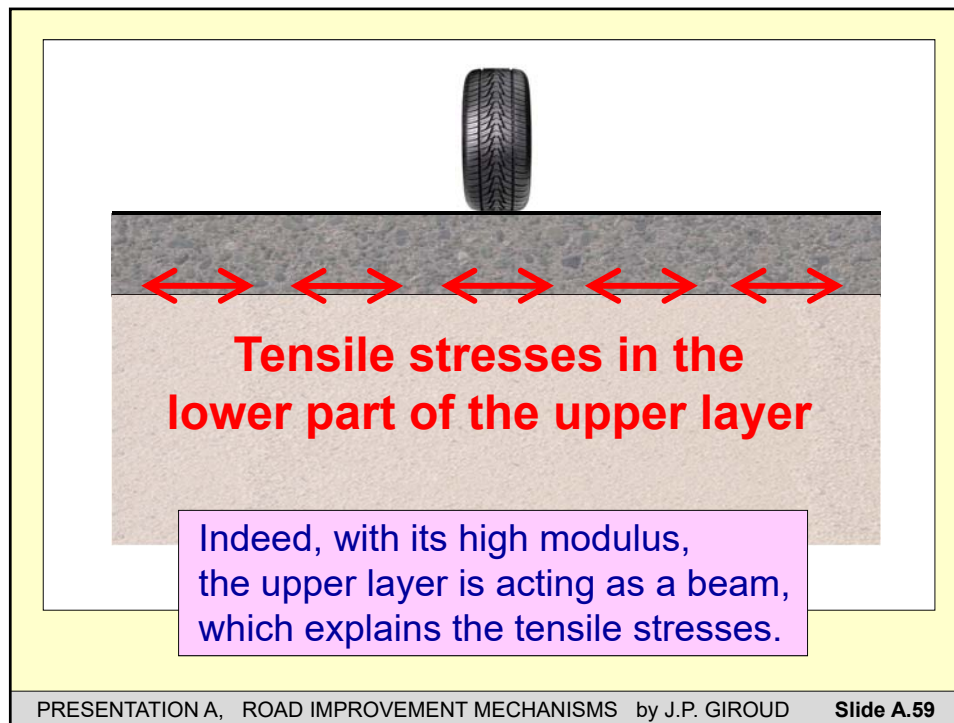
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.56

As already mentioned,
and as illustrated in the previous slides,
the theory of elasticity shows that,
in a two-layer system,
the stress distribution
on the lower layer under the wheel
depends on the modulus
of the upper layer
relative to the modulus
of the lower layer.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.57



PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.58



But the theory of elasticity assumes that elastic properties are the same in **tension** and **compression**.

This is true for steel.

But this is **not true** for civil engineering materials, such as soils, asphalt concrete, cement concrete.

These materials are much weaker in tension than in compression.

In the case of an **unpaved road**,
the upper layer of the two-layer system
is the aggregate base.

Aggregate **does not resist tensile stresses**.

Therefore, due to tensile stresses
in the lower part of the base,
**the aggregate
becomes disorganized
in the lower part of the base.**

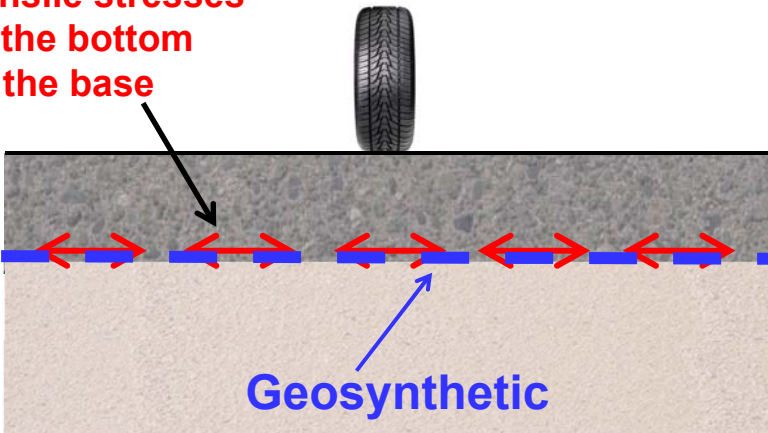
As a result, the base is weakened.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.61

Therefore,
the stress distribution effectiveness
of the upper layer of a two-layer system
can be increased
by **imparting tensile stiffness**
at the bottom of the upper layer.

Hence the use of **geosynthetic**
at the bottom of the upper layer
(i.e. the base).

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.62



Tensile stresses at the bottom of the base

Geosynthetic

A geosynthetic at the bottom of the base imparts **tensile stiffness** to the base, which enables the base to carry tensile stresses.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.63

The geosynthetic can impart tensile stiffness at the bottom of the base, through two mechanisms:

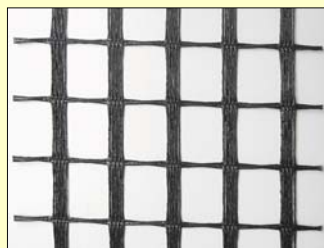
- **interface friction between geosynthetic and base material; and**
- **confinement of base material by the geosynthetic.**

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.64

First, let's discuss friction.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.65

Interface friction exists between base material and a **relatively flat surface**, such as a **geotextile** or the **flat ribs** of some types of geogrids (woven geogrids and welded geogrids).



Courtesy
TENCATE



Courtesy
NAUE

WOVEN GEOGRID

WELDED GEOGRID

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.66

Then, let's discuss confinement.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.67

There are two types of **confinement**:

- **Closed confinement**
of base material
in **geocells**
- **Open confinement**
by **interlocking** between
aggregate and **geogrids**

This is fundamental.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.68

CLOSED CONFINEMENT IN GEOCELL is easily understood.



The base material
is not free
to escape
from a cell.

In other words,
the base material
is **closely confined**.

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The term “**closed confinement**” is used
rather than “**total confinement**”
or “**absolute confinement**”, because
lateral displacement of base material
is not “totally” or “absolutely” prevented.

Indeed, the base material
can move a little because,
even with soil present in the cells,
the geocell can deform (to some degree).

Only rigid cells would provide
“*total confinement*” or “*absolute confinement*”.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.70

Confinement of soil
in a given cell of a geocell
results from:

- **tension in the geosynthetic material** that constitutes the wall of the cell;
and
- **normal stresses** applied on the walls of the cell by the soil confined in the surrounding cells.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.71

Confinement is effective
if the soil is properly compacted.

In the case of geocells,
placement and compaction of soil
in the cells is labor intensive,
which is a drawback of geocells.

An advantage of geocells
is that confinement is effective
with any type of soil,
as seen in the following slides.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.72

Closed confinement in geocell is effective
with any type of soil, such as **sand**.



Courtesy
GeoGlobe
Europe
A.Rosen

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.73

Closed confinement in geocell is effective
with any type of soil, such as **aggregate with fines**.



Courtesy
A. Rosen

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.74

In contrast, geogrid-base **interlocking** works only with a **coarse granular material** such as aggregate.

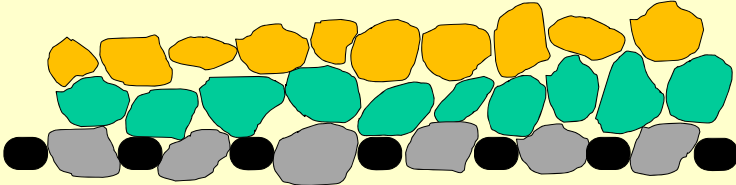
Interlocking is a **synergistic association** of geogrid and aggregate.

Interlocking is the **key mechanism** in geogrid-stabilized unpaved roads, and the interlocking mechanism will be discussed in detail.

NEXT SLIDE

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.75

We will use a **schematic representation** of geogrid/aggregate interlocking



This sketch can only be schematic, because it is two-dimensional, whereas the actual situation is three-dimensional.

Let's start with a cross section of geogrid.

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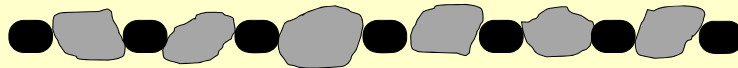
SCHEMATIC REPRESENTATION OF GEOGRID/AGGREGATE INTERLOCKING



Cross section of the geogrid

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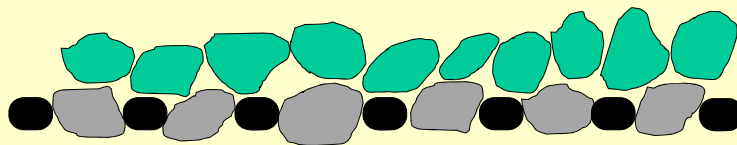
SCHEMATIC REPRESENTATION OF GEOGRID/AGGREGATE INTERLOCKING



The gray aggregate is **directly confined**
by **interlocking** with the geogrid.

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SCHEMATIC REPRESENTATION OF GEOGRID/AGGREGATE INTERLOCKING

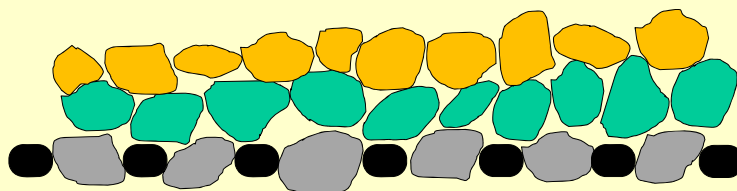


The gray aggregate is **directly confined**
by **interlocking** with the geogrid.

Interlocking between **gray** and **green** aggregate
provides confinement to the **green** aggregate.

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SCHEMATIC REPRESENTATION OF GEOGRID/AGGREGATE INTERLOCKING



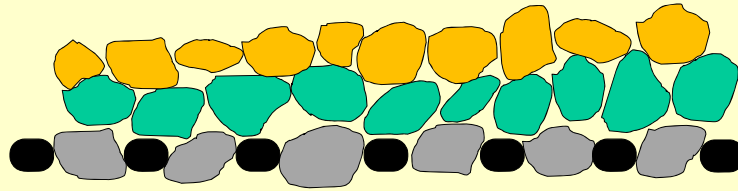
The gray aggregate is **directly confined**
by **interlocking** with the geogrid.

Interlocking between gray and green aggregate
provides confinement to the green aggregate.

Interlocking between **green** and **yellow** aggregate
provides confinement to the **yellow** aggregate.

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SCHEMATIC REPRESENTATION
OF GEOGRID/AGGREGATE INTERLOCKING



The gray aggregate is **directly confined**.

Confinement is progressively **less effective** with increasing **distances** from the geogrid.

*Yellow aggregate is less confined than green aggregate.
Green aggregate is less confined than gray aggregate.*

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As we just saw, only **one layer** of aggregate is **directly confined** by the geogrid.

And the **degree of confinement** of the aggregate **decreases** with increasing distances from the geogrid.

Hence the term “**open confinement**” used for **geogrid / aggregate interlocking**, as opposed to “**closed confinement**” used for confinement in **geocells**.

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As the **degree of confinement** of the aggregate **decreases** with increasing distances from the geogrid, an **effective confinement thickness** can be considered for practical purposes in the case of **geogrids** .

In the case of **geocells**, the effective confinement thickness is obviously the height of the geocell, *i.e. the thickness of the geocell-confined layer.*

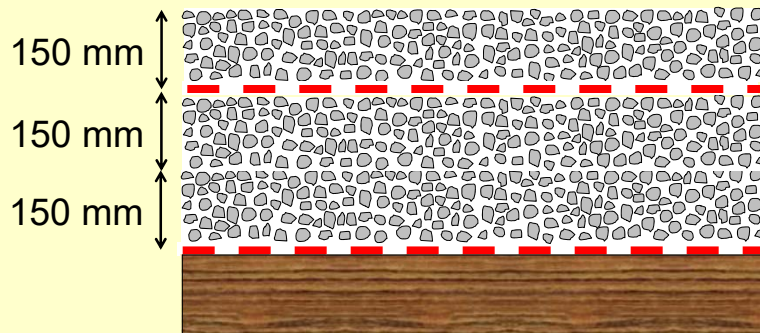
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The **thickness** of aggregate layer **effectively confined** by a geogrid is the subject of on-going research, as indicated in *Presentation D titled **Relevance of Tests and Trials to Real Geosynthetic-Stabilized Roads**, by Michael Dobie.*

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If the base or sub-base thickness exceeds
the effective confinement thickness,
two layers of geogrids may be used.

*Example of a 450 mm thick layer with
effective confinement thickness of 150 mm.*

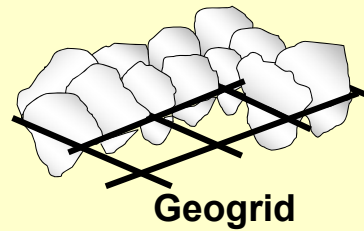


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INFLUENCE OF THE TYPE OF GEOGRID ON INTERLOCKING

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Interlocking exists
between aggregate
and all types of geogrids
(*but in various degrees*).



In the case of **punched-and-drawn geogrids**,
the ribs are narrow.
As a result, there is no significant friction
between the ribs and the aggregate,
and **interlocking** is the only mode of interaction.

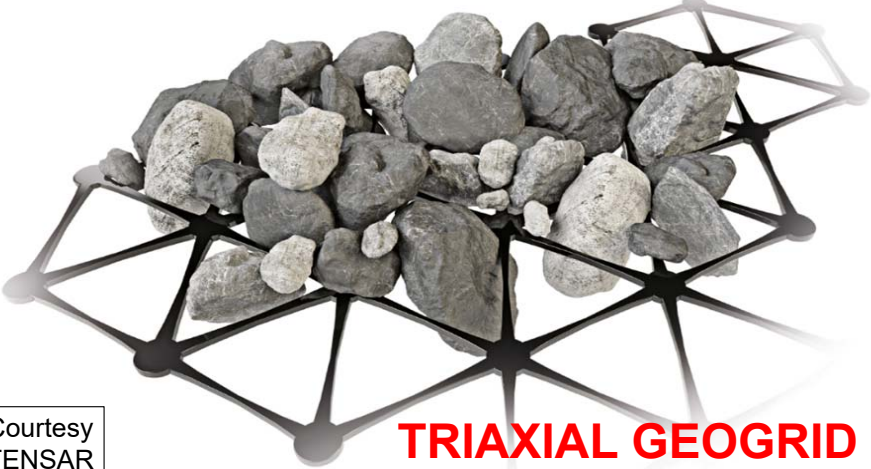
In the case of **welded and woven geogrids**,
the ribs are wide. As a result, there are both
friction and interlocking with the aggregate.

EXAMPLE OF INTERLOCKING BETWEEN AGGREGATE AND PUNCHED-AND-DRAWN GEOGRID



Courtesy
TENSAR

**ANOTHER EXAMPLE OF INTERLOCKING
BETWEEN AGGREGATE AND
PUNCHED-AND-DRAWN GEOGRID**

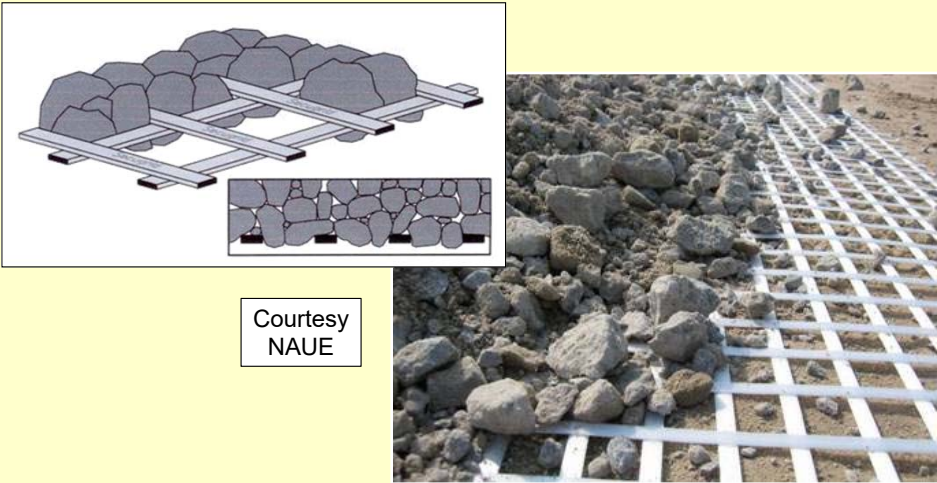


Courtesy
TENSAR

TRIAXIAL GEOGRID

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**EXAMPLE OF INTERLOCKING AND SOME FRICTION
BETWEEN AGGREGATE AND WELDED GEOGRID**



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**There is a fundamental difference
between friction and interlocking:**

- In the case of **friction**,
tensile stiffness is **transferred** from
the geosynthetic to the aggregate;
whereas
- in the case of **interlocking**,
tensile stiffness is **generated** by synergy
between geosynthetic and aggregate.

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Therefore, if **friction** is the mechanism,
the geosynthetic must have
high tensile stiffness
to be able to transfer stiffness
to the aggregate.

*The situation is far more complex
if interlocking is the mechanism.*

If **interlocking** is the mechanism,
a **variety of parameters** are involved.

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**REVIEW
OF THE
PARAMETERS
OF
INTERLOCKING**

**First, the size
of
geogrid apertures**

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ROLE OF THE **SIZE** OF GEOGRID APERTURES

- It is known that the effectiveness of geogrid-aggregate interlocking depends on the **size** of the apertures compared to the **size** of aggregate.
- However, this is complex because the size of aggregate is quantified using a **grading curve**, **not a single value**.

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Formulas have been proposed, for example:

$$A = 1.2 \text{ to } 1.6 d_{90} \quad (\text{Brown et al. 2007})$$

$$d_{50} \leq A \leq 2 d_{85} \quad (\text{FHWA Manual on geosynthetics, 2008})$$

But, it is generally considered that **so many parameters** have an influence on the selection of optimum geogrid aperture size that it is **not possible** to propose a **general rule** applicable to all types of geogrids.

Therefore, the **experience** acquired by suppliers for their specific geogrids can be beneficial to design engineers.

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After the size, the shape of the geogrid apertures

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SHAPE OF GEOGRID APERTURES

Square or rectangular apertures in **biaxial** geogrids



Courtesy
NAUE

Triangular apertures in **triaxial** geogrids



Courtesy
TENSAR

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ROLE OF THE SHAPE OF GEOGRID APERTURES

- The effectiveness of geogrid-aggregate interaction depends on the **relative geometry** of the geogrid and aggregate.
- **Square** or **rectangular** apertures can be expected to promote a **cubic** arrangement of aggregate, which is a **loose** arrangement.
- This could **limit the benefit of interlocking**.

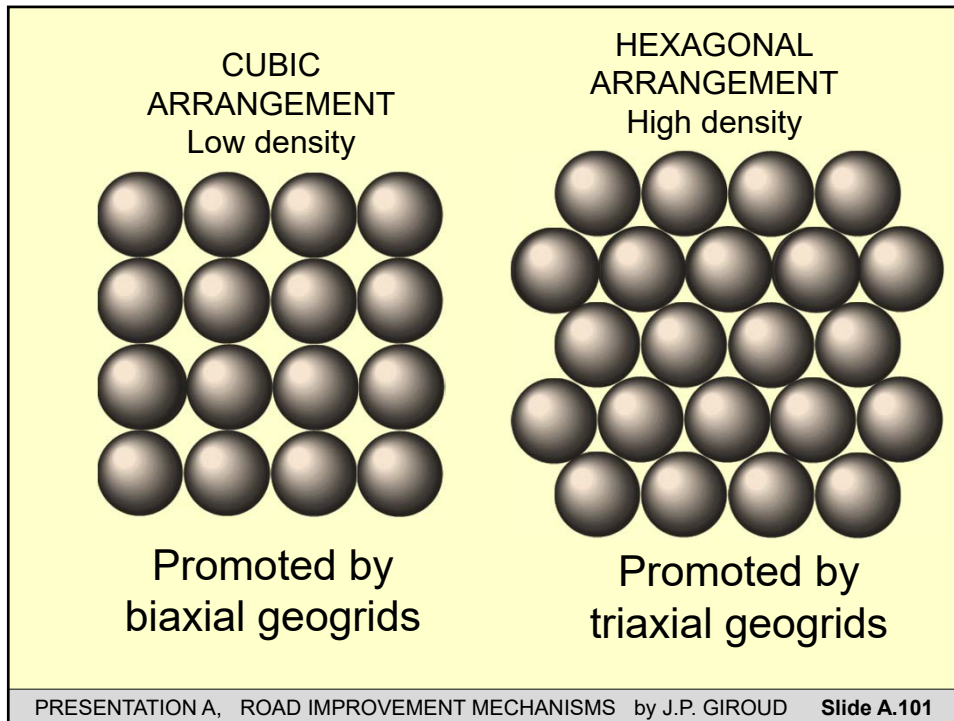
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ROLE OF THE SHAPE OF GEOGRID APERTURES

- In contrast, **triangular** apertures can be expected to match or promote a **hexagonal** arrangement of aggregate, which is the **densest** arrangement.
- Therefore, triangular apertures may lead to maximum stiffness of the stabilized aggregate, i.e. **maximum interlocking**.

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Mechanisms of Road Improvement by Geosynthetics by J.P. Giroud



**After the apertures,
the ribs**

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**CROSS SECTIONS OF RIBS OF
PUNCHED-AND-DRAWN
BIAXIAL
GEOGRIDS**



The ribs are relatively flat.

Courtesy
TENSAR

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**ROLE OF THE SHAPE AND STIFFNESS
OF RIBS**

- Ideally, the ribs should offer maximum contact area with aggregate, while causing **minimum disturbance** of the aggregate arrangement.
- This leads to the concepts of **optimum shape and stiffness** of the ribs and mechanical compatibility between geogrid and aggregate.

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In the case of **punched-and-drawn** geogrids:

- ribs should be **relatively high** to increase contact with the aggregate, but should **not be too wide** in order not to disturb the aggregate;
- ribs should be **not too stiff**, while they should not be too flimsy, because excessively stiff ribs may disorganize the aggregate structure, and locally decrease the aggregate density.

There may be an **optimum rib stiffness**.

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The goal of **optimum** rib **stiffness** is to have **maximum stiffness** of the aggregate-geogrid composite rather than **maximum stiffness** of the geogrid.

This discussion of rib stiffness is essentially qualitative.

Clearly, more research is needed to quantify the influence of rib stiffness on interlocking.

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After the apertures, the junctions between ribs

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ROLE OF THE JUNCTIONS BETWEEN RIBS

- The mechanical behavior of the junctions between ribs is important in the case of **punched-and-drawn geogrids**, because they interact with aggregate **only through interlocking**.
- But this may not be important for geogrids that interact with aggregate through **both friction and interlocking**.

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After this discussion of **base modulus increase** provided by the geosynthetic (through closed confinement or open confinement, i.e. interlocking), let's discuss the **lateral restraint** provided by the geosynthetic.

Lateral restraint refers to **reduction** of **lateral displacement** of base material under repeated loading.

Lateral restraint and confinement are the same thing, as discussed in the next slide.

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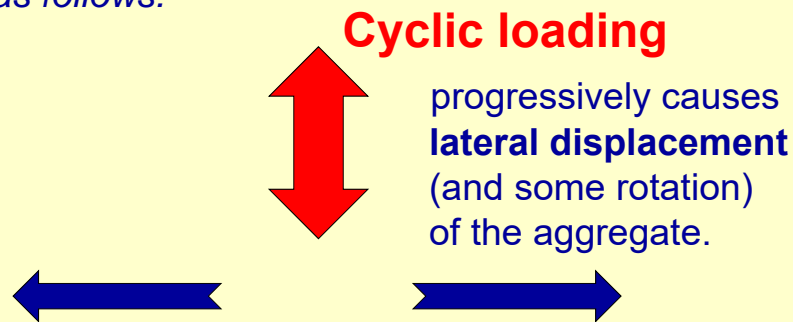
LATERAL RESTRAINT AND CONFINEMENT

The mechanical action of a geosynthetic, which results in **lateral restraint**, is **equivalent** to the application of a lateral **confining stress**, a familiar concept in geotechnical engineering.

Lateral restraint and confinement are the two aspects of the **stabilization function** of geosynthetics.

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The need for lateral restraint can be summarized as follows:



Hence the need for **lateral restraint**, which prevents (or minimizes) lateral displacement (and rotation) of aggregate particles.

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COMMENT

It should be noted that, while the **loading is cyclic**, the resulting lateral displacement is not cyclic.

The non-elastic part of the lateral displacement, i.e. the permanent displacement, keeps increasing at each load cycle (i.e. *monotonic increase*).

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Lateral restraint is a **long-term benefit** of using geosynthetic stabilization.

Thanks to lateral restraint of the base material, the **service life** of a base is **increased**, because the base material stays together and provides **stress distribution** during a **longer period of time** than a base without geosynthetic.

Geosynthetic stabilization **improves stress distribution**, and, thanks to lateral restraint, the improved stress distribution is provided for a **longer time**.

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Furthermore, since lateral restraint keeps the base material together:

- Coarse particles of the base are *less likely* to **migrate** downward and **penetrate** into the subgrade.
- The base material is *less likely* to be **contaminated** by **soft soil** squeezed from the subgrade or by **fine particles** migrating upward from the subgrade under the action of water pressure.

This further contributes to increasing the road service life.

*This will be discussed later in this presentation when we discuss the **separation function**.*

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In summary, lateral restraint contributes to the **long-term performance** of unpaved roads in two ways:

- by slowing down **base deterioration** due to lateral spreading of base material;
and
- by allowing a geosynthetic to contribute(*) to **separation** between base material and subgrade soil.
(* *contribution to a degree that depends on the type of geosynthetic*).

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Lateral restraint of base material
being in fact an aspect of confinement
is provided by geosynthetics
to **various degrees**:

- **Closed confinement** in **geocell** provides effective lateral restraint with **most types of soil** in the cells.
- **Open confinement** with **geogrid** (i.e. *interlocking*) is effective if **adequate aggregate** is used for the base material.

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LATERAL RESTRAINT OF BASE MATERIAL
and, now, the case of geotextiles.

In the case of **woven geotextiles**,
interface friction provides
limited lateral restraint:

- because friction requires
relative geotextile/base displacement
to be mobilized;
and also
- because the magnitude of friction is limited
since friction is proportional to normal stress
and the overburden stress is low in roads.

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LATERAL RESTRAINT OF BASE MATERIAL
and, now, the case of geotextiles:

In the case of **nonwoven geotextiles**,
lateral restraint of aggregate
may be increased
if the nonwoven geotextile
deforms sufficiently
to be indented by adjacent aggregate.

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It is important to repeat that
confinement and lateral restraint are linked
because they are two aspects
of the same geosynthetic function :
stabilization,
also called “mechanical stabilization”.

The **increase in modulus** of the base
results from
the **lateral restraint of the base material**
and, therefore, results from
the **confinement of the base**.

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Confinement means
“the act of keeping in a limited space”.

- This is exactly **what a geocell does**
to the material contained in the geocell.
- This is **what a geogrid does**
to the adjacent aggregate
assuming there is size compatibility
between the aggregate particles
and the geogrid apertures.

Based on the above definition,
confinement is lateral restraint.

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To confine the base material,
the geosynthetic (geocell or geogrid)
applies a **lateral stress**
on the base material.

It is interesting to note that, in soil mechanics,
this lateral stress is called **confining stress**.

And, it is known in soil mechanics that
confining stress increases the vertical modulus.

Clearly,
the increase in **vertical modulus** of the base
results from **confinement**.

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The foregoing discussion shows that
the **increased modulus** of the base material
is a consequence of **confinement**.
In other words, the increased modulus
is a consequence of **lateral restraint**,
since confinement and lateral restraint
are the two identical characteristics
of the **stabilization function**.

Stabilization has a **beneficial** effect
on unpaved road performance,
both on the **short term** and the **long term**.

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Without confinement of the base,
the **accumulation over time**
(i.e. with repeated traffic loading)
of **permanent displacement** of the base material,
tends to scatter the particles
of the base material (e.g. aggregate),
thereby progressively **decreasing** the base modulus,
which reduces the capacity of the base
to distribute the traffic load.

With confinement, i.e. lateral restraint of the base,
displacement of base material is limited.
As a result, the progressive decrease
of the base modulus is much slower.

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Now,
after this long discussion
of **load distribution by the base**,
in the short term and the long term,
let's discuss
the **stresses applied to the subgrade soil**.

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The stresses applied to the subgrade soil are:

- the stresses at the bottom of the base (i.e. the **stresses as distributed** by the geosynthetic-stabilized base), **minus**
- the **stresses carried directly by the geosynthetic.**

Indeed,
the geosynthetic may carry stresses
through the famous
tensioned membrane effect.

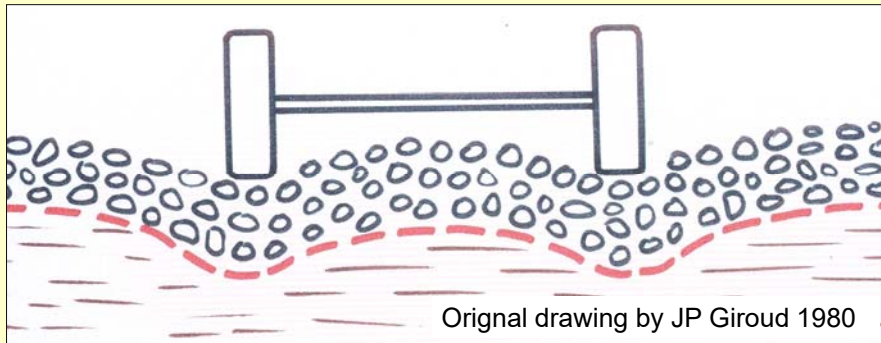
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The tensioned membrane effect is “**famous**” because, in early attempts at explaining the behavior of unpaved roads, **it was thought** that the tensioned membrane effect was the **main mechanism** governing the performance of unpaved roads.

We will see that it is not the case.

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Explanation of the tensioned membrane effect

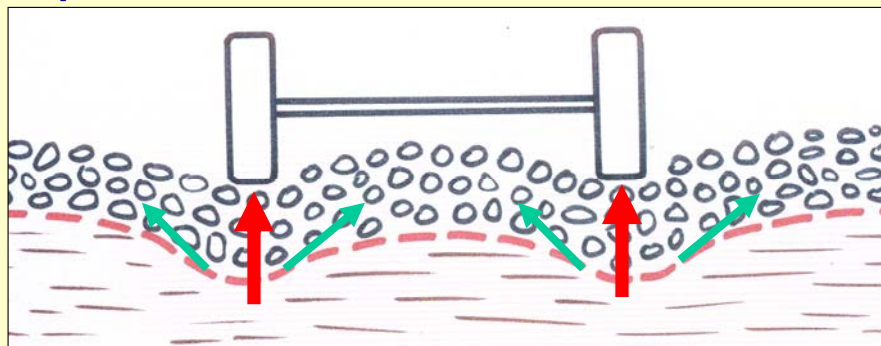


To follow the subgrade deformation resulting from traffic, the **geosynthetic** elongates and is, therefore, under tension.

Under the wheels, due to rutting, the **geosynthetic** has a **concave shape**.

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Explanation of the tensioned membrane effect

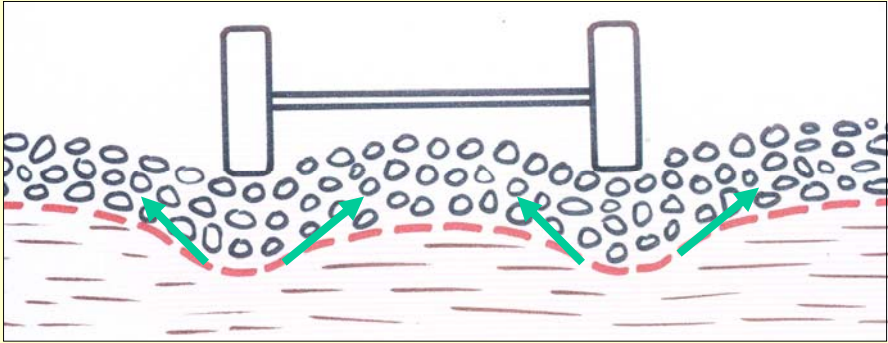


The **geosynthetic tensions** on each side of the concave shapes are shown in **green**.

The **resultants** of these **tensions** are shown in **red**.
These **resultants** are vertical and upward.
Therefore, they contribute to **wheel support**.

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The need for lateral anchorage



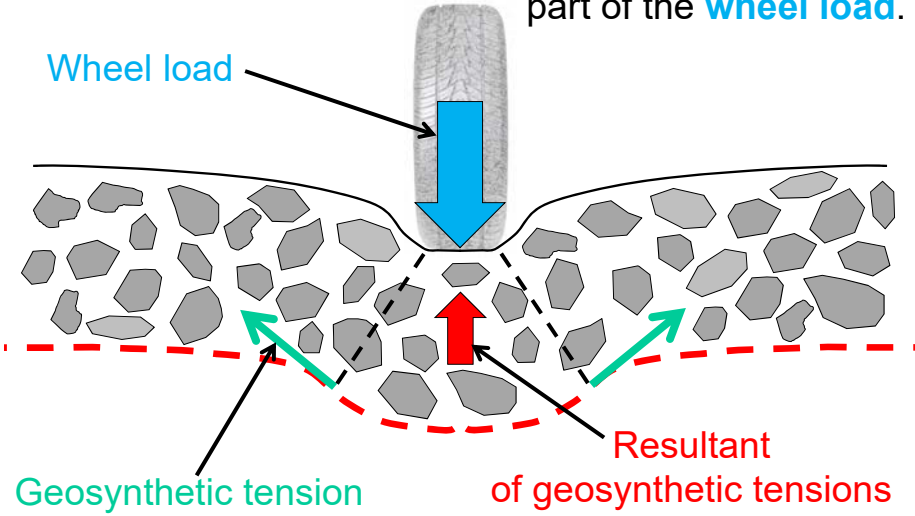
The **geosynthetic tensions** can develop as shown only if the geosynthetic is **anchored laterally**.

The higher the geosynthetic tensile modulus, the longer the required **anchorage length**.

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TENSIONED MEMBRANE EFFECT SUMMARY

The **resultant** of geosynthetic **tensions** supports part of the **wheel load**.



Wheel load

Geosynthetic tension

Resultant of geosynthetic tensions

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Clearly, the tensioned membrane effect requires **rutting** (in fact, **deep rutting**).

But what is the **effectiveness** of the tensioned membrane effect ?

This is an important question, because, in the **early days** of unpaved road design, it was thought (as mentioned earlier) that the tensioned membrane effect was the **main mechanism** governing the improvement of unpaved roads by geosynthetics.

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The **effectiveness** of the tensioned membrane effect depends on many **parameters** (Han 2018):

- rut depth;
- geosynthetic tensile modulus;
- subgrade strength;
- road geometry (base thickness and tire contact area);
- geosynthetic lateral anchorage.

The influence of rut depth has been quantified.

Next slides 

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TENSIONED MEMBRANE EFFECTIVENESS

The tensioned membrane effect has been quantified by Giroud & Noiray (1981), and calculations (Giroud et al. 1984) for **typical geogrids** have shown that:

- for **rut depths less than 75 mm**, the **tensioned membrane effect is negligible**;
- For a **rut depth of 150 mm**, the tensioned membrane effect is “10% effective”, i.e. it decreases the required base thickness by 10%.

More on the next slide 

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Han et al. (2019a, 2019b) have performed a theoretical study comparing the lateral restraint effect and the tensioned membrane effect.

They concluded that the tensioned membrane effect can be ignored if the rut depth is less than 75 mm.

This conclusion is consistent with the conclusion from the preceding slide.

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The quantitative evaluations mentioned in the two preceding slides were done for **typical geogrids** currently used.

One may expect that the tensioned membrane effect could be more effective with a geosynthetic having a **very high tensile modulus**.

This expectation is logical, as explained in the following slides.

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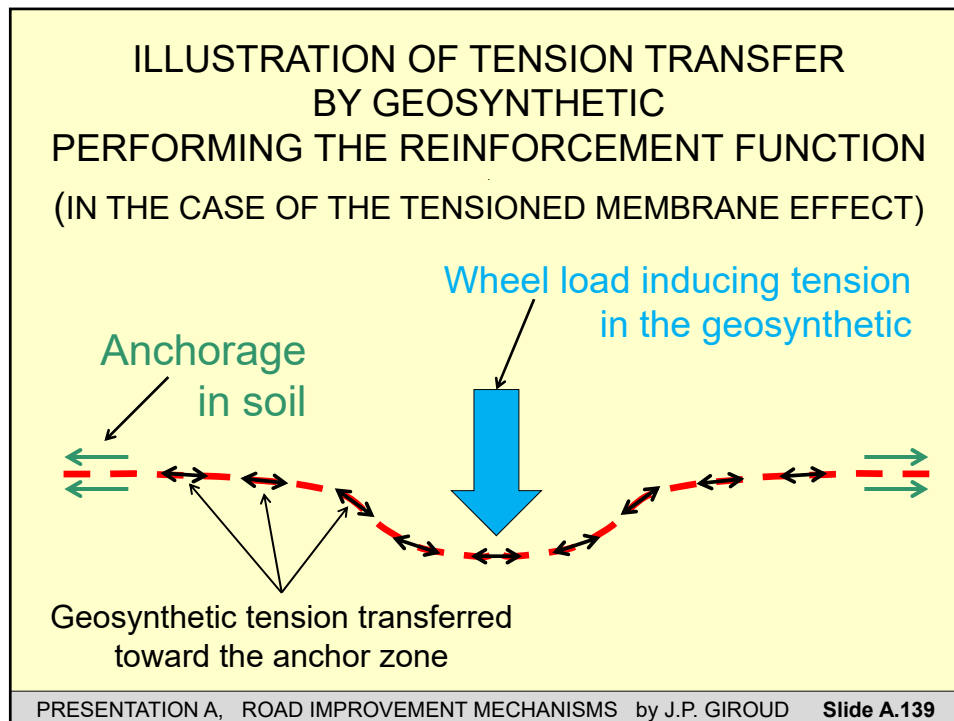
In the tensioned membrane effect, the geosynthetic performs the reinforcement function.

Definition:

A geosynthetic performs the **reinforcement function** when it increases the strength and/or reduces the deformation of a soil structure by carrying tensile forces that the soil alone would not carry.

Typically, the reinforcement function is performed by a geosynthetic, which **transfers tensile forces** from one place to another place where the geosynthetic is **anchored**.

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To transfer tensile forces,
a geosynthetic having a **high tensile modulus**
is required.

However, a geosynthetic with a high tensile modulus,
such as some woven geotextiles,
may not be as effective as expected
because the required **anchorage length**
would be very long and, therefore,
incompatible with the width of the road,
as pointed out by Han (2018).

Alternatively, a cumbersome and expensive
anchorage structure would be needed
on each side of the road.

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In conclusion of all the above discussions,
the **tensioned membrane effect**
is generally **not a significant contributor**
to the performance
of geosynthetics in unpaved roads
(*except for access roads with deep ruts*).

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Now, let's discuss the improvement
of the **bearing capacity** of the **subgrade**.

It will be seen that improvement
of the subgrade bearing capacity
results from the **reinforcement function**
performed by the geosynthetic,
as in the case of
the tensioned membrane effect
discussed in preceding slides.

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A **major assumption** is made regarding the subgrade.

It is assumed that the **subgrade soil**
is a **low-permeability saturated soil**.

Under traffic loads,
this material is reacting in an **undrained** mode,
i.e. it is **incompressible** and **frictionless**.
(*This is a classical concept in soil mechanics.*)

The subgrade soil is characterized
by its **undrained shear strength**,
also called *undrained cohesion*, hence the symbol c_u .

The undrained shear strength is assumed to be constant
over the entire zone of the **subgrade**
involved in the bearing capacity mechanism.

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The undrained behavior described in the preceding slide
is typical of **clay** or **clayey soils**,
but some unpaved roads are constructed on **peat**.

Peat is **compressible** and has **friction**.

The saturated clay assumption,
(**incompressible** and **frictionless**)
mentioned in the preceding slide,
is not applicable to peat.

*No design method
for unpaved roads constructed on peat
has been identified
during the preparation of this presentation.*

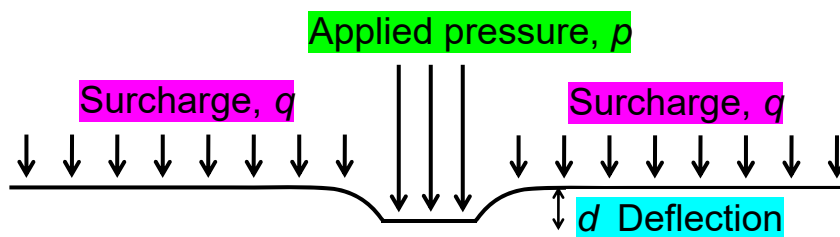
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.144

Let's get back to basics of soil mechanics
to understand **bearing capacity**.

Only the case of a **frictionless soil**
will be considered,
as this is the assumption just made
for the **behavior of the subgrade**.

Bearing capacity is the quantification
of the ability of a soil **to carry a load**
applied on a given area.

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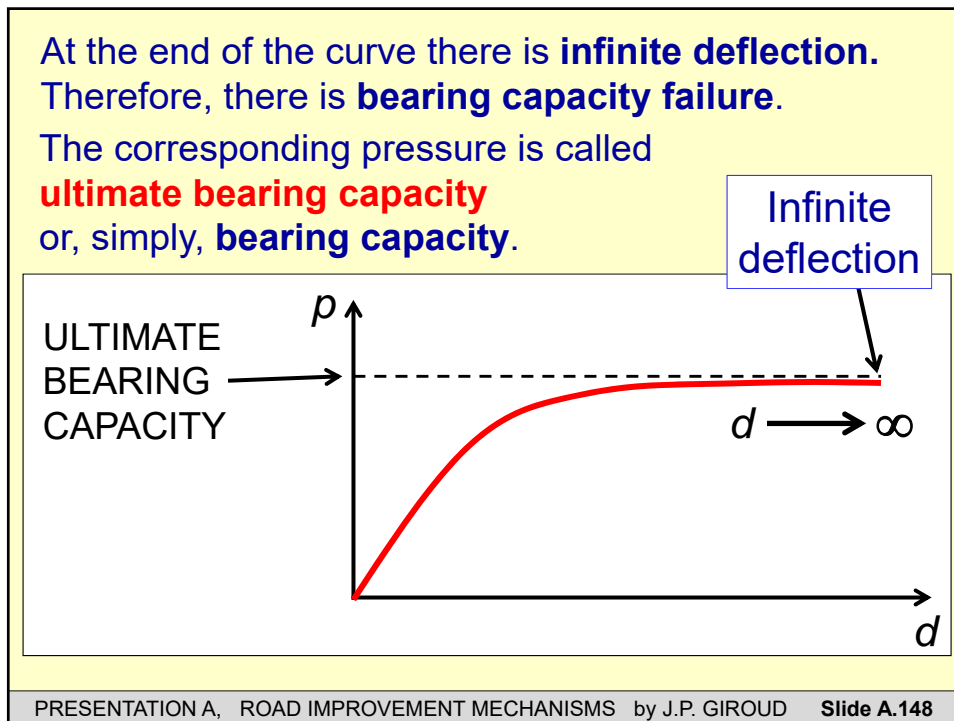
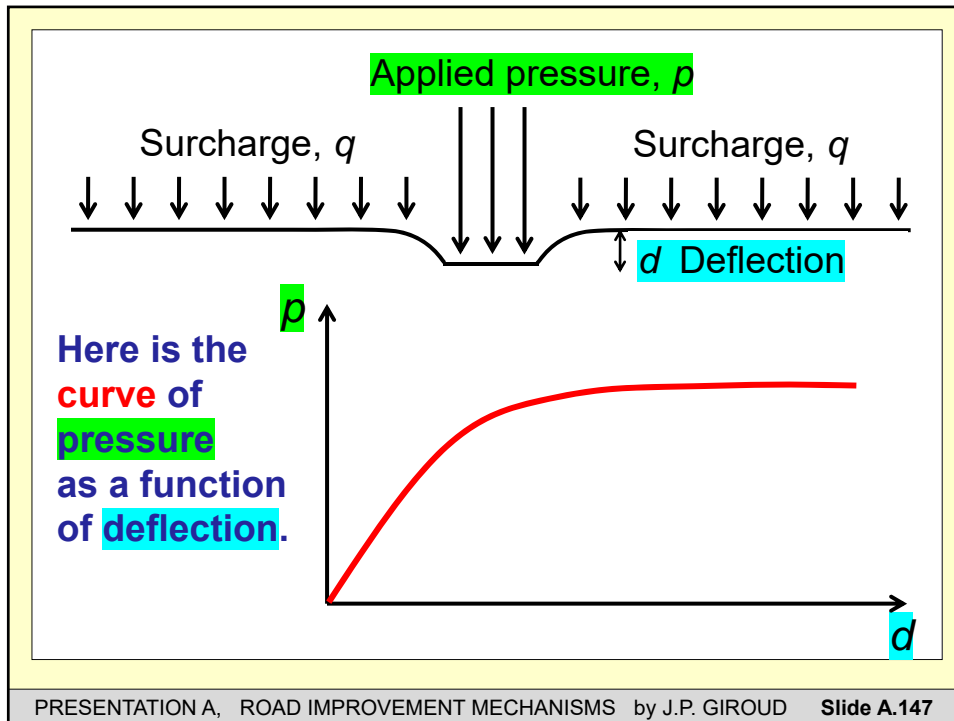


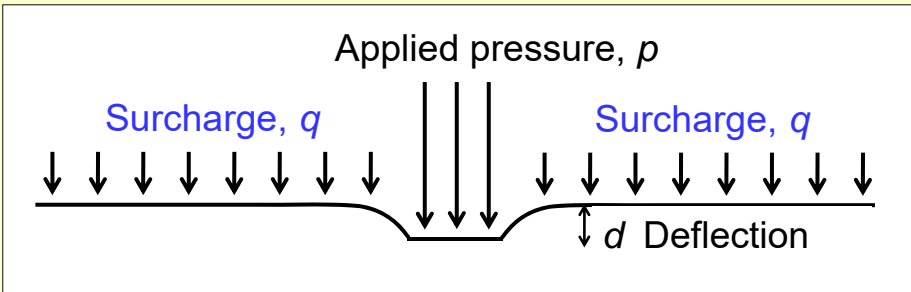
The basic bearing capacity situation
is that of a **pressure applied** over an area
next to a **surcharge**.

As the **pressure** is progressively applied,
the **deflection** of the soil surface increases.

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Mechanisms of Road Improvement by Geosynthetics
by J.P. Giroud





In the case of a **frictionless soil**,
the **ultimate bearing capacity**
is given by the following equation:

$$p_{ult} = N_c c_u + q$$

IMPORTANT COMMENT

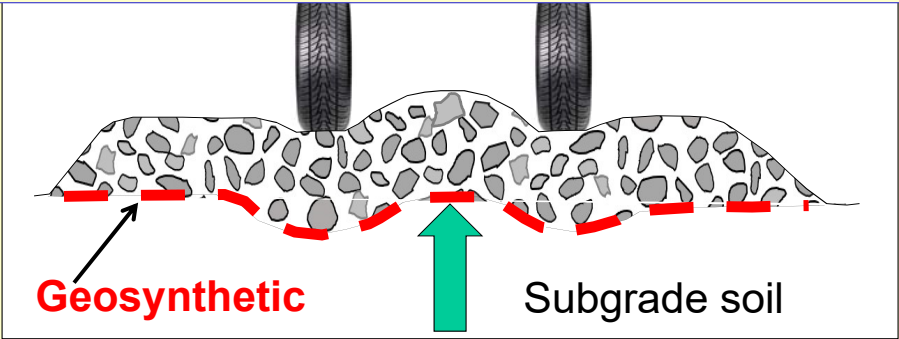
The **surcharge, q** , increases the bearing capacity.

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We will now see that
a **geosynthetic**
located between base and subgrade
applies a surcharge on the subgrade,
which increases the bearing capacity
of the subgrade.

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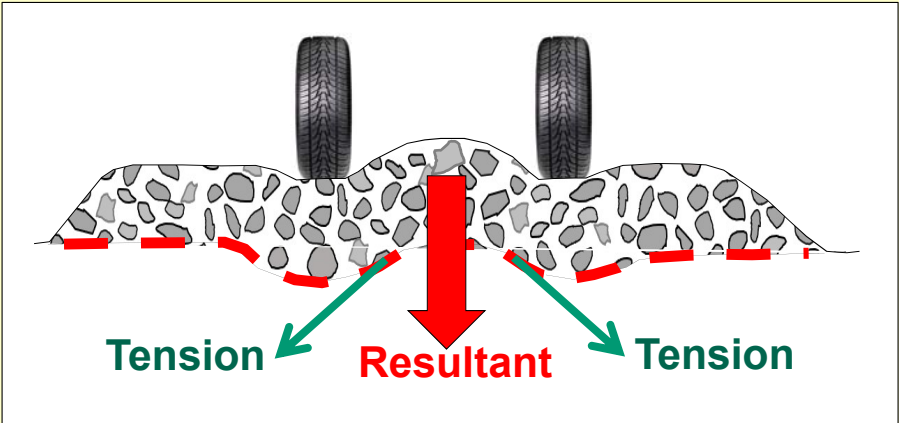
The subgrade soil tends to heave between the wheels.



Geosynthetic Subgrade soil

Restraint of subgrade heave provided by the geosynthetic **under tension** controls the **vertical displacement** of the subgrade soil between the wheels.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.151

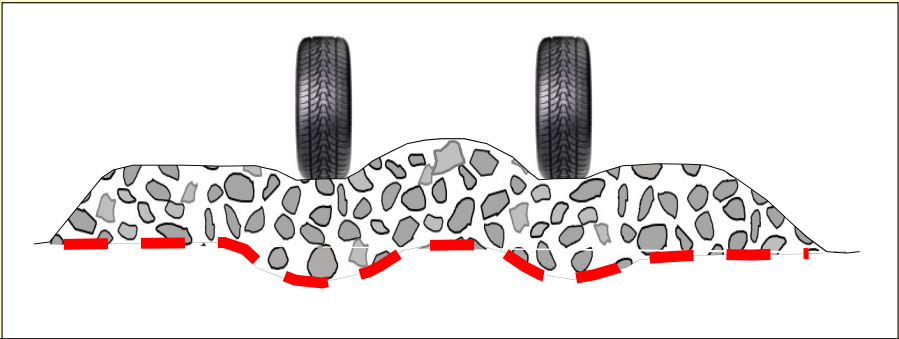


Tension **Resultant** **Tension**

The **resultant** of the geosynthetic **tensions** is vertical and oriented downward. This **resultant** acts as a surcharge.

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Mechanisms of Road Improvement by Geosynthetics by J.P. Giroud



*It is important to note that the weight of the base is not accounted for as a surcharge because it acts **both under and between** the wheels.*

In other words, the weight of the base cancels out in the bearing capacity equation.

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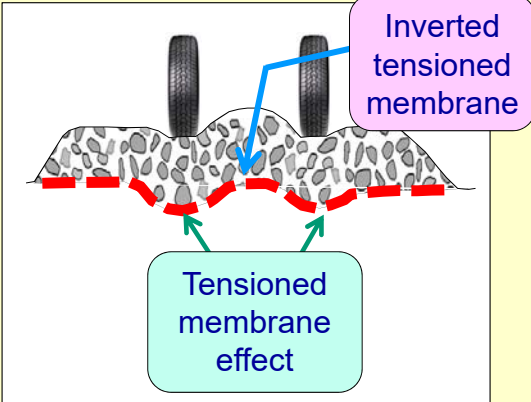
Geotextile restraining the subgrade soil vertically



Test at WES

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.154

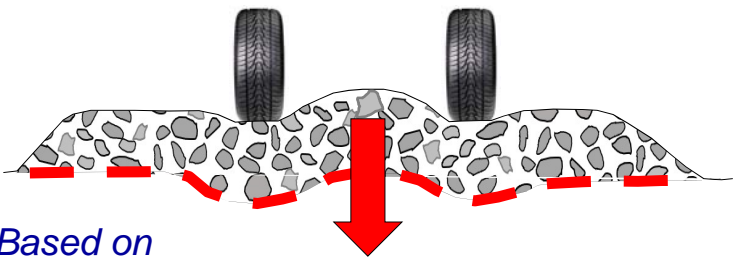
Restraint
of the
subgrade heave
is similar to
**tensioned
membrane
effect**
(but, upside down).



The diagram shows a cross-section of a road with two tires on top. Below the road surface is a layer of aggregate and a red dashed line representing a geosynthetic membrane. The membrane is shown in a wavy, inverted shape, with arrows pointing upwards from it towards the subgrade. A blue box labeled 'Inverted tensioned membrane' points to the membrane, and a green box labeled 'Tensioned membrane effect' points to the upward arrows.

This “**inverted tensioned membrane effect**”
applies a downward pressure on the subgrade,
which acts as a **surcharge**,
and results in an **increase in bearing capacity**
of the subgrade.

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The diagram shows a cross-section of a road with two tires on top. Below the road surface is a layer of aggregate and a red dashed line representing a geosynthetic membrane. A large red arrow points downwards from the membrane towards the subgrade.

*Based on
the preceding slides,*
when a geosynthetic is present,
the subgrade restricted heave
is associated with a **vertical pressure**.

*We will show that this **vertical pressure** acts
as a **surcharge** increasing the bearing capacity
of the subgrade.*

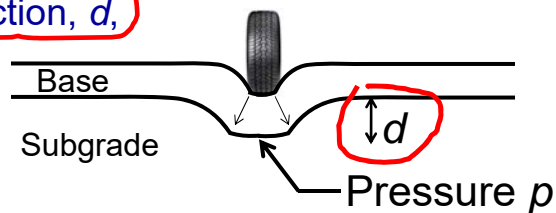
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.156

Since the inverted tensioned membrane effect is similar to the tensioned membrane effect, there is tension transfer in the geosynthetic, as explained in Slide A.139.

Therefore,
the subgrade bearing capacity increase results from the geosynthetic performing the **reinforcement function**, like in the case of the tensioned membrane effect.

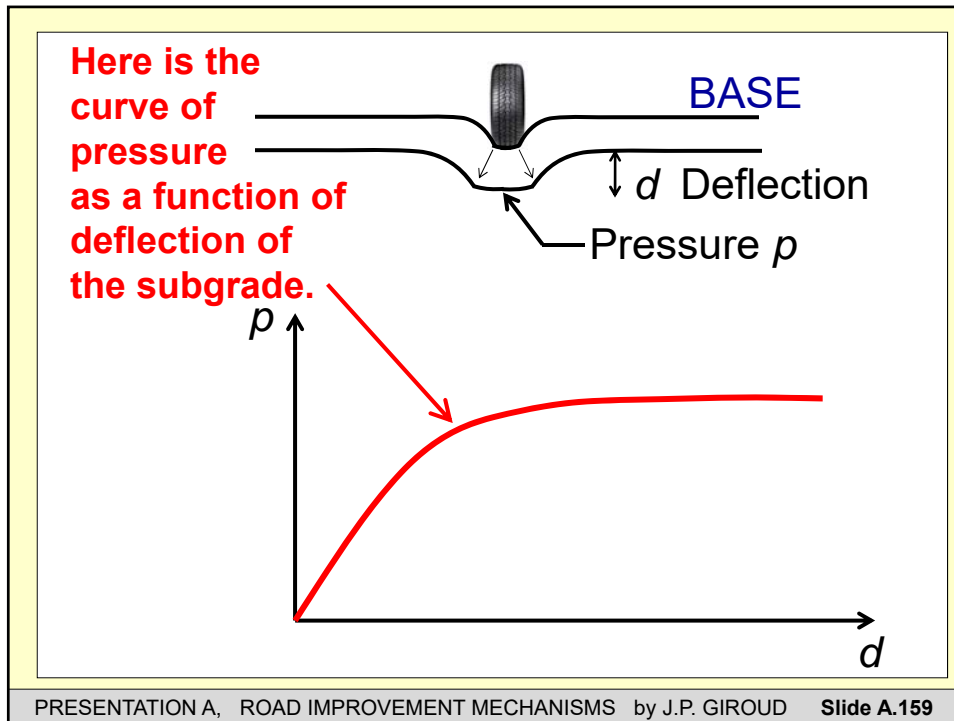
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.157

Consider the **deflection, d** , of the subgrade under a wheel.



*It is important to note that the deflection that is discussed here is the deflection at the top of the **subgrade** not the deflection at the top of the base (rut).*

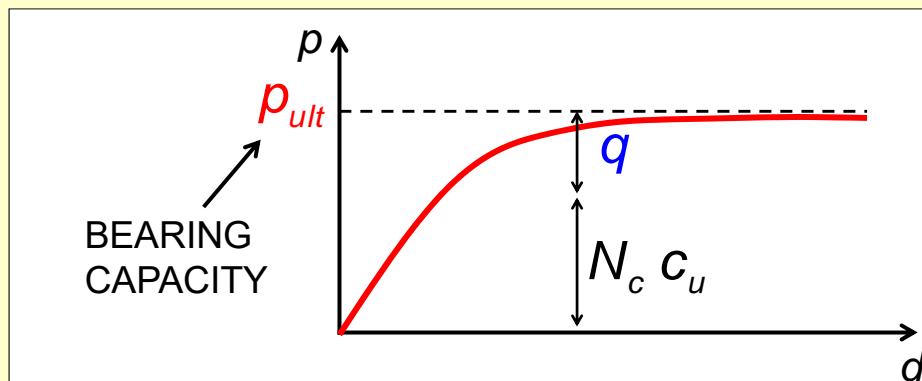
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.158



Here again is the bearing capacity equation:

$$p_{ult} = N_c c_u + q \quad \text{where } q \text{ is the surcharge}$$

This equation is represented on the figure.



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As seen earlier, **subgrade heave restraint** generates a vertical pressure acting as a **surcharge**,
as in foundation design.

As shown by the bearing capacity equation,
a **surcharge**, q ,
increases the **bearing capacity**:

$$p_{ult} = N_c c_u + q$$

Therefore, the subgrade heave restraint applied by the geosynthetic
increases the bearing capacity of the subgrade.

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At this point, the question is:

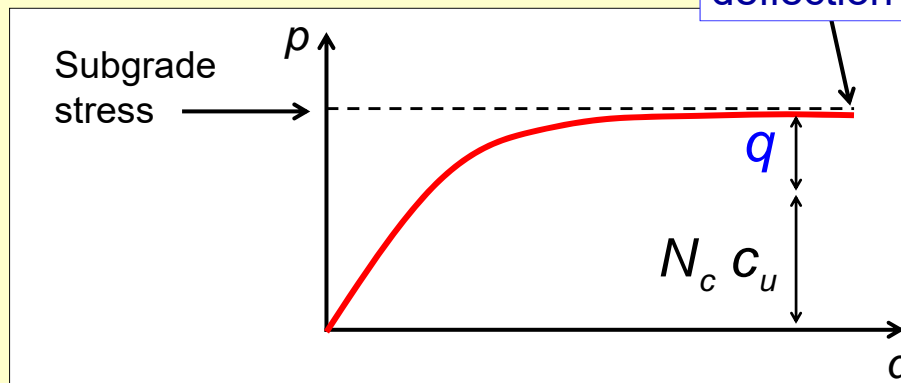
Can we allow
the **stress on the subgrade**
to be as high as
the subgrade bearing capacity ?

$$p_{ult} = N_c c_u + q$$

i.e. the bearing capacity calculated
including the surcharge, q .

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This graph shows that,
if the subgrade stress is $N_c c_u + q$,
the **deflection is infinite**
at **first passage of axle**.

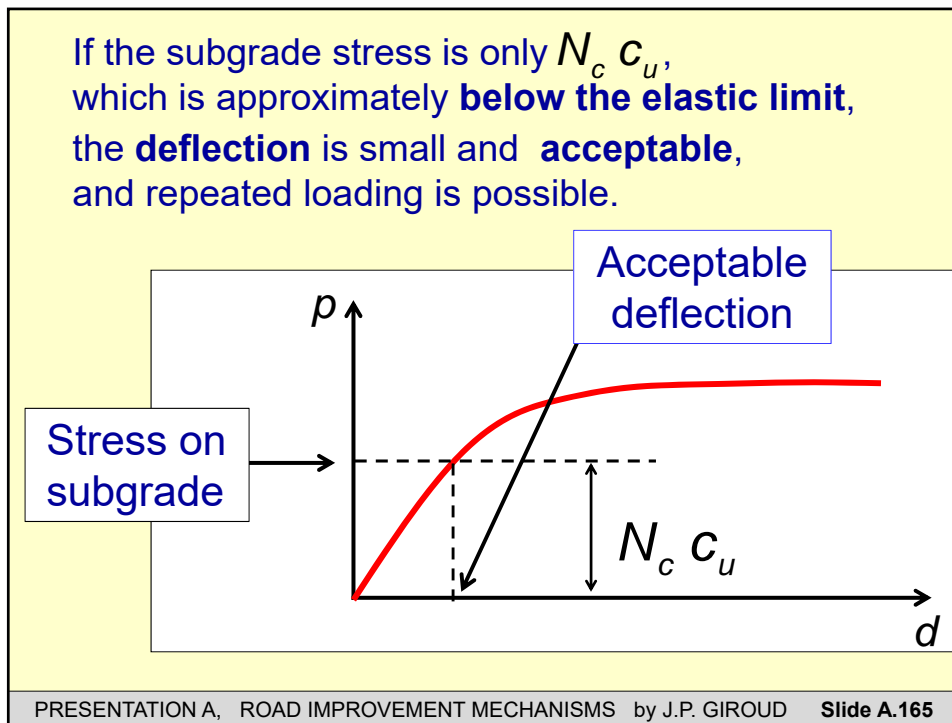


PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.163

An **infinite deflection**
at first passage of an axle
is, of course, **unacceptable**
(*i.e. the road fails*
at first passage of a vehicle).

Rather than loading the subgrade
at the ultimate bearing capacity
(which is the **plasticity limit**)
the load on the subgrade should be
less than the **elastic limit**,
which will allow **repeated loading**.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.164



Therefore, in the case of an **unpaved road with geosynthetic**, the **allowable stress on the subgrade soil** is the subgrade bearing capacity calculated **without** taking into account the **surcharge**:

$$\text{Allowable stress} = N_c c_u$$

Note: The surcharge, q , exists, but its role is to **provide a margin** between the *elastic limit* and the *plasticity limit*.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.166

In conclusion,
geosynthetic reinforcement
makes it possible to take **full advantage**
of the **bearing capacity** of the subgrade
(*albeit without accounting for the surcharge*)
while maintaining an **acceptable deflection**.

*This is why we discussed bearing capacity
with emphasis on deflection.*

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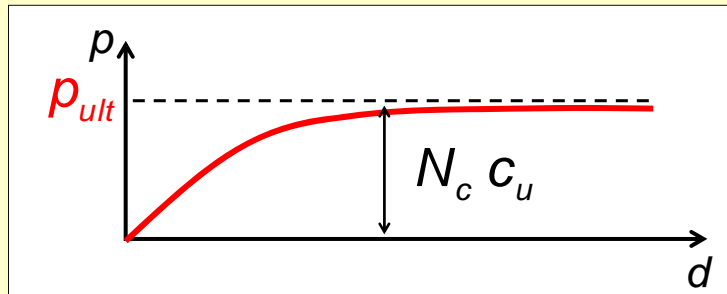
Now, what about
an unpaved road
without geosynthetic ?

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.168

If there is no geosynthetic, the surcharge due to the geosynthetic is zero ($q = 0$).

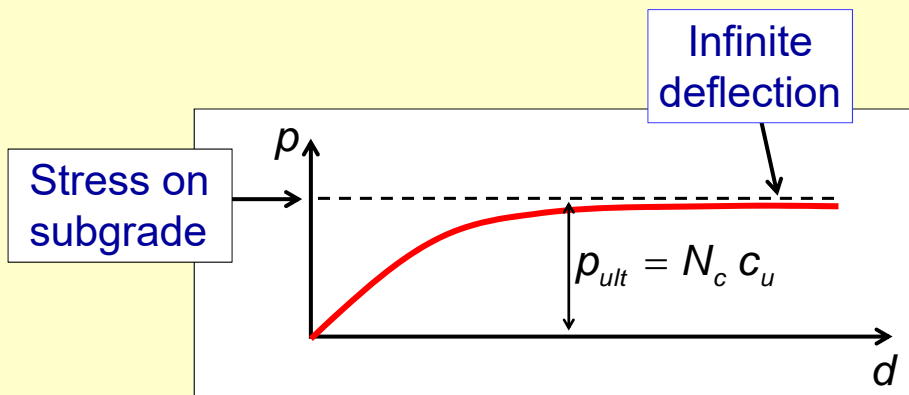
Therefore, the bearing capacity equation becomes: $p_{ult} = N_c c_u + 0$ because $q = 0$

hence the curve of pressure versus deflection:



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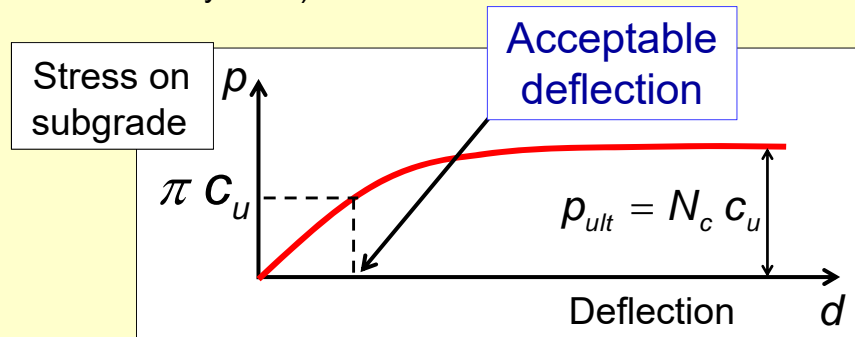
This figure shows that, in the case where there is **no geosynthetic**, the **deflection is infinite** if the stress on the subgrade is $N_c c_u$



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In the case where there is **no geosynthetic**, the **deflection** is small and **acceptable** if the stress on the subgrade is at the **elastic limit** of the curve, given by:

$\pi c_u = 3.14 c_u$ which is much lower than p_{ult}
(Giroud & Noiray 1981)



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Based on the preceding slides:

An **unpaved road with no geosynthetic** (i.e. without subgrade heave restraint) should not be loaded above $3.14 c_u$, which is much less than $p_{ult} = N_c c_u$. It undergoes infinite deflection, i.e. it fails at **one axle pass**, if the load at the top of the subgrade is equal to the ultimate bearing capacity p_{ult} .

In contrast, we have seen that an **unpaved road with geosynthetic** has an acceptable deflection under the same load, p_{ult} , on the subgrade.

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Last question:

What is the value
of the **bearing capacity factor**, N_c ,
to be used in the calculation of p_{ult} ?

According to the plasticity theory,
the most typical value of N_c ,
in the case of a frictionless soil, is:

$$N_c = \pi + 2 = 5.14$$

*However, this **well-known value** is
for the case where there are **no shear stresses**
at the base/subgrade interface.*

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According to the theory of plasticity,
a surcharge with **inward inclined stresses**
increases the bearing capacity
compared to surcharge with normal stresses.

The bearing capacity factor is:

$N_c = 5.71$ in the case of inclined inward stresses
and

$N_c = 5.14$ in the case of normal stresses

This is illustrated on the next slide 

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Bearing capacity equation: $p_{ult} = N_c c_u + q$

Bearing capacity, p_{ult}

Surcharge, q

Normal stress

$N_c = 5.14$

Bearing capacity, p_{ult}

Surcharge, q

Inclined stress

$N_c = 5.71$

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Two conditions should be met:

- (1) for the stresses to be inclined the base/subgrade interface should be rough rather than smooth; and
- (2) for the stresses to be inclined in the inward direction, the lateral displacement of the base and the geosynthetic should be less than the lateral displacement of the top of the subgrade (in other words, lateral restraint of the base is required).

The two conditions are met in the case of a geogrid-stabilized aggregate base:

- aggregate that protrudes through the geogrid apertures creates a rough interface with the subgrade; and
- Thanks to the lateral restraint, the lateral displacement of the base is less than the lateral displacement of the subgrade.

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The two conditions being met in the case of a **geogrid-stabilized** aggregate base the value of N_c is:

$$N_c = \frac{3\pi}{2} + 1 = 5.71$$

The two conditions are not met in the case of a **geotextile-stabilized** aggregate base.

The value of N_c is then:

$$N_c = \pi + 2 = 5.14$$

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.178

How are **shear stresses** at the base-subgrade interface **possible with a frictionless soil** ?

The subgrade soil being **incompressible**, it tends to move outward as the deflection progresses.

If the base is laterally restrained by a geogrid, the relative displacement of base vs. subgrade generates inward shear stresses on subgrade.

Even though the subgrade soil is frictionless, shear stresses can develop, but they are **limited** to the undrained shear strength ($\tau = c_u$), which is sufficient to increase the bearing capacity factor from 5.14 to 5.71.

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Summary: the allowable stress on the subgrade is:

Case with **no geosynthetic**:

$$\text{Allowable stress} = \pi c_u = 3.14 c_u$$

Case with **geotextile**:

$$\text{Allowable stress} = (\pi + 2) c_u = 5.14 c_u$$

*(because interface is smooth
and/or lateral restraint is negligible in this case)*

Case with **geogrid**:

$$\text{Allowable stress} = \left(\frac{3\pi}{2} + 1 \right) c_u = 5.71 c_u$$

(thanks to rough interface and lateral restraint)

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Benefit from using geosynthetic:

Reference case with **no geosynthetic**:

$$\text{Allowable stress} = \pi c_u = 3.14 c_u$$

Case with **geotextile** : (BENEFIT 64%)

$$\text{Allowable stress} = (\pi + 2) c_u = 5.14 c_u$$

Case with **geogrid** or **geocell**: (BENEFIT 82%)

$$\text{Allowable stress} = \left(\frac{3\pi}{2} + 1 \right) c_u = 5.71 c_u$$

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**BEARING CAPACITY FACTOR
IN THE CASE OF
GEOCELL-STABILIZED BASE**

In the case of geocell-stabilized base,
the bearing capacity factor depends
on the material used to fill the cells
and on the presence or not of a geotextile
between the geocell and the subgrade.

In many cases, a geotextile is used
between the geocell and the subgrade,
then $N_c = 5.14$.

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The bearing capacity factors presented in the preceding slides are used in the Giroud-Han design method for unpaved roads, which has been presented and discussed in many papers and has been included into computer programs.

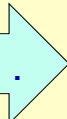
Bearing capacity factors are further discussed in Presentation B titled “Design of Geosynthetic-Stabilized Unpaved Roads and Case Histories” by J. Han.

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IMPORTANT COMMENT ON BEARING CAPACITY

The bearing capacity factors given in the preceding slides are based on the following **assumptions** presented earlier in this presentation:

- the subgrade soil is a saturated low-permeability material acting in the undrained mode, i.e. acting as a **frictionless** material; and
- the **undrained shear strength**, which characterizes this material, is **constant** over the entire subgrade zone involved in the bearing capacity mechanism.

If these assumptions are not met . . . 

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The above assumptions are not met

- if the subgrade soil exhibits **friction**
or
- if the undrained shear strength
increases as depth increases.

In both cases,
the shear strength increases as depth increases.

Indeed, if the subgrade soil exhibits friction,
its shear strength increases with normal stress,
therefore it increases as depth increases
since the normal stress increases with depth.

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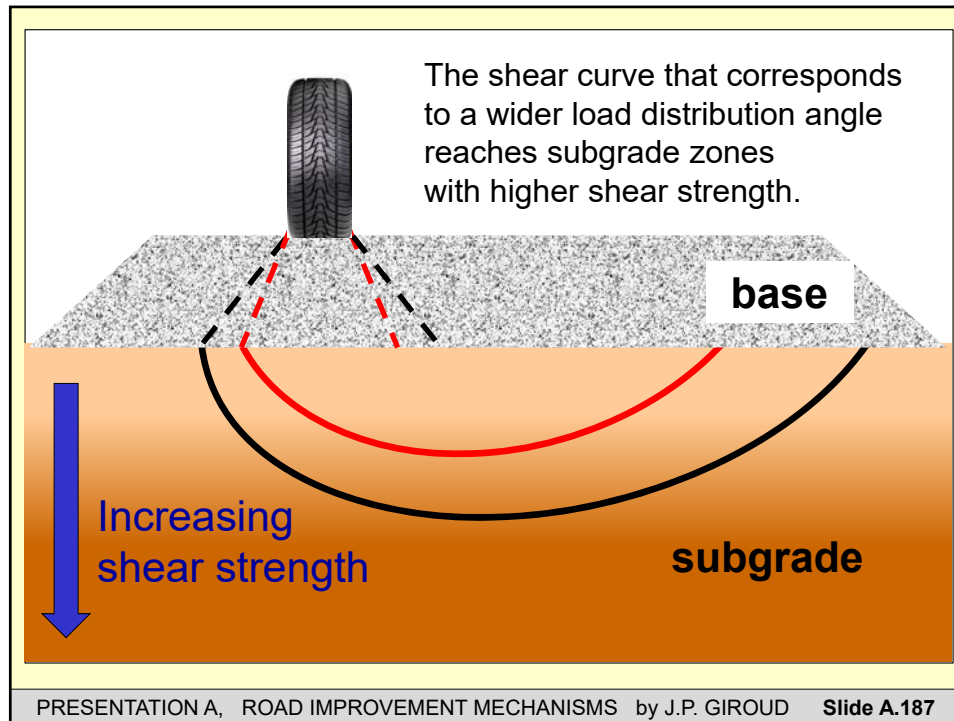
If the shear strength increases as depth increases,
then the **bearing capacity increases**
if the **load distribution angle** is widened
as a result of base stiffening.

In other words, in this case,
there is **interaction** between
load distribution by the base
and subgrade **bearing capacity.**

The mechanism is explained
in the following slide.

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Mechanisms of Road Improvement by Geosynthetics
by J.P. Giroud



*Now,
two final comments
on the analysis
of mechanisms.*

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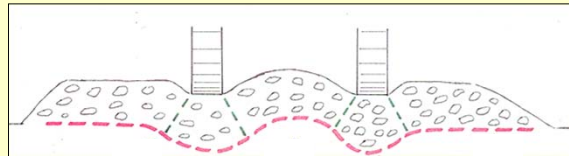
FIRST COMMENT

A geosynthetic provides two types of restraint:

- **Lateral restraint of base**,
which ensures long-term performance
by preventing lateral spreading of base material;
and
- **Subgrade heave restraint**,
which increases
the bearing capacity of the subgrade.

But, these two types of restraint are associated
with two different functions of the geosynthetic.
This is addressed later in this presentation.

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SECOND COMMENT

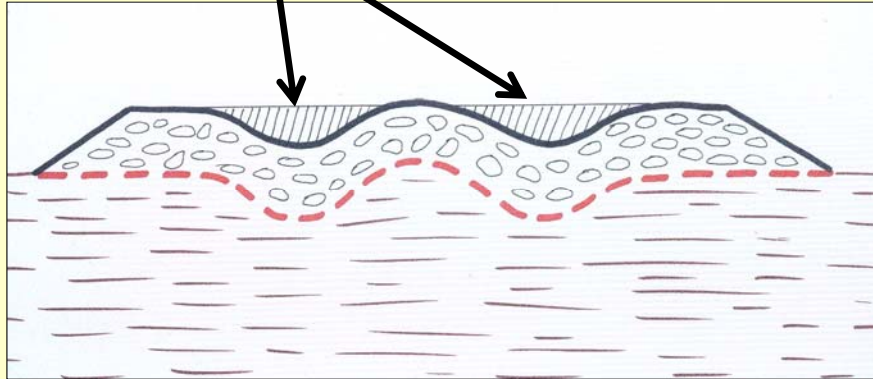
- **Subgrade bearing capacity improvement**
is possible only
if the geosynthetic is **under tension**
associated with **limited wavy deformation**.
- Also, the **tensioned membrane effect** works
only with geosynthetic under tension
due to **deep wavy deformation**.

Therefore, channelized traffic is important.

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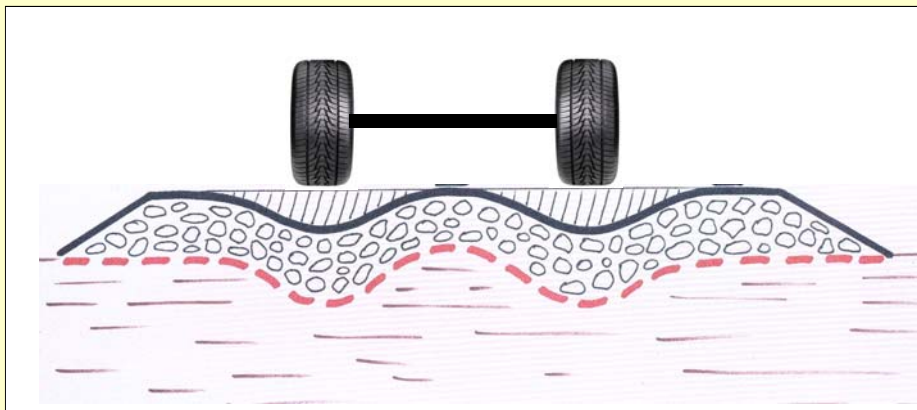
Typically, ruts are periodically backfilled as part of unpaved road maintenance.

BACKFILL



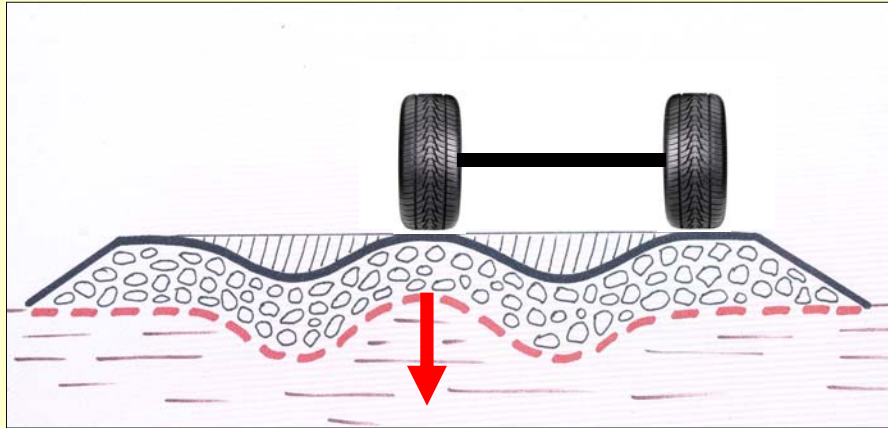
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If the traffic continues to be channelized, the geosynthetic remains under tension and the **subgrade bearing capacity** is increased; and, eventually, in case of **deep rutting**, the **tensioned membrane effect** may be mobilized.



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If the traffic is no longer channelized,
the geosynthetic tension decreases
and the subgrade bearing capacity decreases.



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The traffic is **not** channelized
in the case of **unpaved areas**
(working platforms, log yards, etc.).

Therefore, unpaved areas **do not benefit** from
the tensioned membrane effect and
subgrade bearing capacity improvement.

Unpaved areas benefit
only from stabilization.

In unpaved roads,
traffic is generally channelized, but . .

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Traffic may not be channelized
in some unpaved roads.



From Keller &
Sherar (2003)

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So far we have discussed the functions
of **stabilization** and **reinforcement** ,
which are
mechanical means of road improvement.

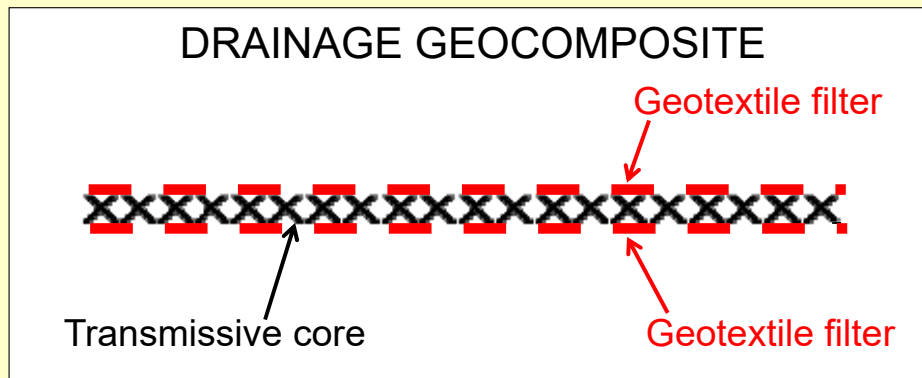
But, as all geotechnical engineers know,
the **behavior of soils** is **influenced by water**,
generally in a detrimental manner.

Therefore, **drainage** has a **beneficial** effect
on road performance.

Drainage can be called an
hydraulic means of road improvement.

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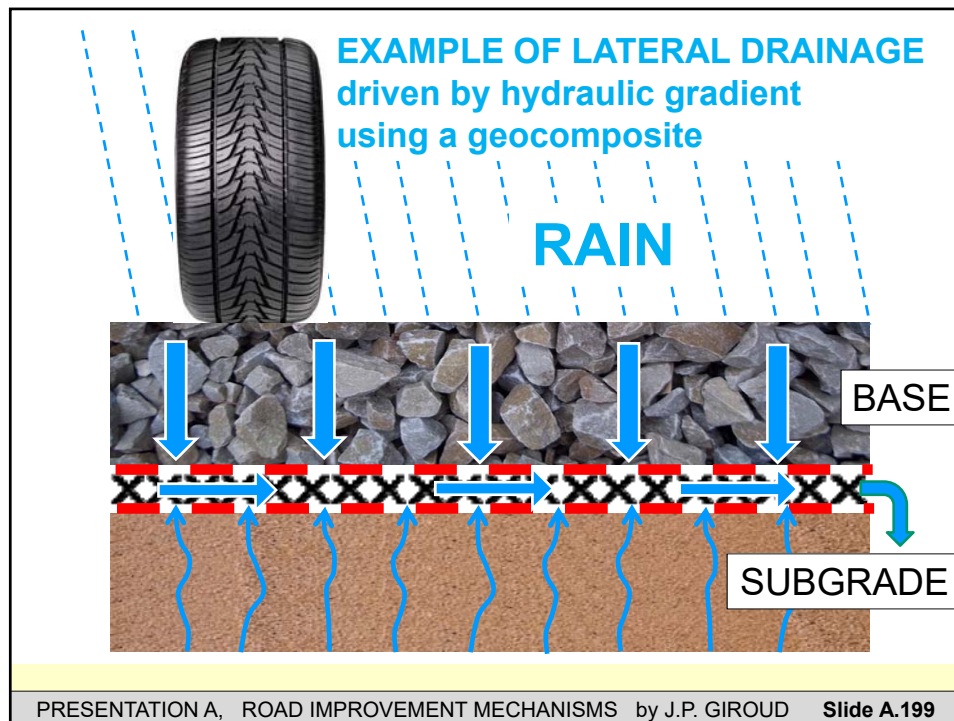
Lateral drainage can be achieved using
a **thick nonwoven geotextile**
or, if high hydraulic transmissivity is needed,
a **drainage geocomposite**.



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The **following slide**
illustrates schematically
lateral drainage
by a **drainage geocomposite**
between base and subgrade
of an unpaved road.

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In the preceding slide
the geocomposite
is between base and subgrade
of an unpaved road.

However, a geosynthetic
able to provide drainage
can be placed at **various levels**
in unpaved roads and paved roads,
in particular between sub-base and subgrade
in a paved road.

The importance of drainage can be illustrated as follows:

The impact of drainage

on paved road performance is quantified in the AASHTO design method for flexible pavements

(which will be mentioned later in this presentation)

by a factor, m , which varies

from **0.4** (**very poor drainage**
and high exposure to moisture)
to **1.4** (**excellent drainage**
and low exposure to moisture).

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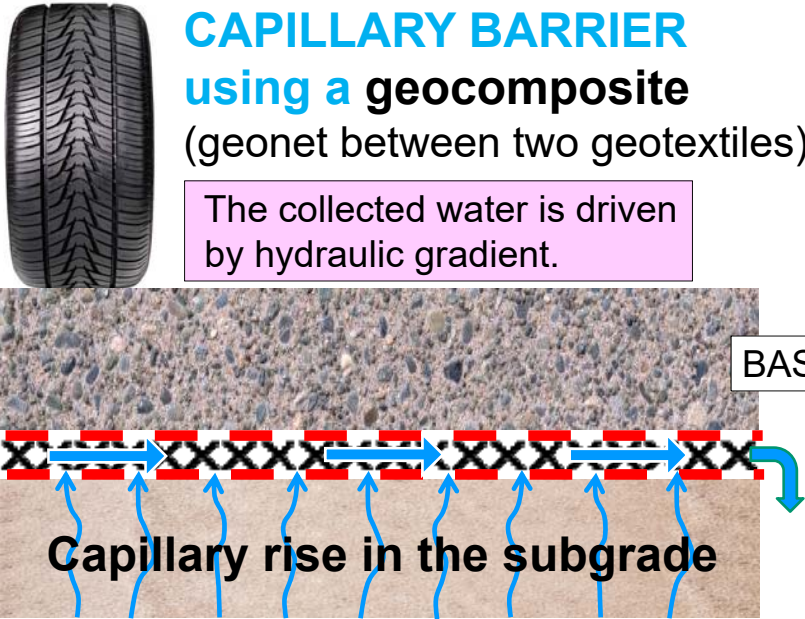
Another aspect of water control in a road is the case of water moving upward by **capillarity** through the subgrade soil.

Water moving upward by capillarity can be stopped by a **capillary barrier**, which consists of a layer of a material characterized by:

- a **high permeability** and
- a **thickness greater than the capillary rise** in this material.

A geonet, protected by geotextile filters, can be used as capillary barrier.

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CAPILLARY BARRIER
using a **geocomposite**
(geonet between two geotextiles)

The collected water is driven by hydraulic gradient.

BASE

Capillary rise in the subgrade

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Another possibility to collect and drain water that migrates upward in the subgrade soil by capillarity is to use a **wicking geotextile**.

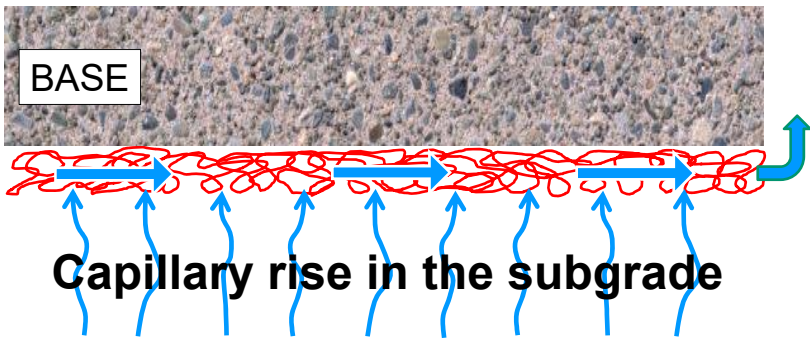
Wicking geotextiles contain fibers that include very fine channels, which promote **capillarity**.

Capillarity that takes place in the soil, is thus controlled by capillarity that takes place within the wicking geotextile.

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CAPILLARY BARRIER using a **wicking geotextile**

The blue arrows  indicate capillarity within the wicking geotextile.




Capillary rise in the subgrade

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At the edge of the road,
water is driven out of the geotextile,
because **air suction** is greater
than soil suction
(except when air is saturated with water).



Capillary rise in the subgrade

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A **wicking geotextile** can also be effective
in the case of **water migrating downward**:

A wicking geotextile, located beneath the base course,
can drain laterally precipitation water
that infiltrates through the surface course (if any)
and the base course.

*In this case, water migration in the wicking geotextile is driven
by **suction** if the geotextile is unsaturated,
and by **hydraulic gradient** if the geotextile is saturated.*

If a base course contains fines,
water can move by capillarity in the base pore space,
in the downward direction, if it is driven by suction exerted
by a wicking geotextile located beneath the base course.

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In conclusion,
geosynthetics can contribute
to lateral drainage in two ways:

- Drainage driven by **hydraulic gradient**
 - In this case drainage geocomposites
or thick nonwoven geotextiles are used.
- Drainage by **capillarity**
 - In this case, wicking geotextiles are used.

*Note: Wicking geotextiles can also convey water
driven by hydraulic gradient when they are saturated.*

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Another aspect of **water control** is the use of a geomembrane to **control the water content** of a base course that is not made of aggregate but of a **layer of compacted soil** using the “**Membrane Encapsulated Soil Layer**” (MESL) technique.

An other use of geomembrane for water control is, as water barrier, in the case of expansive subgrade soil (addressed later in this presentation).

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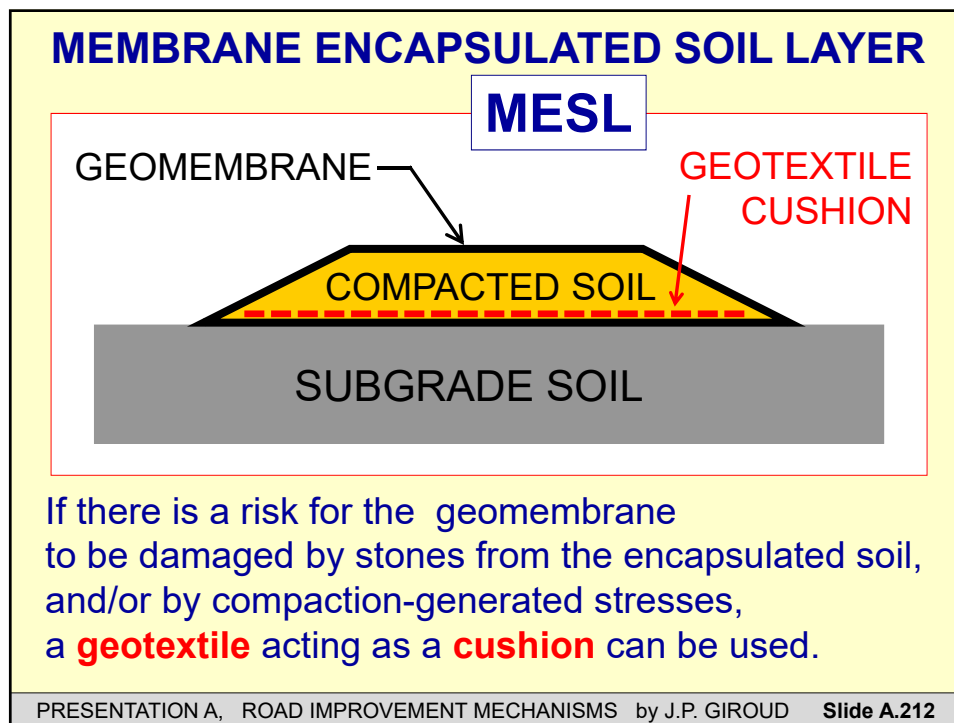
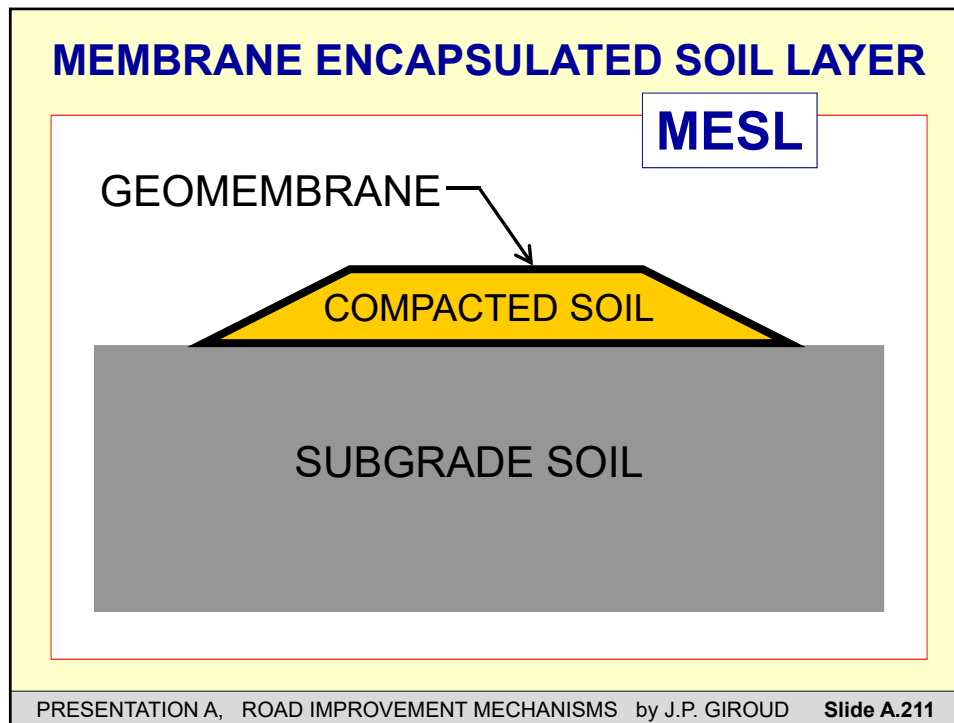
MEMBRANE ENCAPSULATED SOIL LAYER (MESL)

The MESL technique consists in constructing the **base course** of a road using a **layer of compacted fine soil**.

Such soil layer has **adequate modulus** and **strength** to support traffic as long as the **water content remains constant**.

To that end, the soil layer is **encapsulated in a geomembrane**.

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The MESL technique is illustrated by
an old case history from the 1970s:

A section of the Moscow-Riga Highway
in the former Soviet Union
has an MESL base.

In this case,
the geomembrane
had a high puncture resistance.
Therefore, no geotextile cushion was used.

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The geomembrane is delivered.



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The bituminous geomembrane is unrolled.



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The soil layer is compacted.



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**The geomembrane is wrapped
around the compacted soil layer.**



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The completed MESL



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The Membrane Encapsulated Soil Layer (MESL) technique has rarely been used.

However,
with the **increasing cost of aggregate**,
and the increasing **emphasis**
on using local materials,
it can be expected that
the **MESL technique**
should be **used more often** in the future.

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A DIFFERENT APPROACH

- So far, we have explained how geosynthetic improvement works in unpaved roads by **analyzing the mechanisms**.
- Another approach consists in **analyzing the modes of failure or dysfunction**.

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In other words:

- **The approach used so far consisted in analyzing the **functioning** of a road.**
- **The approach that will be used in the following slides consists in analyzing the **dysfunctioning** of a road.**

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The two symptoms of dysfunctioning of an unpaved road:

- **Complete collapse**
- **Excessive rutting**

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Complete collapse is a structural failure.

Complete collapse is rare.

Rutting is a functional failure (or service failure).

The **most typical** symptom of dysfunction is **excessive rutting**.



Courtesy
TENSAR



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There are many causes of rutting.

They can be organized in three categories.

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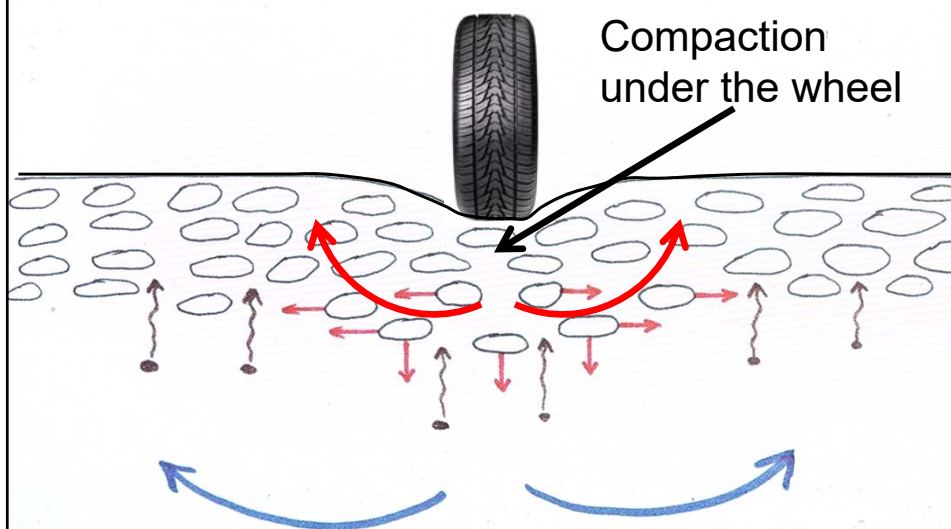
CAUSES OF RUTTING

- **Deformation of base layer**
 - Compaction of base material under repeated traffic loading
 - Lateral spreading of base material
 - Bearing capacity failure (i.e. shear failure) of base layer
- **Inter-mixing base material/subgrade soil**
 - Loss of base material into the subgrade
 - Intrusion of fine subgrade soil into the base, which makes the base more likely to deform
- **Deformation of subgrade**
 - Accumulation of subgrade deformation due to repeated traffic loading
 - Bearing capacity failure of subgrade (possibly due to reduced load distribution resulting from base deterioration)

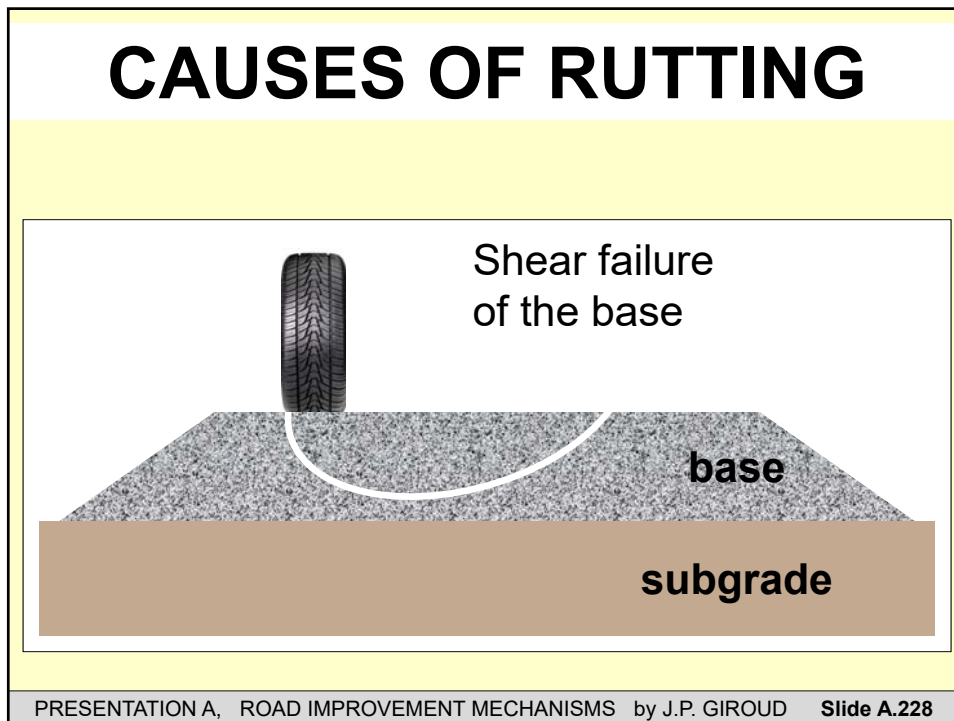
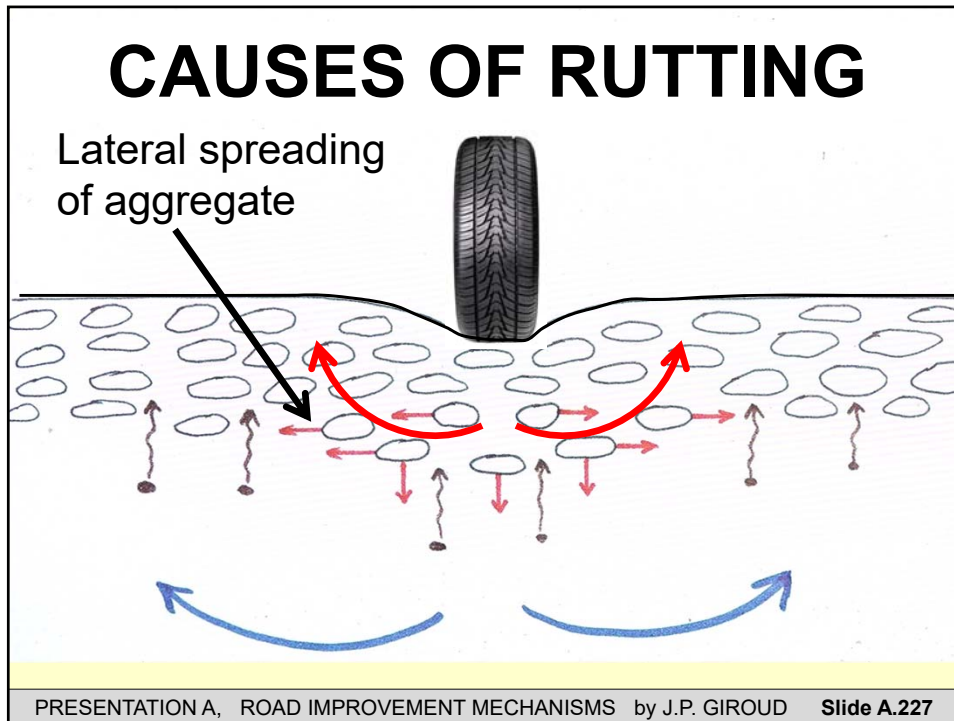
ILLUSTRATED IN SLIDES ⇒⇒⇒⇒⇒

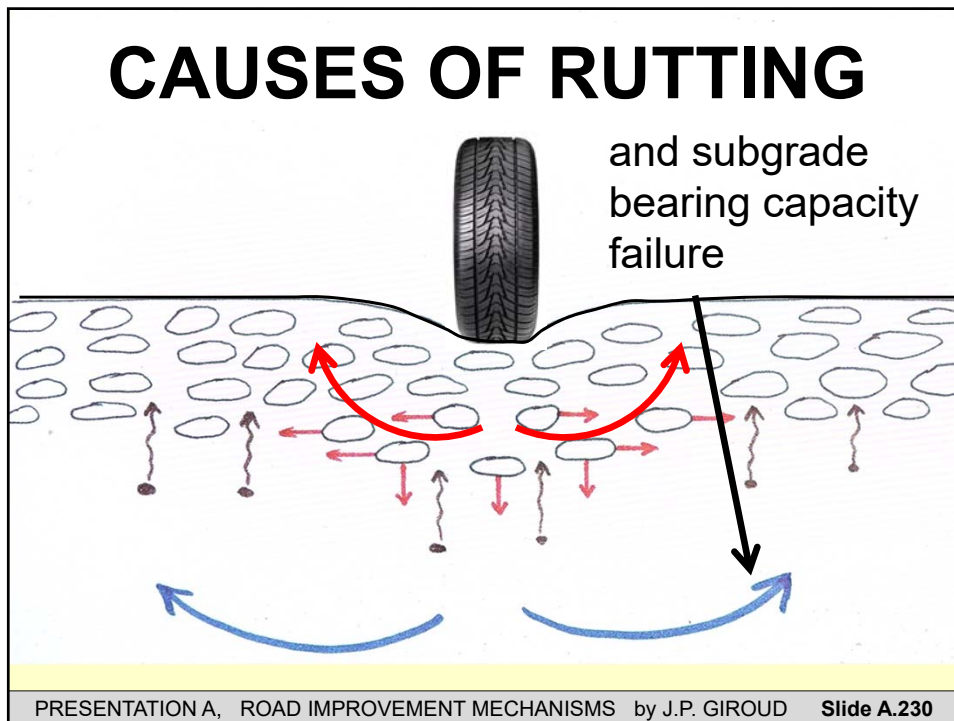
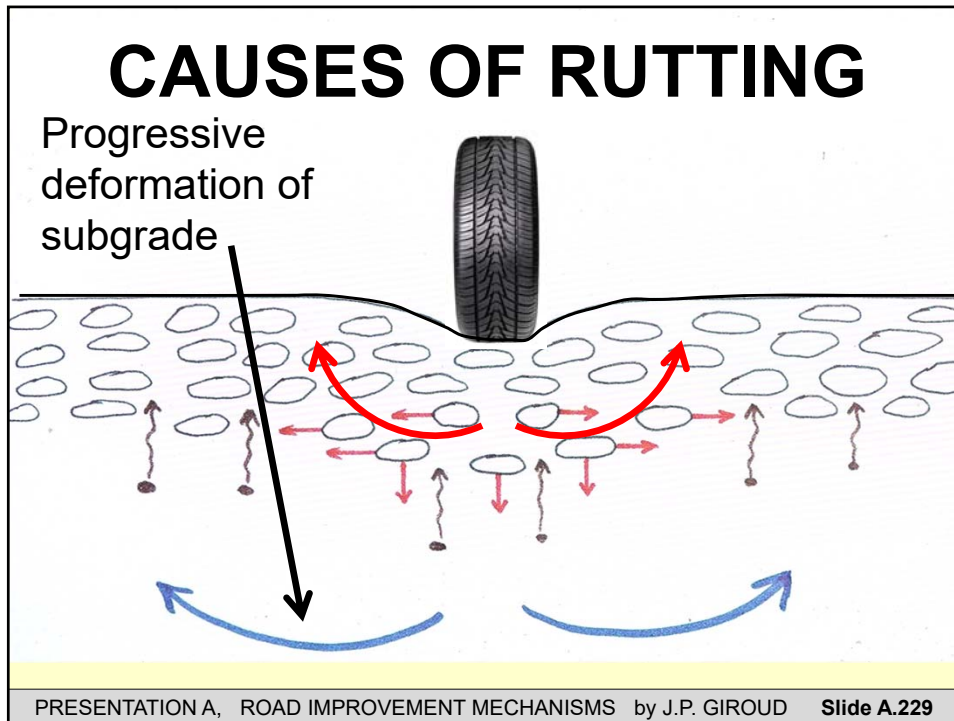
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CAUSES OF RUTTING



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**Based on the preceding slides,
the causes of rutting include**

- Deformation of base layer
- Deformation of subgrade

which we have discussed.

There is **another cause:**

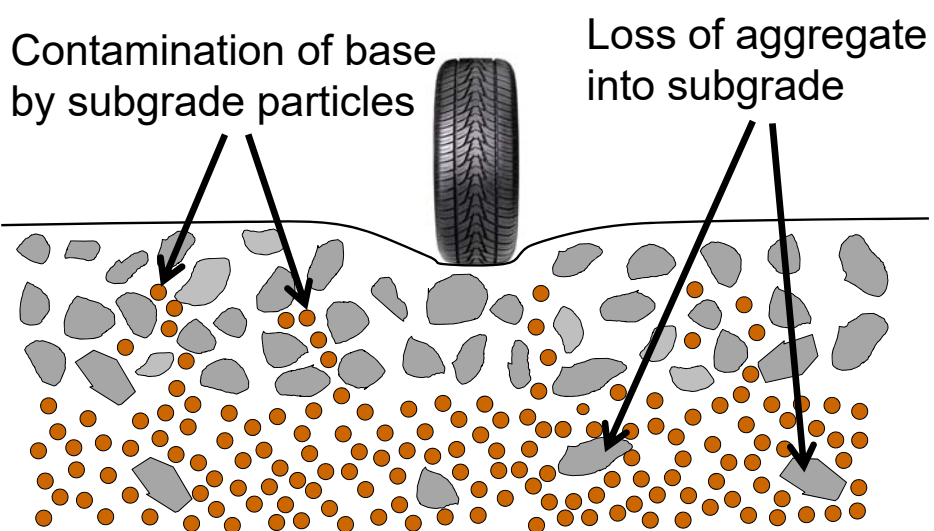
Inter-mixing base material/subgrade soil:

- **Loss** of base material into the subgrade
- **Migration** of fine subgrade soil into the base, which makes the base more likely to deform

This is illustrated in the following slide ⇒⇒⇒⇒

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A PROGRESSIVE CAUSE OF RUTTING



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This is important, because it only takes
a **small amount of fines**
from the subgrade soil
to significantly **reduce** the **strength**
of an aggregate base.

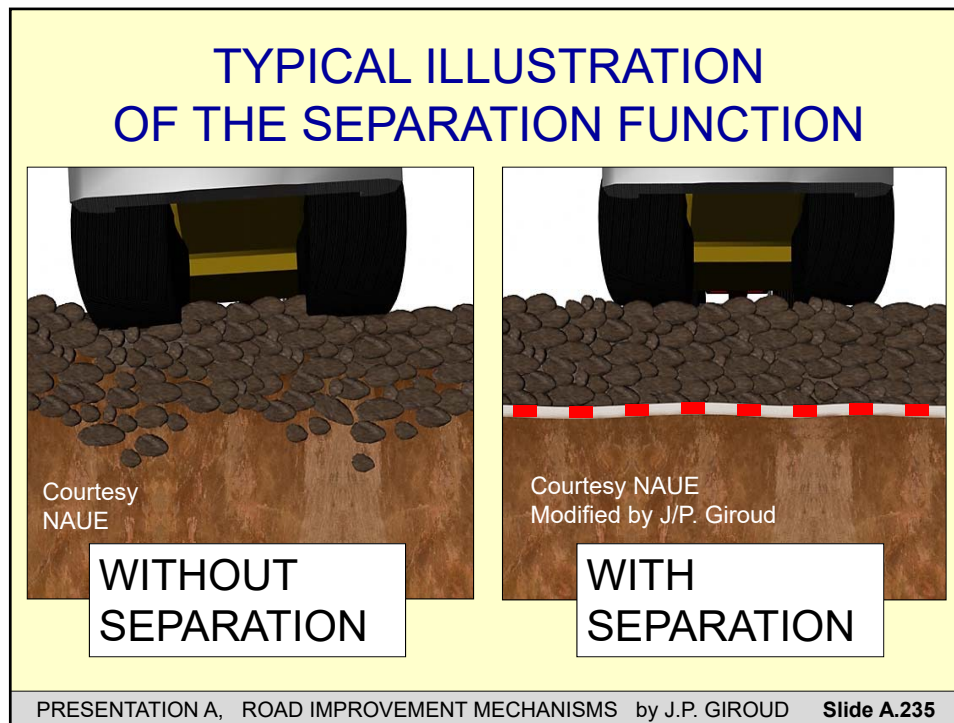
In the ultimate case
of **massive contamination**
of the aggregate base
by fines from the subgrade,
the base would behave like the subgrade.

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By **separating**
the base and the subgrade,
a **geosynthetic performs two tasks:**

- **it prevents the loss**
of base material into the subgrade;
and
- **it prevents migration**
of subgrade soil into the base.

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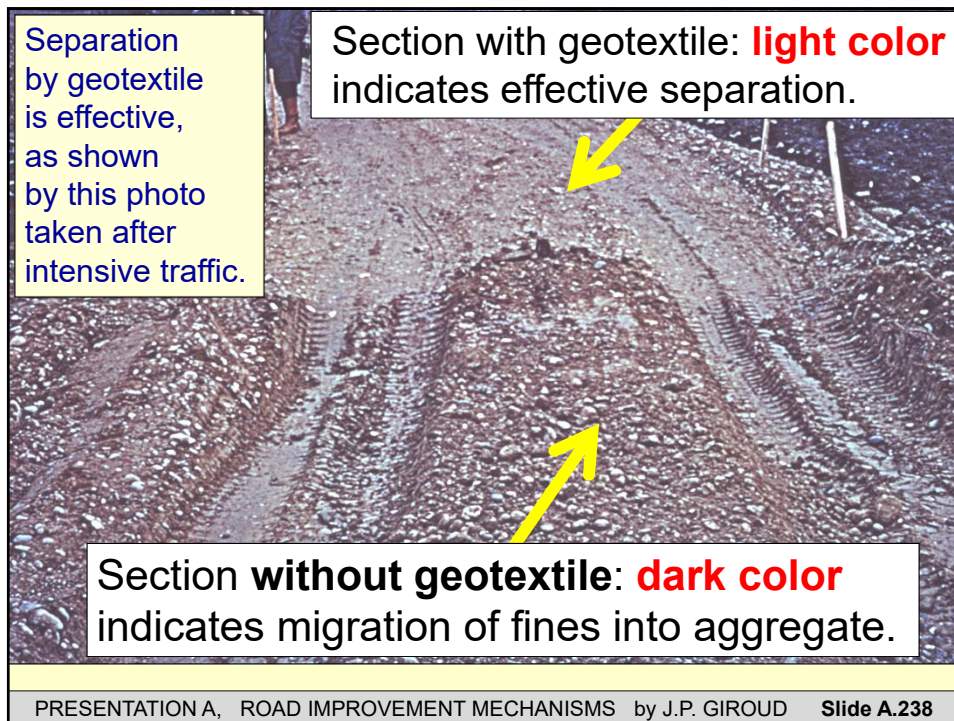


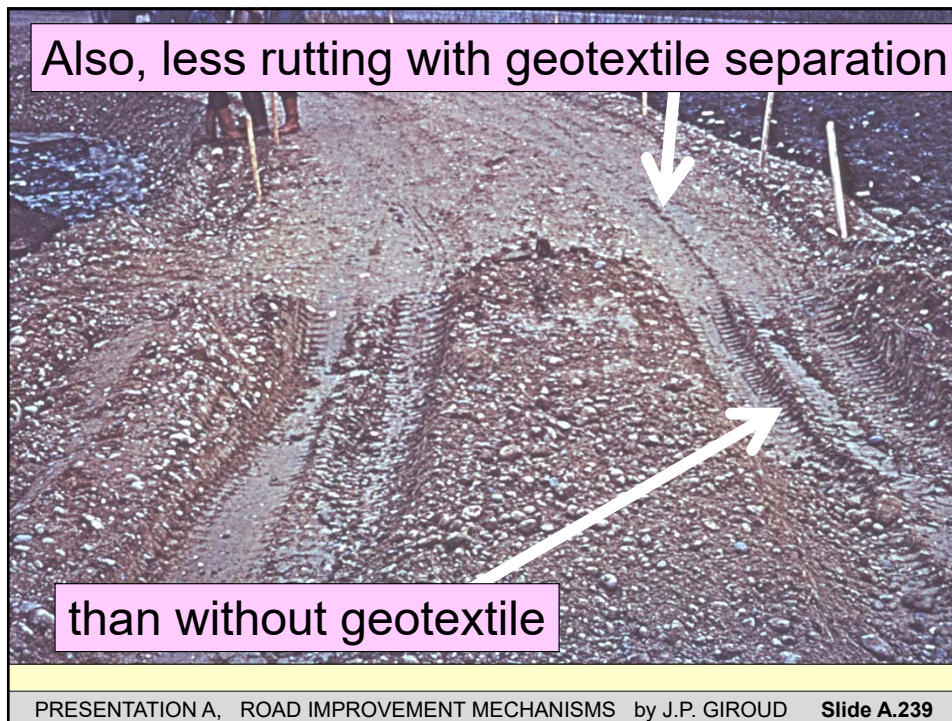
Which type of geosynthetic provides separation?

- The obvious answer is: **a geotextile.**
- Indeed, a geotextile with adequate **puncture** and **tear strength** prevents the **loss of aggregate** into the subgrade and, with adequate **opening size**, prevents **migration of fine particles** from the subgrade into the base.

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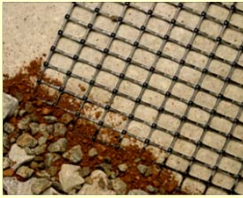
Mechanisms of Road Improvement by Geosynthetics by J.P. Giroud





Geotextiles obviously provide separation

- **But a geogrid can also provide some degree of separation.**
- A **geogrid** with adequate aperture size with respect to aggregate particle size prevents the **loss of aggregate** into the subgrade.
- A **geogrid**, that provides **lateral restraint** to the aggregate, keeps the aggregate together, thereby reducing the opportunities for **contamination of the aggregate base layer** by fine particles from the subgrade.



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Sometimes, a geotextile performing the **separation** function is associated with another geosynthetic performing a mechanical function, such as **reinforcement** or **stabilization**.

The difference between the **reinforcement function** and the **stabilization function** is explained later in this presentation.

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ASSOCIATION OF TWO GEOSYNTHETICS



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In the preceding slide,
the geotextile and the geogrid are **independent**.

This is generally considered to be **preferable**
to a geotextile bonded to a geogrid
at the manufacturing stage, because,
if the geotextile is **bonded** to the geogrid,
interlocking between geogrid and aggregate
may be hampered.

However, there is a **drawback**:
If geotextile and geogrid are independent
and the aggregate
is too large or not sufficiently compacted
to penetrate through the geogrid apertures,
the geogrid/geotextile interface may be a slip surface.

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To **prevent sliding**
between the geogrid and the geotextile,
and to **speed up installation**,
the geogrid and the geotextile can be
bonded together at the manufacturing stage.

However, as mentioned in the preceding slide,
if the geotextile is **bonded** to the geogrid,
interlocking between geogrid and aggregate
may be hampered.

A possible solution is
to **bond geogrid and geotextile only at edges**
of geogrid panels.

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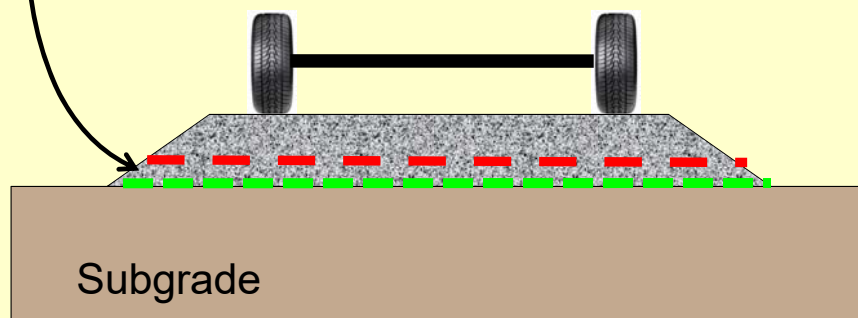
**Another possibility for the case where
a geotextile separator is needed
beneath a geogrid is to place:**

- a thin layer of aggregate (e.g. 50 mm)
on top of the geotextile,
- then, the geogrid
on top of this thin layer of aggregate,
- then, the rest of the base
on top of the geogrid.

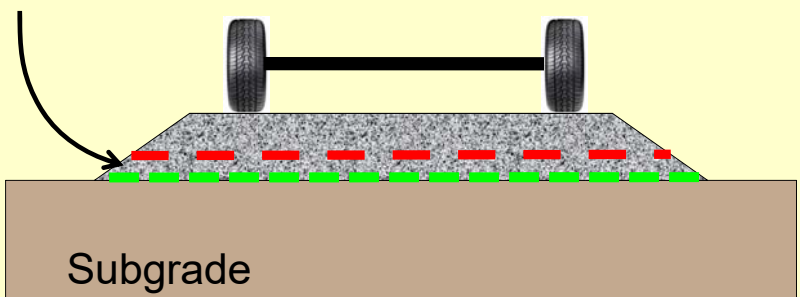
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**THIN AGGREGATE LAYER
BETWEEN GEOGRID AND GEOTEXTILE**

Thin layer of aggregate between
geogrid and **geotextile**



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Thin layer of aggregate between **geogrid** and **geotextile**

Subgrade

There are drawbacks:

- Installation is **time-consuming**.
- The thin layer of aggregate is **difficult to compact**.

And it is important to note . . .

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**. . . with most subgrades,
the geotextile is indispensable.**

In other words, it is **not recommended**
to place a thin layer of **aggregate**
directly on most subgrades
prior to placing the geogrid.

Indeed, with most subgrade soils,
in the absence of geotextile,
this first layer of aggregate
will **progressively migrate** into the subgrade.

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In preceding slides,
we discussed the case
where the **stabilization** function
is performed by a **geogrid**
and the **separation** function by a **geotextile**.

Let's now discuss the case where
the **stabilization** function
is performed by a **geocell**
and the **separation** function by a **geotextile**.

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ASSOCIATION OF TWO GEOSYNTHETICS



Here,
geotextile
separation
and
geocell
stabilization.

Geotextile

Courtesy
Strata Systems Inc.

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When is it necessary to add a geotextile to a geogrid or a geocell for separation ?

A geotextile separator should be added when **filter criteria** between the **subgrade soil** and the **base material** are not satisfied.

This is typically the case if the base material is an **open graded aggregate** and there is a significant amount of **finer in the subgrade soil**.

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Maintaining the integrity of the base through proper separation is **beneficial** not only **for the base** but also **for the subgrade**, because it ensures that the base will properly distribute the stresses on the subgrade.

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Designing for separation includes two aspects:

- The geotextile should act as a **filter** to prevent migration of fine subgrade particles into the base.
- The geotextile should **not be damaged** by coarse and angular aggregate.

Therefore, . . .



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Designing for separation includes two aspects, . . . the selected geotextile should be such that:

- **Filter criteria** are met between the geotextile filter and the subgrade soil.
- The geotextile has sufficient **resistance to concentrated stresses** (“*survivability*”), which is characterized by sufficient resistance to **grab, tear, puncture, and burst**.

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**IN SUMMARY,
the selected geotextile
should be such that:**

- **Filter criteria** are met
and
- The geotextile has sufficient **resistance
to concentrated stresses** (“*survivability*”).

*A detailed discussion of filter criteria
is beyond the scope of this presentation .*

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**IN SUMMARY,
the selected geotextile
should be such that:**

- **Filter criteria** are met, and
- The geotextile has sufficient **resistance
to concentrated stresses** (“*survivability*”).

*Guidance is provided in manuals for minimum values,
measured in standard tests,
of the **four properties** (grab, tear, puncture , burst)
that characterize resistance to concentrated stresses.*

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**Two types of geotextiles
are commonly used for **separation**:**

- **Nonwoven geotextiles**
can be adequate filters
and can have
high resistance to concentrated stresses.
- **Slit-film woven geotextiles**
are often used because of their low cost,
but they are not adequate filters.

And high-strength woven geotextiles
are naturally used for **reinforcement**.

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IN CONCLUSION,

An unpaved road can be improved
by a single **geosynthetic providing**
the three following benefits:

- **Improved load distribution**
- **Lateral restraint of base**
- **Increased bearing capacity of subgrade**

And the long-term integrity of the unpaved road
can be ensured by a geosynthetic providing **separation**
between **aggregate** and **subgrade soil**,
and by a geosynthetic providing **drainage**.

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Clearly, the benefits of geosynthetics
in unpaved roads are:

- to **improve** the behavior of the road
(by improving load distribution by the base
and increasing bearing capacity of the subgrade)
and
- to **maintain** these benefits
over an extended period of time
(by lateral restraint, separation, drainage).

Improve and **maintain** are the keywords.

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In conclusion:

The **improved performance**
of unpaved roads,
associated with the use of geosynthetics
is **characterized by factors** such as :

TBR = Traffic Benefit Ratio

BCR = Base Course Reduction

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We now have a good understanding
of the mechanisms
of unpaved road improvement,
and we can discuss **terminology**.

A frequently asked question is:
*what is the difference between
reinforcement and **stabilization**?*

Answer and more in the following slides 

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The **reinforcement** function
consists in **transferring load**
from the soil to the geosynthetic
and then from the geosynthetic
to a part of the soil
where the geosynthetic is safely anchored.

To perform the reinforcement function,
the geosynthetic must be strong
(indeed "**reinforcement**" implies "**force**").

**Stabilization is different
from reinforcement.**

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A geosynthetic that performs
the **stabilization** function
does not transfer load somewhere else.

A geosynthetic that performs
the **stabilization** function
acts everywhere it is present
thereby forming a **composite material**
with the associated soil.

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Stabilization is a synergistic function,
which includes, at the **same time**,
and **everywhere** along the geosynthetic,
load transfer **from the soil** to the geosynthetic
and
resistance transfer **from the geosynthetic** to the soil.

Stabilization is possible
thanks to **confinement**:

- **Closed confinement** of soil
within geocells,
- **Open confinement** (i.e. **interlocking**)
between aggregate and geogrid.

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Interlocking requires
mechanical and geometric **compatibility**
between **geogrid** and **aggregate**.

Clearly, in the case of stabilization,
stronger is not necessarily better.

*This is different from the reinforcement function,
a function that requires strong geosynthetic.*

A good example is a **geocell**,
a deformable geosynthetic (when it is not filled),
which provides **stabilization**
by forming a composite material with the soil.

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The result of **stabilization**
is a **composite material**
composed of
geosynthetic and soil **working together.**

This is different
from the **reinforcement** function
where **the geosynthetic does all the work.**

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Whereas **reinforcement** relies on **force**,
stabilization
relies on **displacement restraint**,
for example **lateral restraint**
of the aggregate base.

Indeed, stabilization means “making stable”,
in other words, *keeping things **unchanged***.

Indeed, thanks to stabilization by geogrid or geocell,
the appearance of the road remains unchanged
for a long time,
which is a long-term benefit of stabilization.

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However, saying that a road is **unchanged**
as a result of stabilization may be **misleading**.

Keeping a road structure unchanged
in spite of traffic loading seems ideal.

The reality is even better:
as shown in this presentation,
the road is not only unchanged in his appearance,
but its **performance is improved**,
thanks to stabilization:

- Higher base modulus hence better load distribution
- Slower base deterioration under traffic load

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Performance improvement is possible because **stabilization**, like any mechanical action, **requires some deformation**.

Lateral restraint does not mean *zero deformation* i.e. it does not mean “absolutely unchanged”.

Lateral restraint implies **small deformation**, i.e. the deformation required to **mobilize** the **confinement** mechanism.

In other words, improvement requires deformation.

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Because of the need for some deformation to mobilize the lateral restraint mechanism, the **effectiveness of confinement increases with the number of passes** until it reaches a plateau.

In some cases, however, the confinement effectiveness starts decreasing after a large number of passes if **geogrid apertures** or **geocell pockets** become **deformed** or **damaged**.

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Now, what happens
if the road deformation keeps increasing ?

As rutting develops,
the **tensioned membrane effect**
becomes progressively more effective.

The **tensioned membrane effect**,
where the geosynthetic
transfers part of the load laterally
to areas where it is anchored,
clearly involves the **reinforcement function**
of the geosynthetic.

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Last question
in the discussion of
the stabilization and reinforcement functions:

What is the geosynthetic function
involved in
the increase in
the subgrade bearing capacity ?

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The subgrade bearing capacity increase is provided by a geosynthetic that performs the **reinforcement** function, because the geosynthetic **tension**, which is associated with the downward load that provides subgrade heave restraint is **transferred laterally**.

The same geosynthetic, which is located between base and subgrade, **performs two functions**:

reinforcement to increase subgrade bearing capacity and
stabilization to improve the base.

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The term “**subgrade stabilization**”, often used to describe the improvement of a road by the use of a geosynthetic, is **potentially confusing** because the geosynthetic does not really stabilize the subgrade.

Rather, the geosynthetic increases the bearing capacity of the subgrade by providing the **reinforcement function**.

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The term “**improvement**” includes
all means that are aimed at
improving the road performance:

- Improvement by **mechanical means**
(functions: stabilization and reinforcement)
- Improvement by **physical means**
(function: separation)
- Improvement by **hydraulic means**
(functions: drainage and water barrier)

(A similar terminology could be used
for non-geosynthetic means of improvement
such as *improvement by **chemical means***,
and *improvement by **biological means***.)

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Now, let us see
how the lessons learned
from the detailed analysis
of the **mechanisms**
of **unpaved road** improvement
can be applied to **paved roads**.

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First,
some general comparisons
between
paved roads and unpaved roads

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UNPAVED AND PAVED ROADS

- **Unpaved** roads can be **permanent** (“low-volume roads”) or **temporary** (construction by-pass, access roads).
- **Paved** roads are generally **permanent** (highways and other roads, streets).

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SERVICE LIFE OF PERMANENT AND TEMPORARY ROADS

- A permanent road typically has a service life of **10 years** or more.
- A temporary road typically has a service life of less than **one year**.

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NUMBER OF PASSAGES FOR PERMANENT AND TEMPORARY ROADS

- More than 1 million for some paved roads
- More than 100,000 for permanent unpaved roads
- Less than 10,000 for temporary unpaved roads
- Less than 1000 or 100 for access roads

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STRUCTURE OF A PAVED ROAD

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While an **unpaved road**
is typically a **two-layer system**,
a **paved road**
is typically
a **four-layer system**
or
a **three-layer system**

The reason is given on the next slide

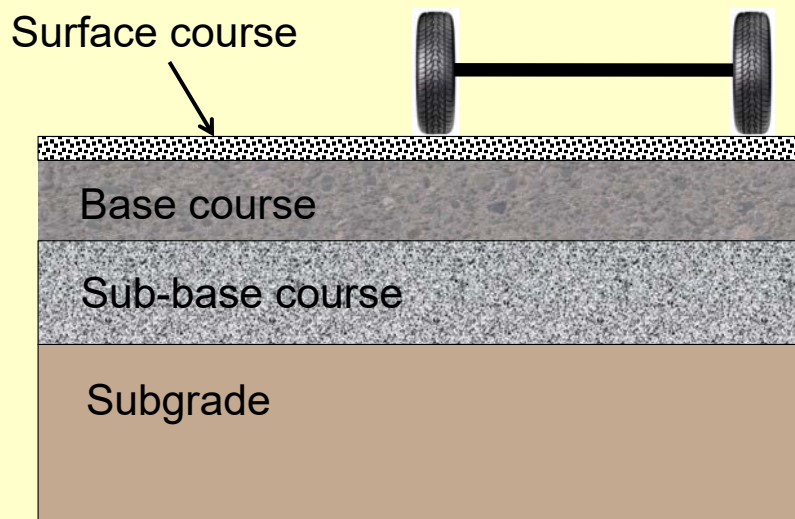
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.282

A **flexible pavement** is
a four-layer system or a three-layer system
for the following reason:

- The **modulus** of the surface course is high.
- If the surface course was directly on the subgrade, the **modulus difference** between the two layers would be high.
- As a result, the **tensile stresses** at the bottom of the surface course would be **high** and a very thick surface course would be needed.
- Three or four layers provide a better **transition**.

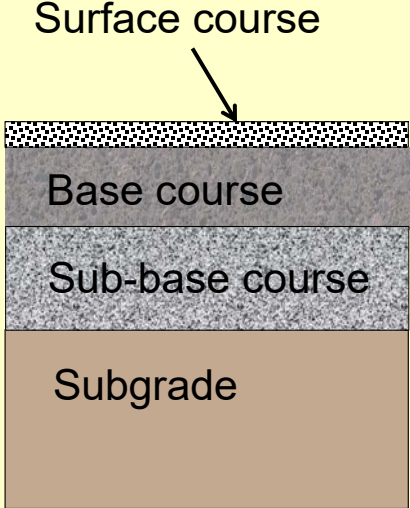
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STRUCTURE OF A PAVED ROAD



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TERMINOLOGY



Surface course

Base course

Sub-base course

Subgrade

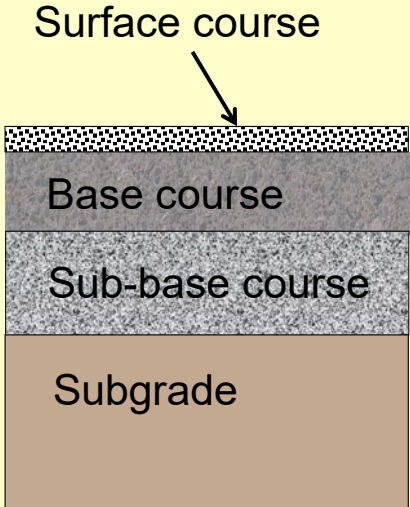
The terms “course” and “layer” are interchangeable.

“Course” is preferred for descriptions, as here.

“Layer” is used when calculations are involved (e.g. *layer thickness*).

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TERMINOLOGY



Surface course

Base course

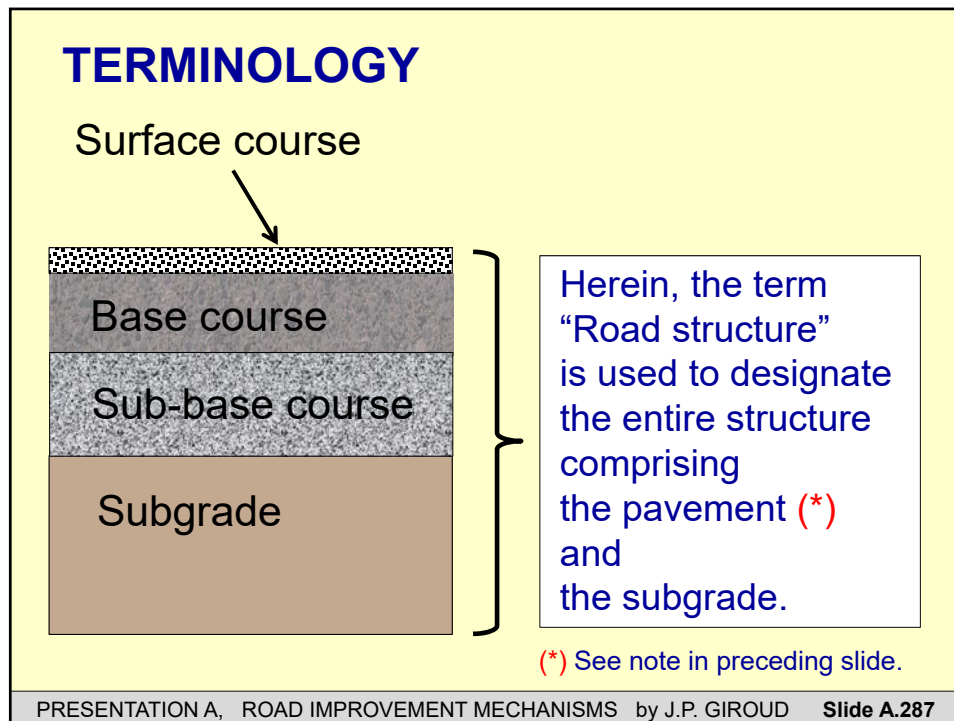
Sub-base course

Subgrade

The term “Pavement”(*) designates the whole set of traffic-supporting layers above the subgrade.

(*) The term “pavement structure” is sometimes used.

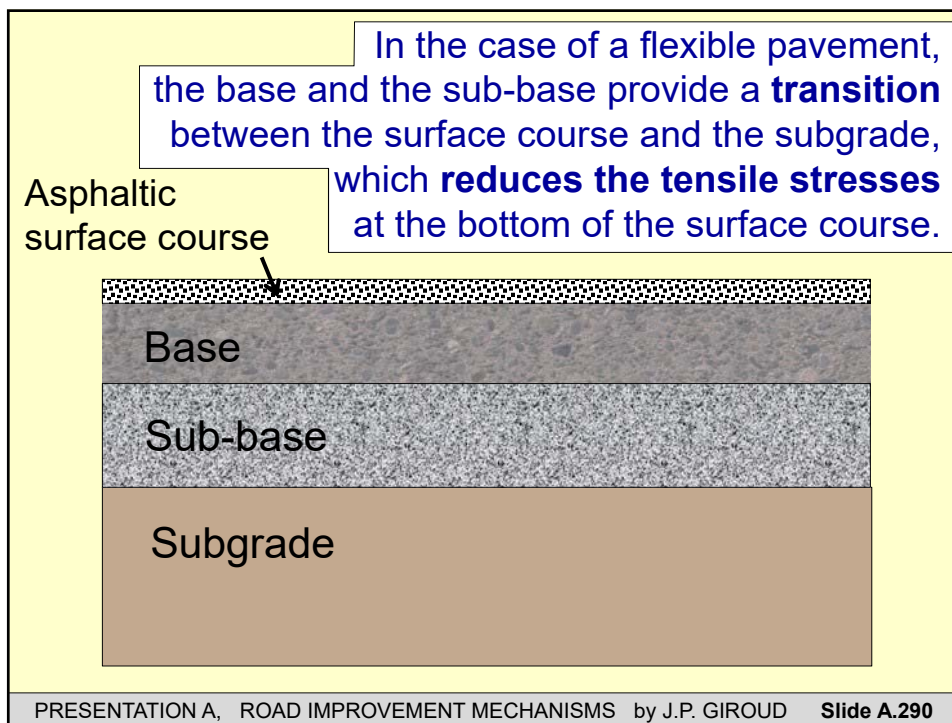
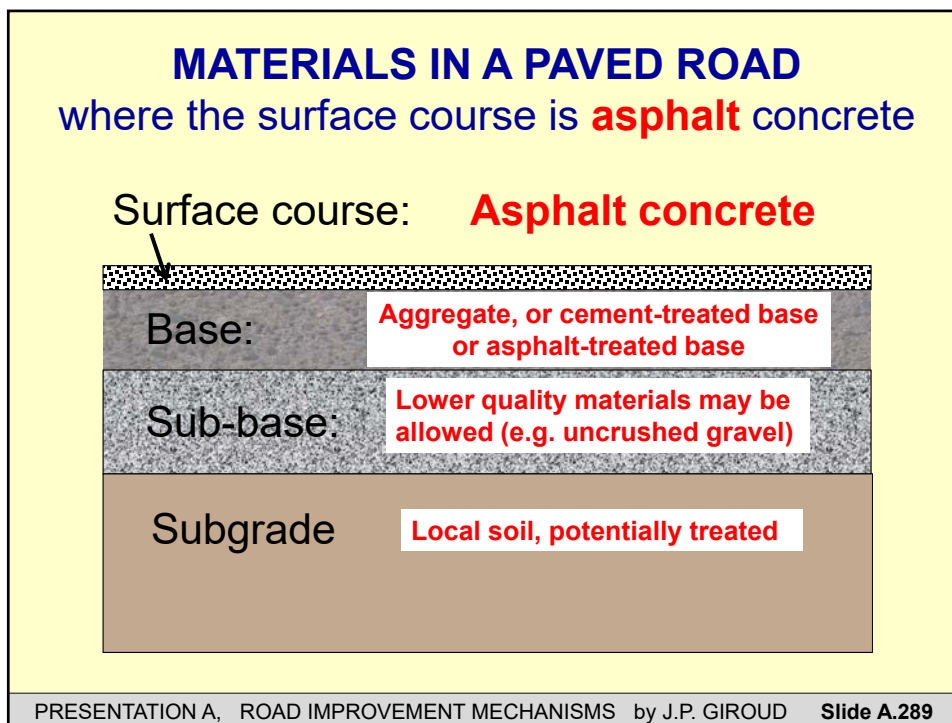
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The term **flexible pavement** designates a pavement where the surface course is made of **asphalt concrete**.

The term **rigid pavement** (or **concrete pavement**) designates a pavement where the surface course is made of **cement concrete**.

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Alternatively,
a paved road with a **concrete surface course**
(i.e. a “rigid pavement” or “concrete pavement”)
can be used.

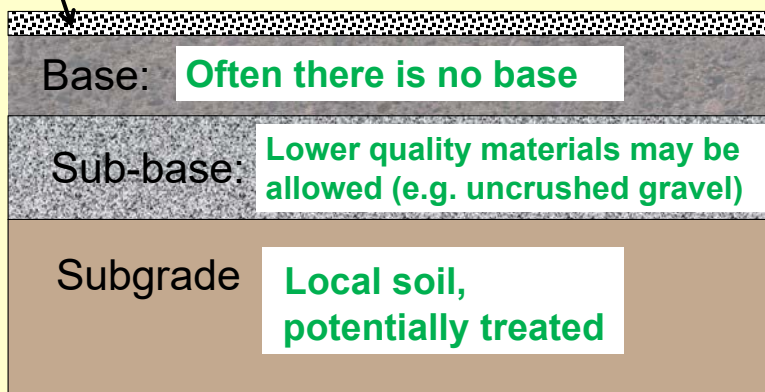
In this case, a four-layer system is not needed
and the base is typically omitted.

A concrete surface course is so strong
that a **concrete pavement can tolerate**
a **huge difference in modulus**
between the surface course
and the underlying material.

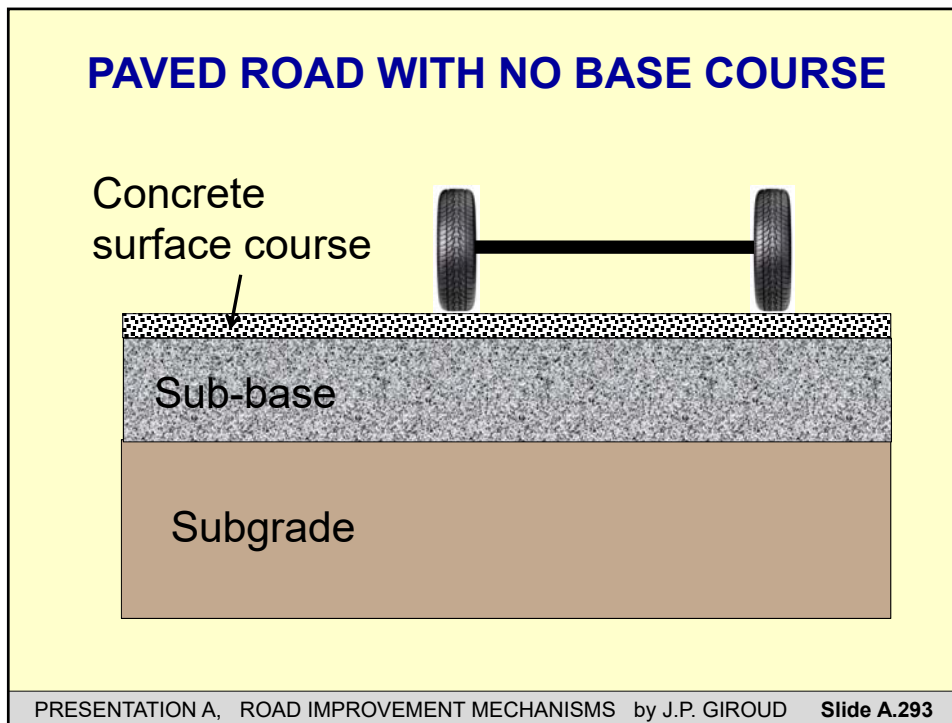
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MATERIALS IN A PAVED ROAD where the surface course is **cement** concrete

Surface course: **Cement concrete**



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As mentioned above,
in many cases,
there is **no base course**
with **concrete surface course**,
because, in this case,
the **surface course** is **so strong**
that it can tolerate
a **huge difference in modulus**
between the surface course
and the underlying material.

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USE OF GEOSYNTHETICS IN PAVED ROADS

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DIFFERENCE BETWEEN FLEXIBLE AND RIGID PAVEMENTS REGARDING THE USE OF GEOSYNTHETICS

- The maximum stress transferred to the subgrade is lower in the case of a rigid pavement (*i.e. cement concrete pavement*) than in the case of a flexible pavement (*i.e. asphalt concrete pavement*).
- Therefore, the use of geosynthetic stabilization is less necessary in the case of cement concrete pavement than in the case of asphalt concrete pavement.

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Geosynthetics are rarely used in paved roads where the surface course is **cement concrete**. The reason for that is:

- For cement concrete pavements (“rigid pavements”), **the structural capacity mainly relies on the concrete slab**.
- The contribution of subgrade or subbase to cement concrete pavement design is limited.
- Therefore, in most cases, **reinforcement or stabilization is not needed**, and a geosynthetic could not significantly contribute.

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Based on the above discussion, this presentation will mostly address **flexible pavements**, i.e. pavements where the surface course is made of **asphalt concrete**.

This presentation will occasionally mention **rigid pavements** (also called *concrete pavements*), i.e. pavements where the surface course is made of **cement concrete**.

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MECHANISMS OF IMPROVEMENT IN PAVED ROADS

The essential mechanisms

for paved roads as for unpaved roads result from the geosynthetic performing the **stabilization** function by providing **confinement** of the associated material , hence **increased tensile stiffness** and **lateral restraint** to the **base** and/or the **sub-base**.

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MECHANISMS OF STABILIZATION IN PAVED ROADS

Other mechanisms considered for unpaved roads **are less important for paved roads**, because strains in paved roads are generally too small to mobilize these mechanisms:

- The increased **bearing capacity** of subgrade is generally negligible, but, in the case of very soft subgrade, a geotextile on top of subgrade may be useful during construction.
- The **tensioned membrane effect** is always negligible in paved roads.

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Therefore, the **design**
of **paved roads**
stabilized with geosynthetics
consists essentially in estimating
the **structural improvement**
of the pavement
by the geosynthetic.

*Note: Remember, the term “pavement”
encompasses all layers above the subgrade.*

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A typical **design method**
for geosynthetic-stabilized **paved roads**
consists in using an **empirical method**,
such as the AASHTO method,
where the **structural number** (SN)
of layers stabilized by a geosynthetic
is **increased by a factor**
that quantifies geosynthetic stabilization.

A mechanistic-empirical method
is also being developed.

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The AASHTO empirical method for designing paved roads with flexible pavement comprises **two steps**.

The **first step** consists in calculating the **structural number** (SN) of the pavement as a sum of the structural numbers of all the layers comprised in the pavement.

*The dimensionless structural number of a layer is obtained by multiplying the thickness of the layer by a “**layer coefficient**” (dimension 1/L) that depends on the layer material properties.*

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The **beneficial effect** of **geosynthetic stabilization** is accounted for in the **first step** of the empirical method as follows:

The **layer coefficient** of the geosynthetic-stabilized layer is **increased** by an empirical factor obtained through full-scale testing performed with the considered layer material and the considered geosynthetic.

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COMMENT:

The **layer coefficient**
in the AASHTO method
is linked to
the **resilient modulus** of the layer.

Therefore **increasing** the layer coefficient
quantifies the fact that
the **resilient modulus** of the layer
has been **increased**
by the confinement (i.e. stabilization)
provided by the geosynthetic.

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The **second step** of the AASHTO method
consists in using an **empirical equation**
*(derived from the 1950s-1960s AASHO Road Test
and statistical analysis; and most recently presented
in the 1993 AASHTO design guide)*
that makes it possible to **calculate**
the **number of passages**
of equivalent standard axle load (ESAL)
on the considered flexible pavement,
for a target reliability, as a function of:

- the structural number
- the resilient modulus of the subgrade, and
- the terminal serviceability of the road.

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While the state of practice has been to use the **empirical method** for more than 50 years, research is being done to develop a **mechanistic-empirical method** (sometimes referred to as “M-E method”).

The mechanistic-empirical method starts being used, but some aspects of the method are still undergoing research and development work.

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The mechanistic-empirical method comprises two parts:

- The **mechanistic** part of the method uses elastic solutions for layered media to determine stresses and strains in the pavement system.
- The **empirical** part of the method uses empirical “transfer functions” that relate stresses and strains to road distress levels, such as a maximum allowable rut depth.

More details are given in the following slides.

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The **mechanistic part**
of the mechanistic-empirical method
uses **elastic solutions** for layered media
to determine “*critical responses*”
of the pavement to wheel loads.

Critical responses are stresses and strains
that govern failure modes.

For example, the *critical response* consists of
horizontal strain
at the bottom of the asphalt concrete surface layer,
if the **considered failure mode**
is fatigue **cracking** of this asphalt concrete layer.

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The **mechanistic part**
of the mechanistic-empirical method
is followed by an **empirical part**.

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Empirical “*transfer functions*” are used to relate the *critical pavement responses* to **distress levels** as a function of the **number of axle passes**.

Examples of distress levels include:
20% fatigue cracks at the asphaltic surface
or
25 mm rut depth.

The empirical “transfer functions” are developed and calibrated using small-scale and full-scale tests.

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The **beneficial effect** of **geosynthetic stabilization** is accounted for as follows in the mechanistic-empirical method:

The **resilient modulus is increased** for the layers influenced by a geosynthetic.

and

the **rate of degradation with time** of these layers **is decreased**, which is taken into account in the transfer functions.

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It should be noted that,
in the mechanistic-empirical method,
the beneficial effects of geosynthetics
are accounted for in a way that is consistent with
the **mechanisms of geosynthetic stabilization**
analyzed in this presentation:

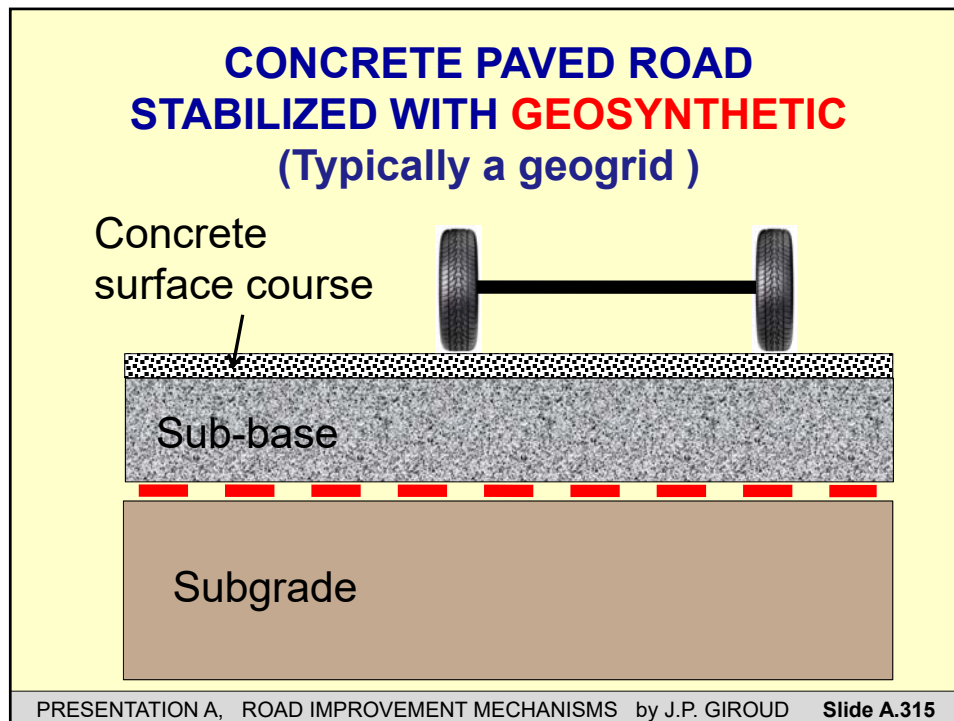
- **Increased modulus** resulting from **confinement** provided by the geosynthetic
- **Reduction of the rate of degradation** thanks to **lateral restraint** provided by the geosynthetic

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Now,
typical uses of geosynthetics
in paved roads

Starting with paved roads
having a concrete surface course
(i.e. rigid pavements)

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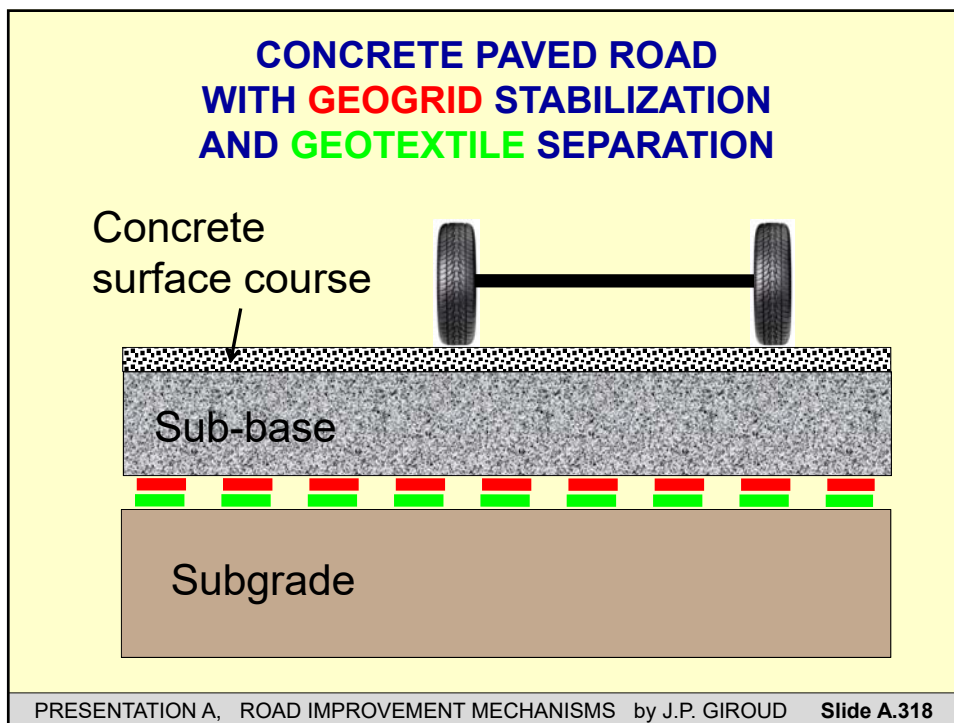
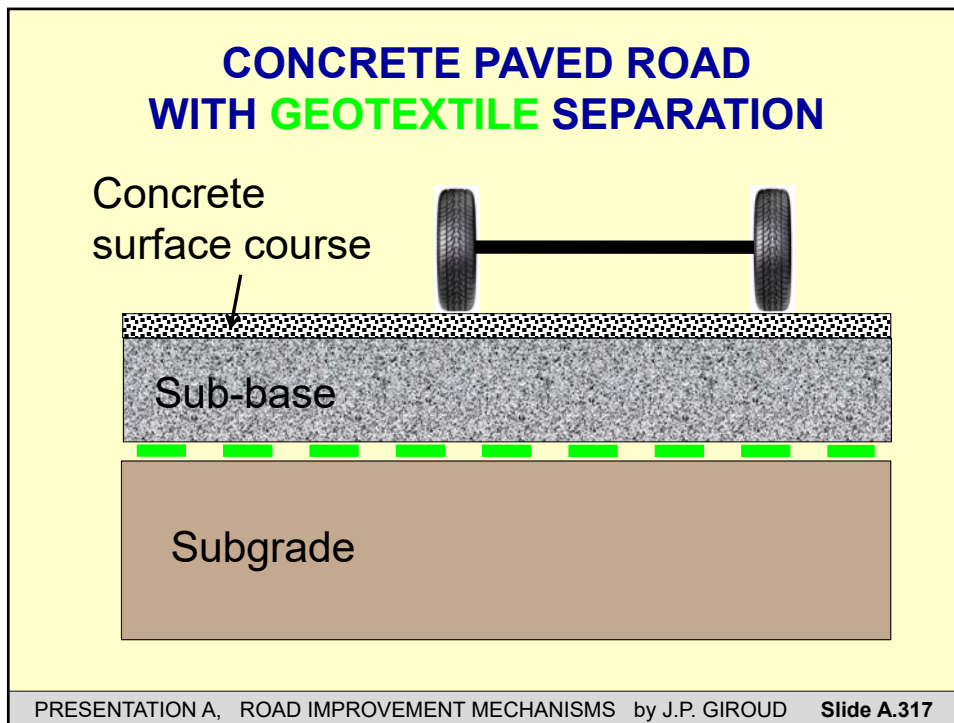


The preceding slide shows a rigid pavement, with no base course (as is often the case).

The geosynthetic (typically a **geogrid**) is mostly useful during construction by stabilizing the sub-base and increasing the subgrade bearing capacity.

If separation is needed, a **geotextile** can be used, either alone as shown on the next slide or associated with a geogrid used for road stabilization.

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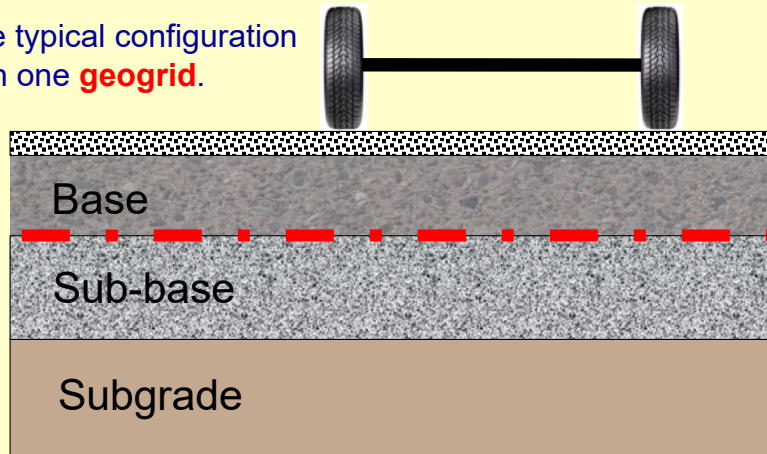


In the following slides,
typical uses of geosynthetics
in paved roads
with an asphaltic surface course
(i.e. flexible pavements)

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STABILIZATION OF A PAVED ROAD

The typical configuration
with one **geogrid**.



The geogrid is used to impart **tensile stiffness**
and provide **lateral restraint**.

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STABILIZATION OF A PAVED ROAD

A configuration with two **geogrids**.

The lower **geogrid** is used in cases where the subgrade is soft.

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STABILIZATION OF A PAVED ROAD

Another configuration with one **geogrid**.

Single geogrid, between sub-base and subgrade, if the thickness base + sub-base is limited (e.g. <math>< 0.3\text{ m}</math>).

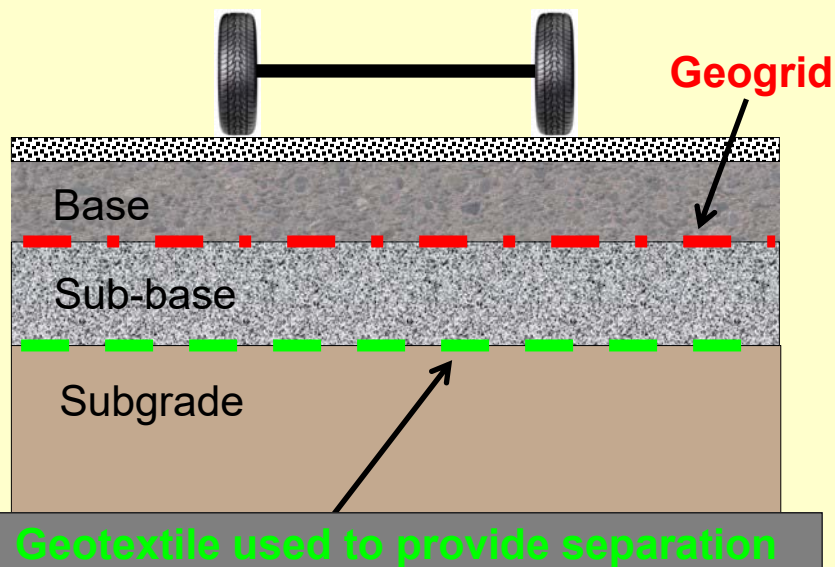
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Of course, there may be
a need for **separation**
between
the **sub-base** and the **subgrade**.

In this case,
a **geotextile** should be used
between
the **sub-base** and the **subgrade**.

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STABILIZATION AND SEPARATION

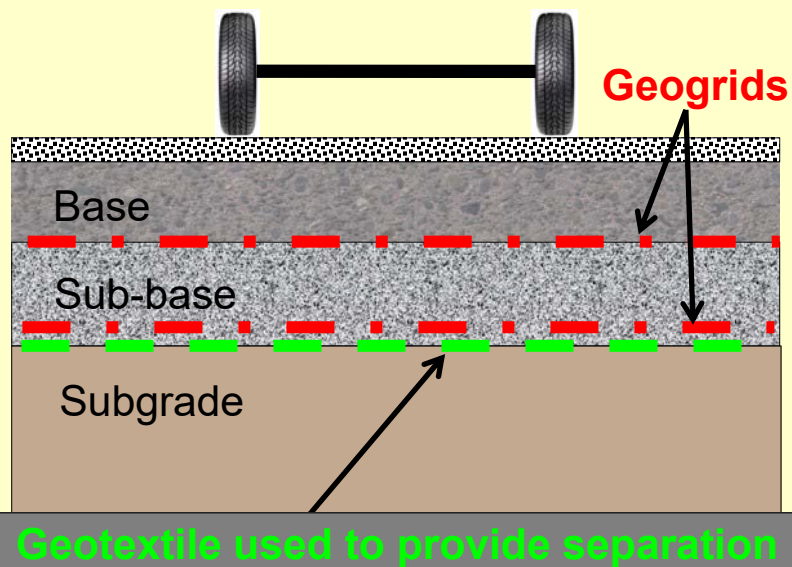


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*On the next slide,
a case with two geogrids
and a geotextile*

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STABILIZATION AND SEPARATION



PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.326

Mechanisms of Road Improvement by Geosynthetics
by J.P. Giroud

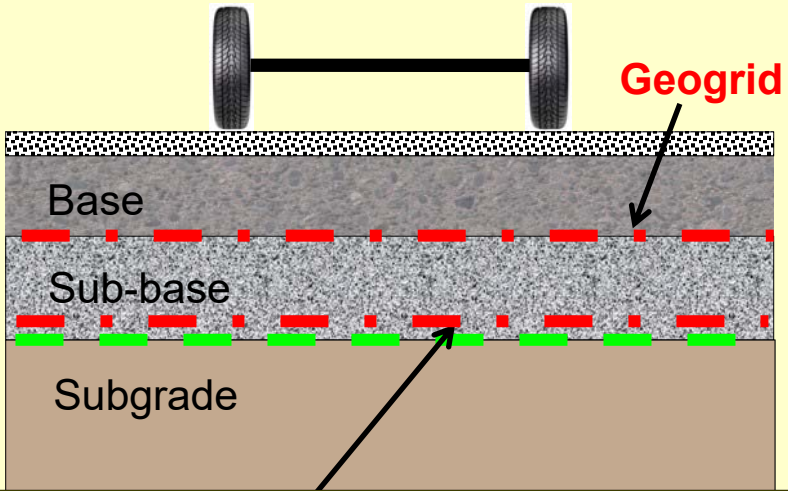
UNPAVED ROAD WITH GEOGRID ON GEOTEXTILE



Courtesy
TENSAR

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The geogrid and the geotextile can be combined.

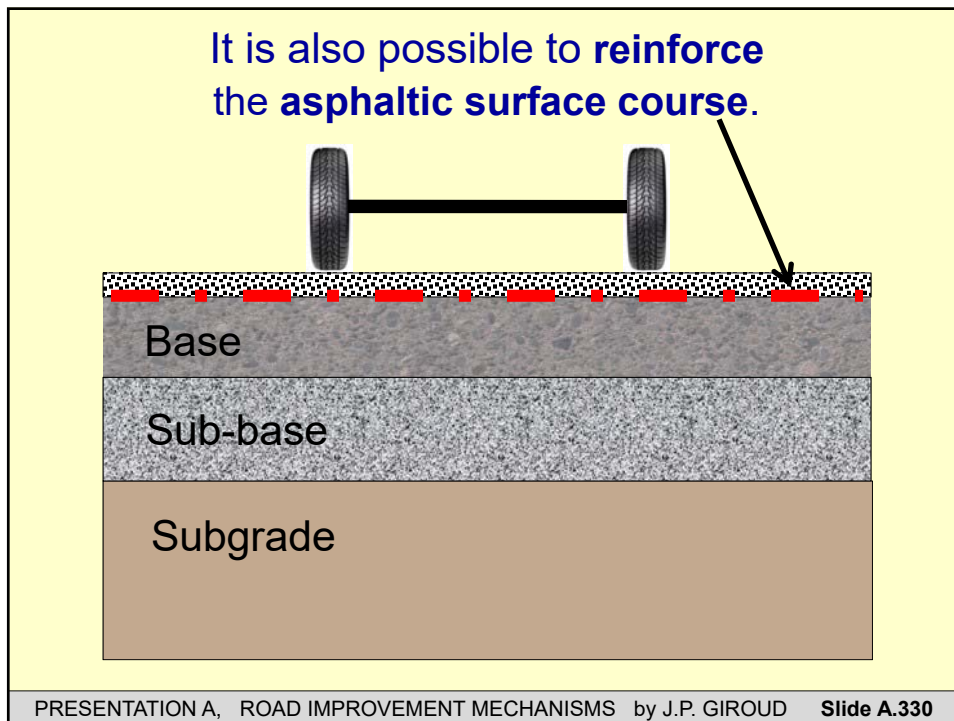
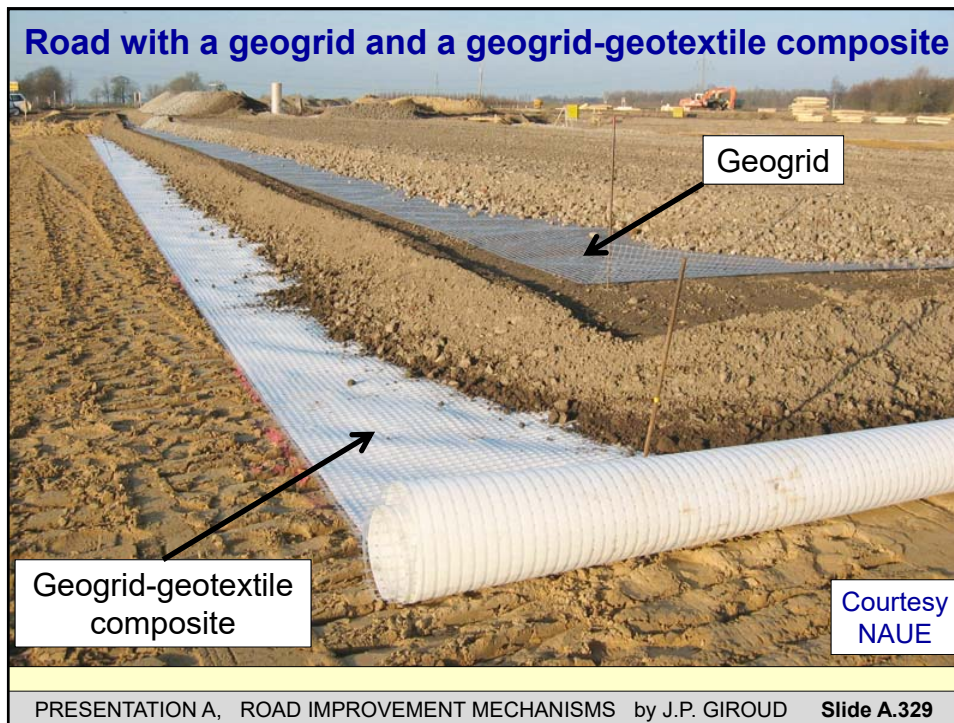


geogrid-geotextile composite

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Supplemental Material to the paper “The use of geosynthetics in roads”
by J.P. Giroud, J. Han, E. Tutumluer & M.J.D. Dobie,
published in *Geosynthetics International*, as gjein.21.00046.

Mechanisms of Road Improvement by Geosynthetics by J.P. Giroud



Reinforcement of the asphaltic surface course
of a flexible pavement (typically by geogrids)
has the following **benefits**:

- It reduces the risk of **fatigue cracks**
in the asphaltic surface course;
and
- It reduces the risk of development of **rutting**
within the asphaltic surface course.

However it is relatively rare to reinforce
asphaltic surface courses
of new flexible pavements
for practical and economical reasons.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.331

Reinforcing the asphaltic surface course
of new flexible pavements
is sometimes done in the case of
cement-treated or **lime-treated**
base courses,
because these base courses **tend to crack**.

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The edges of base course **cracks**
move
under repeated traffic loads
or as a result of
temperature changes and moisture changes.

These movements **induce**
concentrated stresses
in the asphaltic surface course,
which causes cracks in that layer,
hence the use of **reinforcement**
at bottom of the asphaltic surface course.

This leads to discussion of reflective cracking.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.333

DISCUSSION OF REFLECTIVE CRACKING

When the surface course of a road
has reached its serviceability limit,
rather than replacing it,
a layer of asphalt concrete,
called "**asphalt overlay**",
can be placed
on this existing surface course.

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First, let's review the case of **flexible pavements** (i.e. pavements where the surface course is asphalt concrete).

In the case of **flexible pavements**, the asphalt **overlay thickness** can be as low as **40 mm** and as high as **150 mm** depending on **traffic** and **condition** of the existing pavement.

The condition of the existing pavement should be determined by a non-destructive structural evaluation, which is commonly done using a falling-weight deflectometer (FWD).

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.335

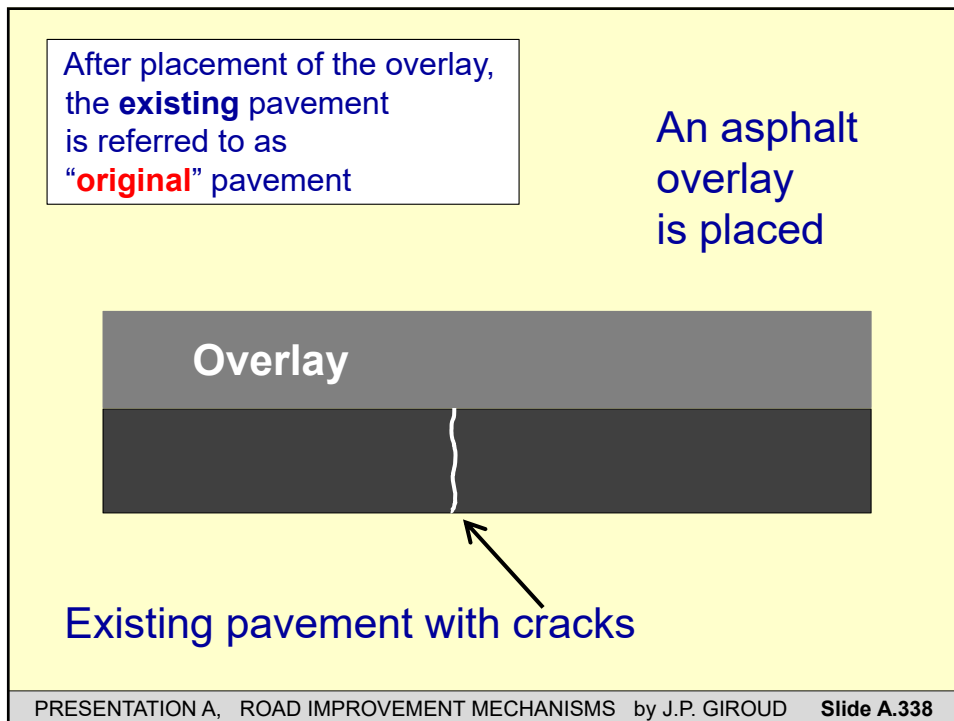
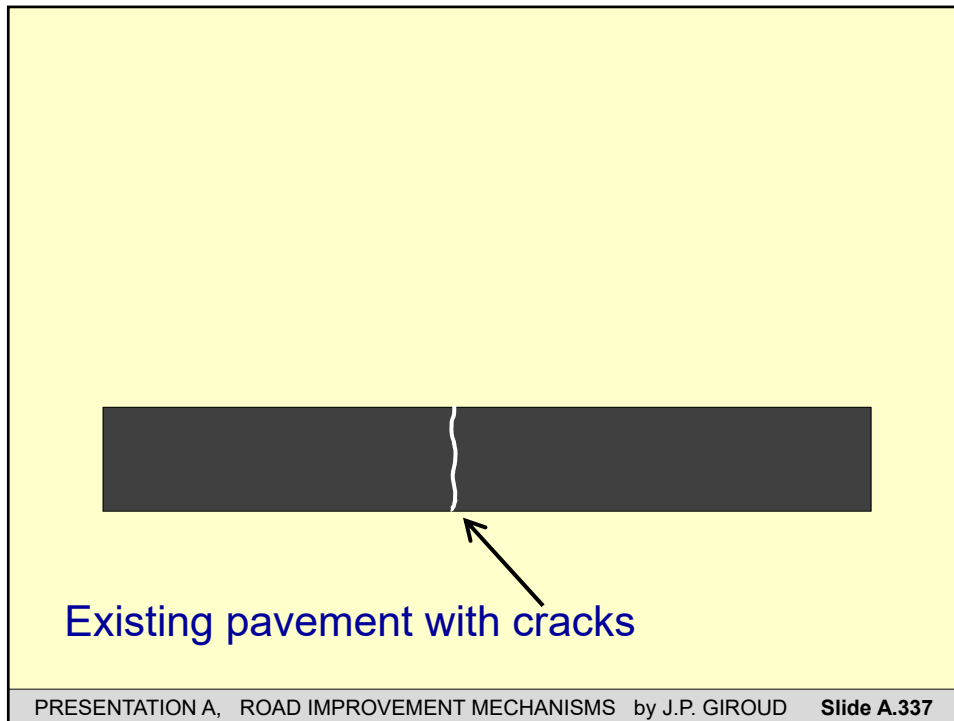
If the existing asphalt concrete surface course is **cracked**, the two edges of a crack undergo **relative movement** as a result of temperature and moisture changes and as a result **repeated traffic loading**.

If an asphalt overlay is placed on top of the existing asphaltic surface course, this overlay is affected as explained in the next slides.

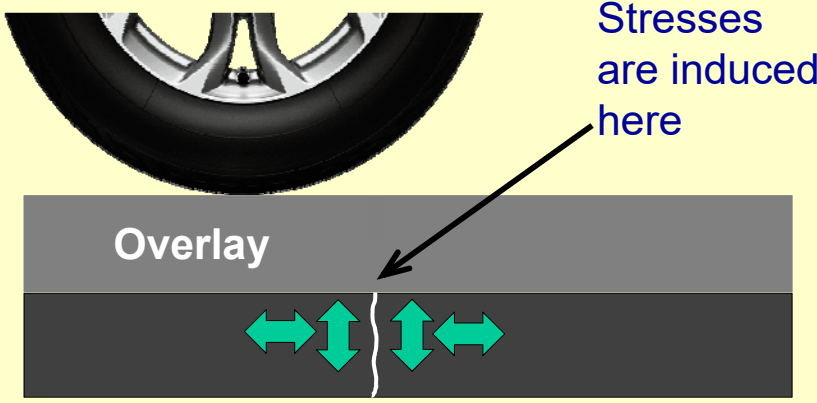
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Mechanisms of Road Improvement by Geosynthetics

by J.P. Giroud



Under repeated traffic loads



Stresses are induced here

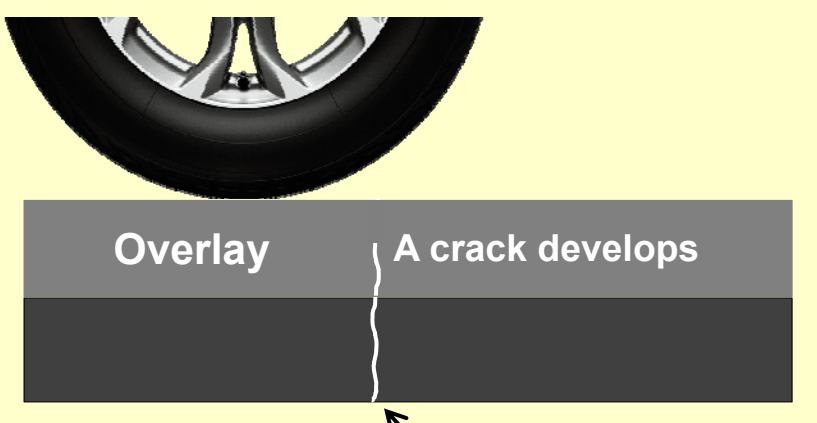
Overlay

The **edges of cracks move**, horizontally and vertically which induce stresses at the bottom of the overlay.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.339

The diagram illustrates the mechanism of stress induction. A tire is shown above a road surface consisting of a dark grey base layer and a lighter grey overlay. A vertical crack is shown in the overlay. Green double-headed arrows indicate horizontal and vertical movements at the crack edges. An arrow points from the text 'Stresses are induced here' to the crack. The text 'Under repeated traffic loads' is at the top left, and 'The edges of cracks move, horizontally and vertically which induce stresses at the bottom of the overlay.' is at the bottom.

As a result of stresses at bottom of the overlay



Overlay

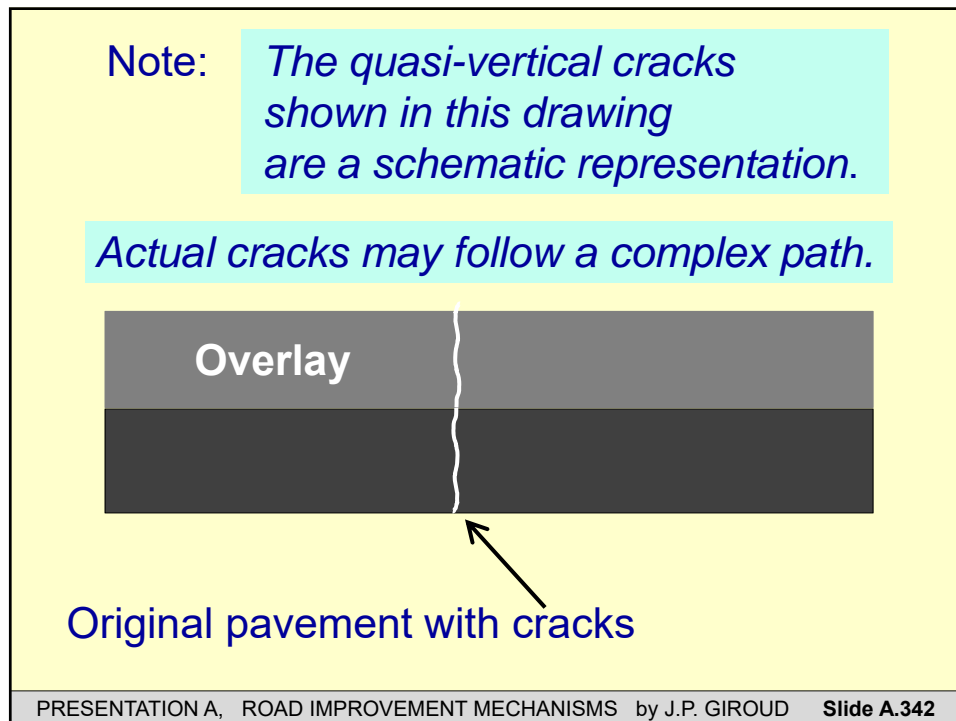
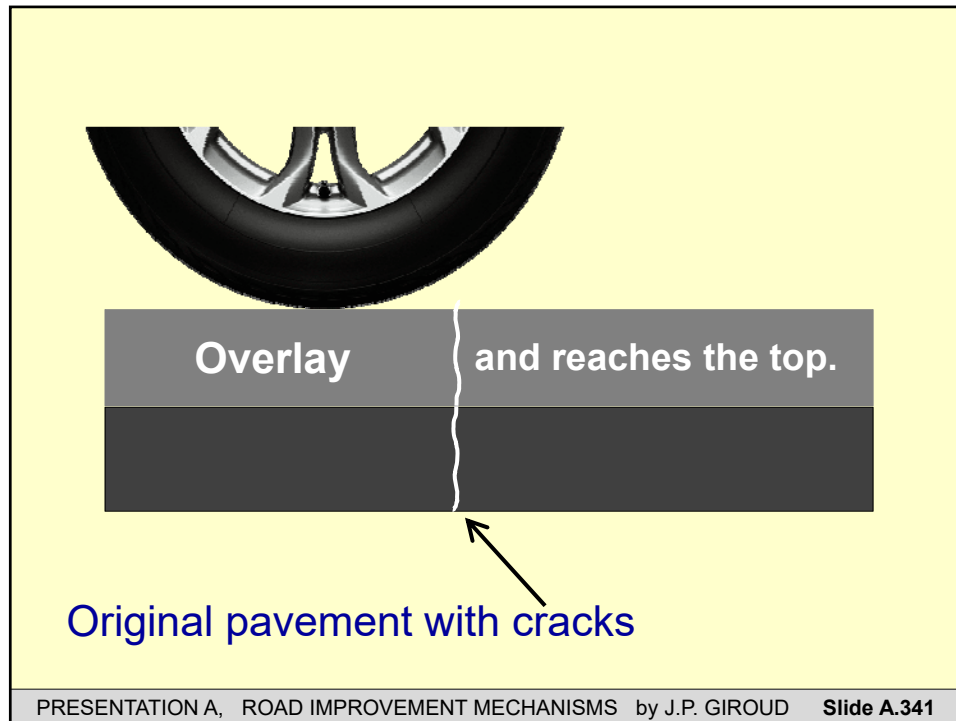
A crack develops

Original pavement with cracks

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The diagram shows the result of the stresses. A tire is shown above the road surface. A crack is shown in the overlay, with the text 'A crack develops' next to it. An arrow points from the text 'Original pavement with cracks' to the crack. The text 'As a result of stresses at bottom of the overlay' is at the top left.

Mechanisms of Road Improvement by Geosynthetics
by J.P. Giroud



The mechanism
of crack development
in asphalt overlays
is summarized in the
following two slides.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.343

The relative movements
of the two sides of cracks
in the original surface course
induce **concentrated stresses**
at the bottom of the overlay:
tensile stresses, bending stresses, shear stresses.

As a result of these concentrated stresses,
cracks appear at the bottom of the overlay
on top of the cracks
of the original surface course.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.344

These **cracks grow progressively**
from the bottom to the top of the overlay.

After some time, a **crack pattern**,
similar to the crack pattern
present in the original surface course,
appears at the surface of the overlay,
hence the term “**reflective cracking**”.

This similarity between the two crack patterns
gives the **impression** that cracks “**propagate**”
from the original asphaltic surface course
into and through the asphalt overlay.

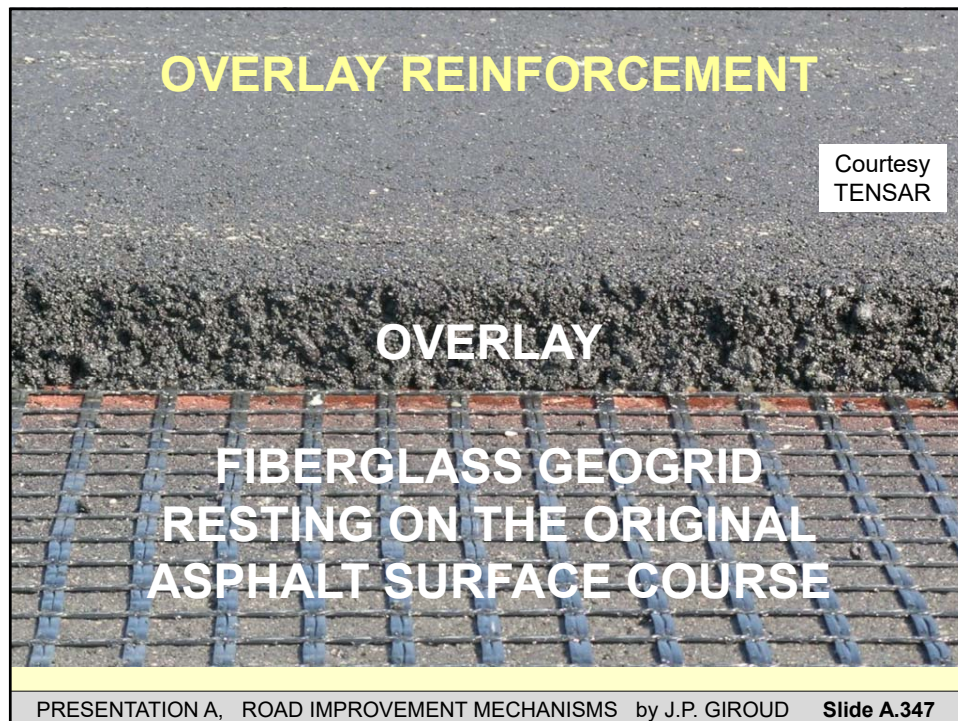
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.345

To **prevent or delay** reflective cracking,
there are two strategies:

The most obvious strategy consists in
reinforcing the overlay using a **geogrid**
at the bottom of the overlay,
which both **strengthens the overlay**
and **reduces stress concentration**.

The following slide shows
a **fiberglass geogrid**
used to reinforce an overlay.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.346



To prevent or delay reflective cracking,
there are two strategies:

The second strategy consists in
placing a **nonwoven geotextile**
on the existing surface course
and
impregnating this geotextile with **bitumen**,
and, then, placing the **overlay**
on top of the geotextile.

This is illustrated in the next slides.

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The slide has a yellow background. It contains text explaining a strategy to prevent reflective cracking. The text is in blue and black, with some words in red and bold. At the bottom, there is a large blue arrow pointing to the right, containing the text 'This is illustrated in the next slides.' in white. At the very bottom, a black bar contains the text 'PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.348'.

Placement of a nonwoven geotextile
on an existing asphaltic surface course

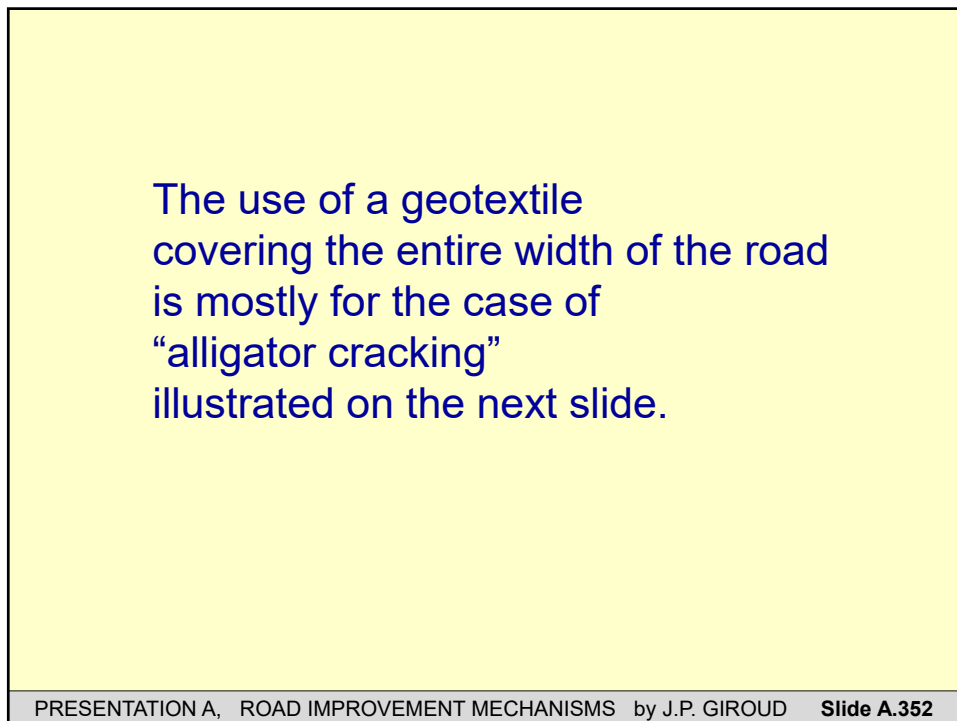


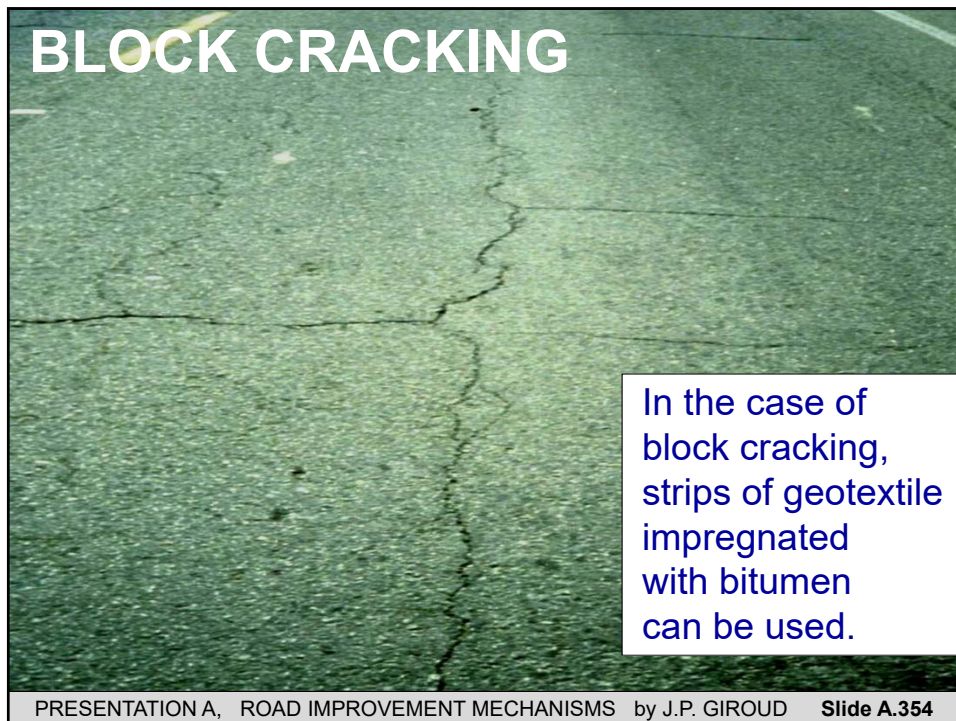
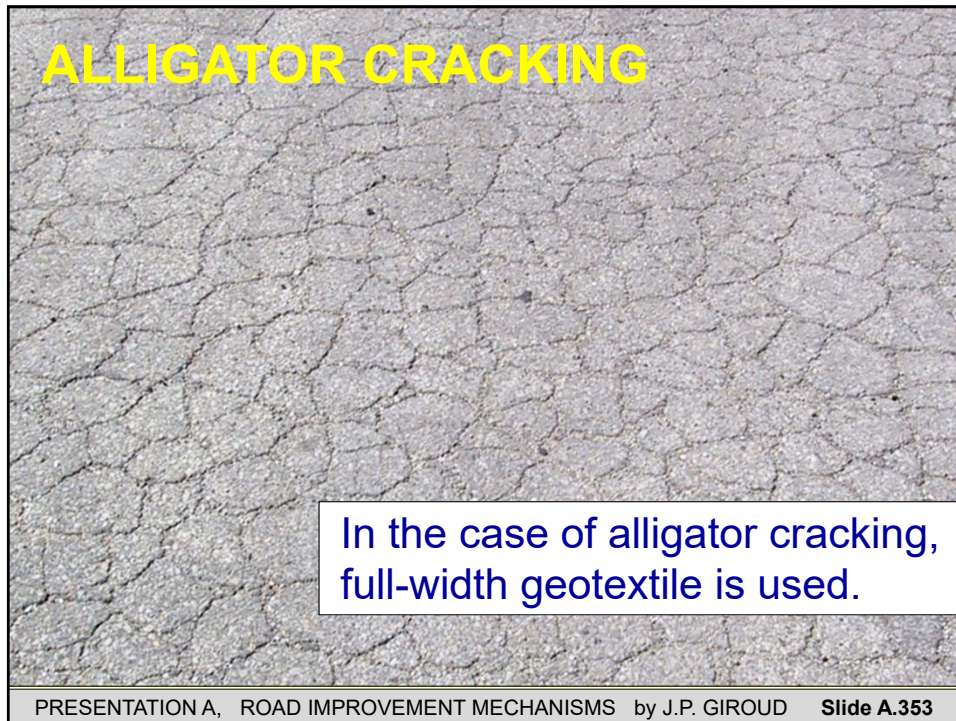
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.349

**It is important to use a system
that places the geotextile
without pleats and wrinkles.**

**This is important because
any extra thickness of the geotextile
(due to a crease or a flattened wrinkle)
may **initiate a crack**
in the asphalt overlay.**

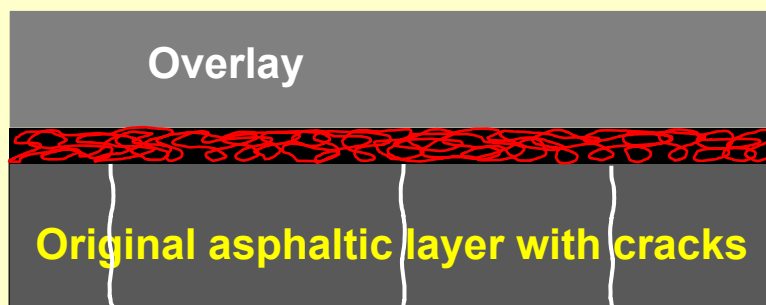
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.350





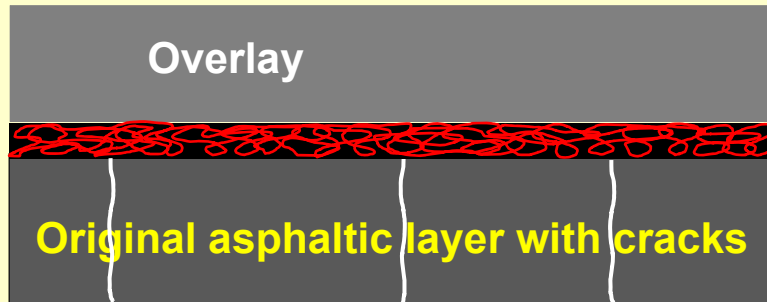


If a **nonwoven geotextile** impregnated with **bitumen** is placed between the original asphaltic layer and the asphalt overlay, movements of the edges of cracks induce localized deformation in the **nonwoven geotextile** impregnated with **bitumen**.



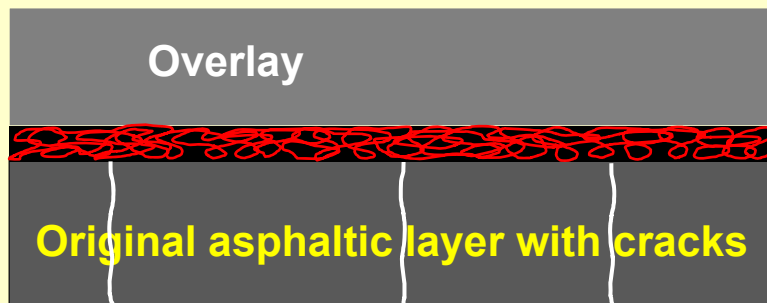
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.356

Due to the visco-elastic behavior of the **nonwoven geotextile** impregnated with **bitumen**, only negligible stresses are induced in the asphalt overlay.



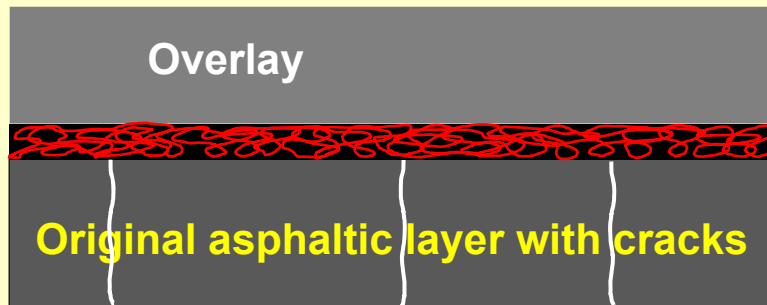
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.357

Therefore, if a **nonwoven geotextile** impregnated with **bitumen** is placed between the original asphaltic layer and the asphalt overlay, **crack development** in the asphalt overlay is **prevented** or **delayed**.



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In this application,
the geotextile impregnated with bitumen
does **not** act as **reinforcement**,
but as **stress-relief interlayer**
(a function also called *cushion*),
thanks to its viscoelastic behavior.



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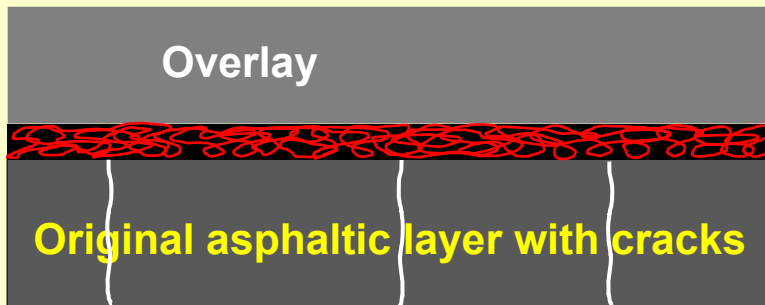
In this application,
the geotextile impregnated with bitumen
does **not** act as **reinforcement**,
but as **stress-relief interlayer**
(a function also called *cushion*),
thanks to its viscoelastic behavior.

Terminology:

The term **stress-relief interlayer** is used herein
because the term
Stress Absorbing Membrane Interlayer (SAMI)
refers to a mixture (of asphalt, polymers, fibers, etc.),
which generally does not contain a geosynthetic,
and is used to perform the same function.

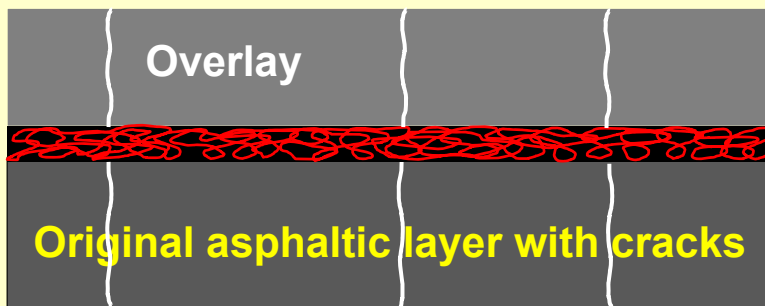
PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.360

In addition,
the **nonwoven geotextile**
impregnated with bitumen
acts as a **fluid barrier**,
preventing rain water from infiltrating
into the pavement layers.



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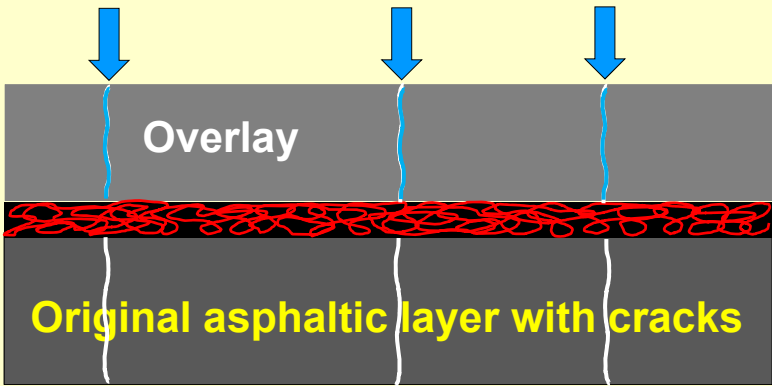
This **fluid barrier function**
is mostly useful after cracks
have developed in the overlay.



PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.362

This **fluid barrier function** is mostly useful after cracks have developed in the overlay.

Rain water infiltrates into the cracks.

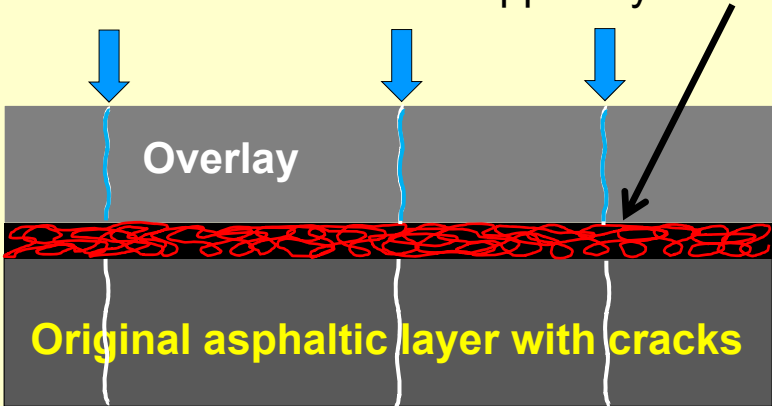


The diagram shows a cross-section of a road with three layers: a top grey 'Overlay' layer, a middle red fibrous geosynthetic layer, and a bottom grey 'Original asphaltic layer with cracks'. Three blue arrows point down into the overlay, with blue lines representing water seeping through cracks in the overlay and down into the original asphaltic layer.

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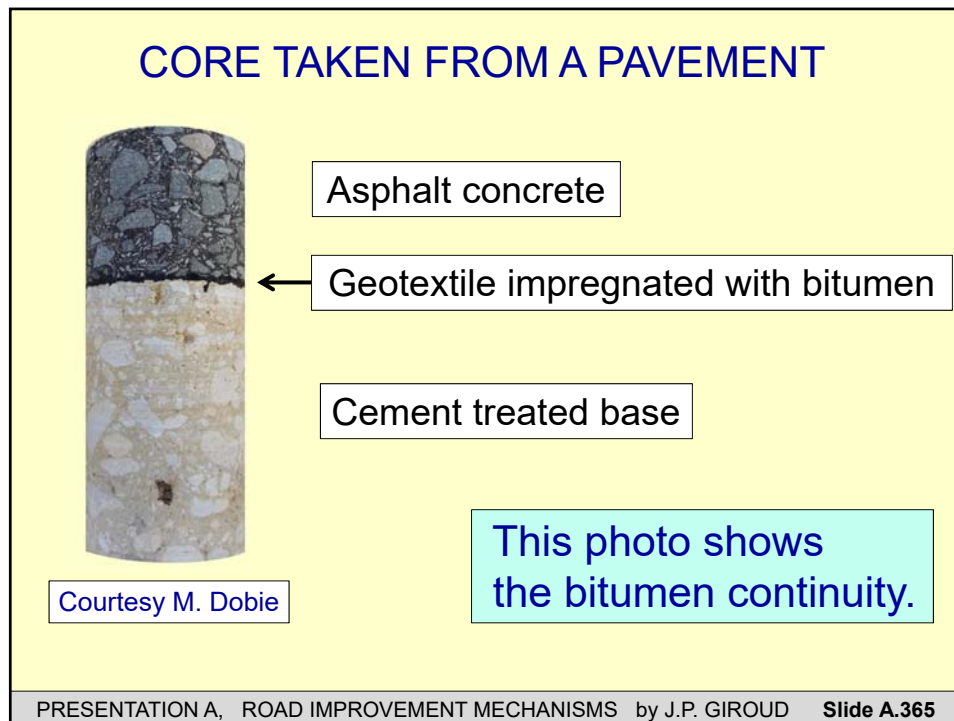
This **fluid barrier function** is mostly useful after cracks have developed in the overlay.

Rain water infiltration is stopped by bitumen



The diagram shows the same road cross-section as Slide A.363. In this version, the cracks in the overlay layer are filled with a dark material, and a black arrow points to this material with the text 'Rain water infiltration is stopped by bitumen'. The blue lines representing water are now blocked at the geosynthetic layer and do not reach the original asphaltic layer.

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In conclusion, in this application,
the **nonwoven geotextile impregnated with bitumen**
performs **two functions**:

- By performing the **stress-relief interlayer function**, the geotextile prevents or delays crack development in the overlay.
- Performing the **fluid barrier function**, the geotextile prevents infiltration of water into the pavement system.

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There is **considerable experience** in the use of nonwoven geotextiles impregnated with bitumen between original asphaltic surface courses and asphalt overlays. This experience shows that:

- A nonwoven geotextile impregnated with bitumen is **always** an **effective waterproof barrier** preventing migration of precipitation water into the underlying pavement layers.
- A nonwoven geotextile impregnated with bitumen is **not always** effective as a **stress-relief interlayer** between the overlay and the original asphaltic surface course.

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Regarding the **effectiveness** of nonwoven geotextile impregnated with bitumen for preventing overlay cracking, the following comments can be made:

- This technique **can be effective** for fine cracks (e.g. 1 mm or less) due to fatigue and thermal contraction.
- This technique **may not be effective** for structural cracks (several mm or more).

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COMMENT on one of the two functions
performed by a geotextile in reflective cracking:

Stress-relief interlayer (i.e. mechanical separation)
is different from stabilization,
because it does not create a composite material;
rather, it partly **dissociates** adjacent materials.

This function is similar to the **protection function**
performed by a nonwoven geotextile
preventing or minimizing damage
to a geomembrane due to adjacent material.

The functions “stress-relief interlayer” and “protection”
are, in fact, the **same function**.

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In summary:
there are **two techniques**
to prevent or delay reflective cracking:

reinforcement by geogrid
(*fiberglass geogrid or polymeric geogrid*)

and

stress-relief interlayer plus fluid barrier
by bitumen-impregnated
nonwoven geotextile.

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The two techniques are somehow combined in a composite geosynthetic (“geocomposite”) that consists of **fiberglass geogrid** laminated with a **nonwoven geotextile impregnated with bitumen**.

In addition to being the waterproof component that ensures the fluid barrier function, the bitumen provides good bonding between the geotextile and the adjacent layers.

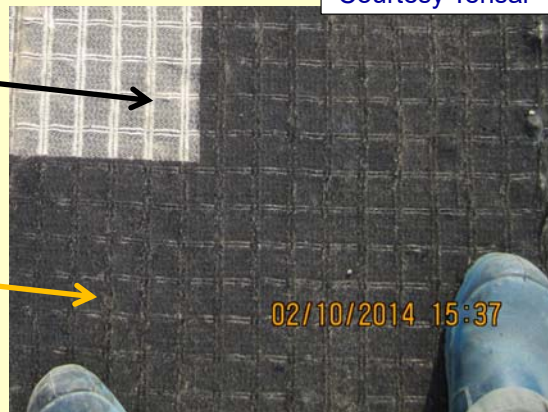
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EXAMPLE OF GEOCOMPOSITE COMPRISING A FIBERGLASS GEOGRID AND A NONWOVEN GEOTEXTILE LAMINATED TOGETHER

Courtesy Tensar

Portion not impregnated with bitumen

Portion impregnated with bitumen



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In preceding slides,
only reflective cracking
for the case of existing
asphalt concrete surface courses
has been addressed.

What about **reflective cracking**
in the case of existing
cement concrete pavements ?

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Cement concrete surface courses
are, in fact, concrete slabs,
which can be **reinforced** with steel bars
or **unreinforced**.

Unreinforced cement concrete surface courses
include **joints** in both directions
every 3 to 5 meters in the longitudinal direction,
and, according to traffic lane width,
in the transverse direction.

As a result, paved roads with
unreinforced cement concrete surface course
are called:
“Jointed Plain Concrete (JPC) pavements”.

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Cement concrete pavements
reinforced with steel bars
include two main types:

- Jointed Reinforced Concrete (JRC) pavements where the surface course consists of reinforced concrete **slabs**, with **joints** every 10 to 15 m.
- Continuously Reinforced Concrete (CRC) pavements with **no joints** other than construction joints.

Note: **Asphalt** concrete pavements have **no joints**.
This is an advantage over concrete pavements.

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As a result of **repeated traffic loading**
and **temperature changes**,
cracks develop in concrete pavements.

If an asphalt overlay is placed on top
of a concrete pavement,
movements of the edges of
both **cracks and joints**
of the concrete pavement
can induce **cracking of the overlay**.

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Joints in the existing concrete pavement are a major problem for overlays.

Indeed, a **joint width** is of the order of 20 mm.

Joint edges move significantly under repeated traffic loads, especially in cases where adjacent slabs are not connected using dowels.

Therefore, the risk of overlay cracking on top of a joint is higher than on top of a crack.

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The **effectiveness** of asphalt overlays on concrete joints is **questionable**.

In the case of concrete pavements with joints, thick asphalt overlays are sometimes used, e.g. 100 or 150 mm thick.

In the case of *continuously reinforced concrete pavements*, thick overlays may not be necessary and 50 mm thick asphalt overlays may be used, because these pavements have cracks, but **no joints**.

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In the cases
where asphalt overlays are used
on existing concrete pavements,
either **geogrid reinforcement**
or **geotextile stress-relief interlayer**
can be used.

*This is the same approach as in the case
where the existing surface course is asphaltic.*

Again, good performance can be expected
only in areas without joints.

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In the case of existing pavements with joints,
another technique (rarely used)
consists in using a thick (e.g. 200 mm) ,
continuously reinforced concrete slab
as **overlay**.

In this case a **thick geotextile**
can be placed between the concrete overlay
and the existing concrete pavement.

The function of this geotextile
is to act as a **slip surface**.

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In the case of
a badly deteriorated concrete pavement,
the use of geotextile
between pavement and concrete overlay
is not a sufficient mechanical separation.

In this case, mechanical separation
between deteriorated pavement
and concrete overlay
is sometimes provided
by a layer of asphalt concrete
(50 to 100 mm thick).

Alternatively, rubblization can be used.

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In the case of
a badly deteriorated concrete pavement,
the “**rubblization**” technique can be used.

The “rubblization” technique consists in
breaking down the concrete surface
into small pieces (***rubble***).

In other words,
the existing concrete is used
to make an aggregate base or sub-base
on which a new pavement is constructed.

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More information on **reflective cracking**
is presented in
Presentation C titled
**Design of Geosynthetic-Stabilized
Paved Roads and Case Studies**
by Erol Tutumluer

Now, practical matters, on the following slides

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.383

In preceding slides, for **paved roads**,
we have discussed
the mechanisms of stabilization.

Now, let's review the failure modes.

We also followed this dual approach
for unpaved roads
when we used a “**road function approach**”
and a “**road dysfunction approach**”.

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In this presentation,
two types of **paved road** failure
are **not** addressed:

- **Failure of the surface course**
(for example: thermal cracking,
reflective cracking, and shear slippage)
- **Failure of the entire structure**
due to subgrade swelling:
 - Swelling of expansive clays,
 - Frost heave followed by a thaw.

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It is important to note that **subgrade swelling**
due to expansive clays or frost heave
is **not related to traffic**.

*It should be noted that
expansive clays and frost heave
can affect **unpaved roads** as well.*

However,
the effect of these two phenomena
is particularly **detrimental to paved roads**
due to the sensitivity
of the surface course to deformations.

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**EXAMPLE OF PAVEMENT CRACKING
DUE TO SWELLING
OF EXPANSIVE SUBGRADE SOIL**



Typically:
Longitudinal
cracking

Courtesy J.G. Zornberg

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**ANOTHER EXAMPLE OF LONGITUDINAL CRACKING
DUE TO SWELLING OF EXPANSIVE SUBGRADE SOIL**



Turnersville
Road
near Austin
(Texas)

Courtesy J.G. Zornberg

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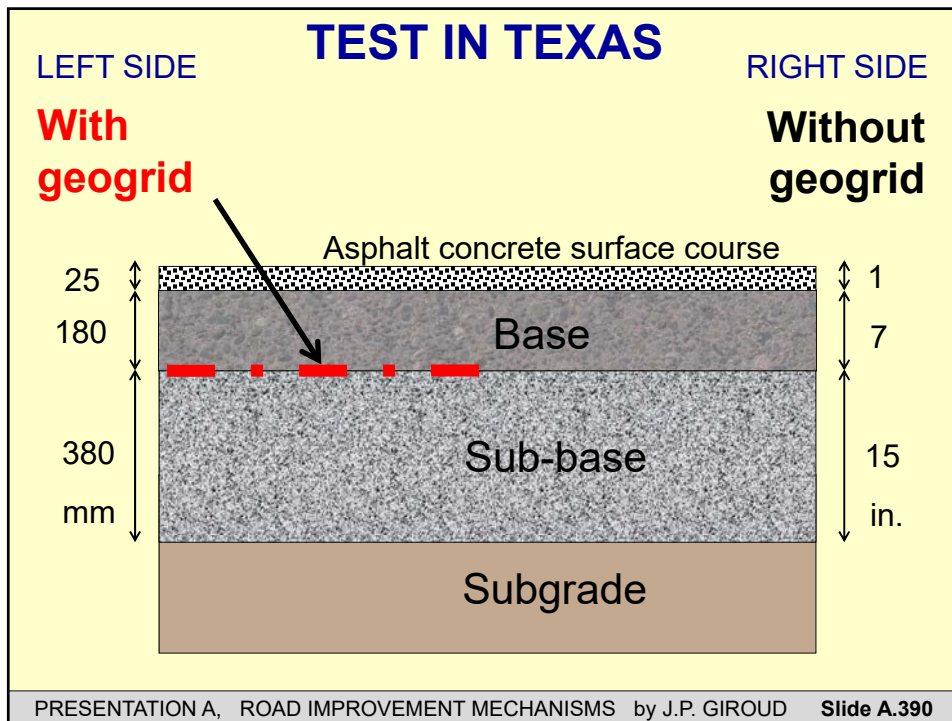
The use of a **geogrid** has been shown (*)
to **preclude the development**
of **longitudinal cracking** of pavements
due to **subgrade swelling**
caused by **expansive subgrade soil**.

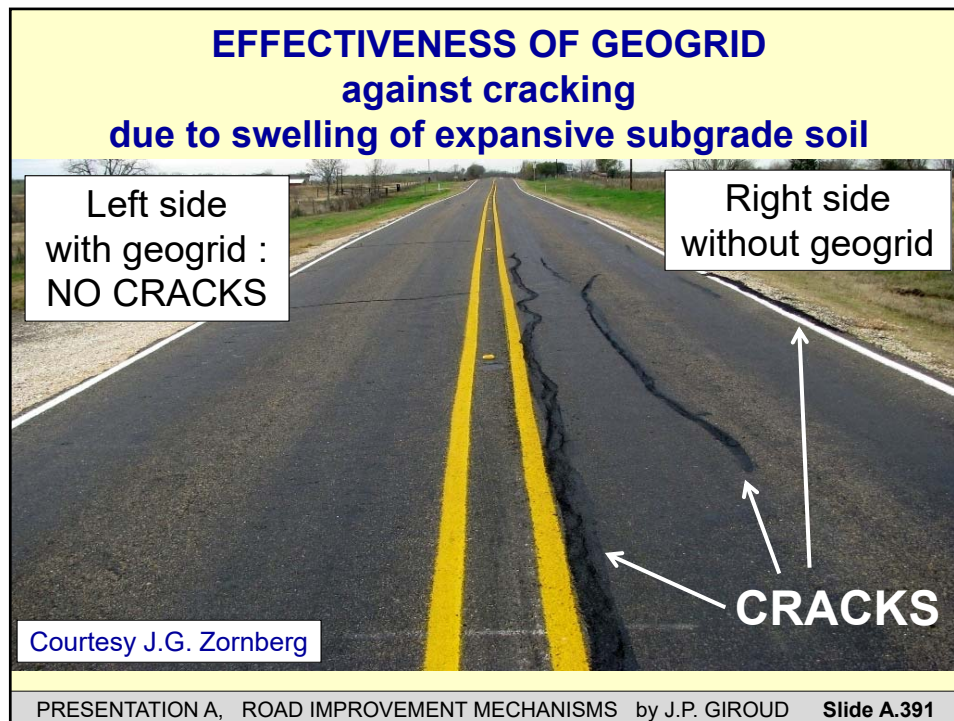
(This has been observed in areas
where longitudinal cracking typically
takes place in roads without geosynthetics.)

*Typically, when a geogrid is used,
cracking is relocated
outside the zone with geogrid.*

(*) Zornberg
& Gupta
(2009)

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*What is the function performed by the geogrid
in the prevention of pavement cracking
due to swelling of expansive subgrade soil?*

This is a complex subject
for which more research is needed.

A tentative analysis is proposed
based on the assumption that
cracking occurs during swelling
of the subgrade soil.

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TENTATIVE ANALYSIS OF THE GEOGRID FUNCTIONS

This tentative analysis is based on the generally accepted assumption that the stabilization function is mobilized under a **strain** smaller than the strain that mobilizes the reinforcement function.

When the subgrade soil starts swelling, the **stabilization function may be mobilized**, which would restrain lateral displacement of the aggregate/geogrid composite material of the road base, thereby preventing the development of small cracks in the asphalt surface course.

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TENTATIVE ANALYSIS OF THE GEOGRID FUNCTIONS

If the subgrade soil keeps swelling, it is possible to assume that additional tension is induced in the geogrid.

As a result, the **reinforcement function may be mobilized**, which would prevent the development of large lateral displacements in the base course, thereby preventing the occurrence of large cracks in the asphalt surface course.

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TENTATIVE ANALYSIS OF THE GEOGRID FUNCTIONS

In conclusion, the tentative analysis seem to show that the **successful use of geogrids** in the prevention of asphalt pavement cracking due to expansive subgrade soil could be explained by the **successive mobilization** of the **stabilization function** and the **reinforcement function** of the geogrid.

Again, this is only a tentative analysis.

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Another approach to the case of expansive subgrade soils consists in controlling infiltration of water into the subgrade to minimize the risk of swelling of the subgrade soil.

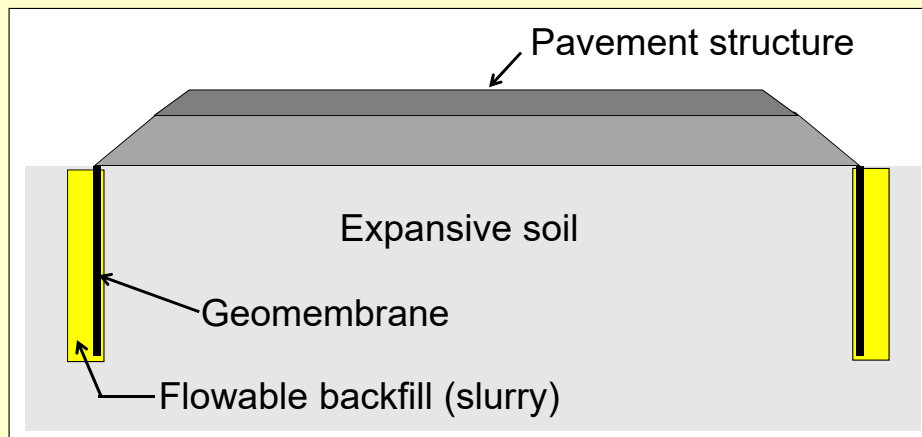
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USE OF GEOMEMBRANES ALONG HIGHWAYS TO CONTROL THE MOISTURE CONTENT OF EXPANSIVE SOILS

- With expansive subgrade soils, the **service life** of a road may be 5 years instead of 20 years.
- Geomembranes are used as water barriers to keep **the moisture content** of the subgrade soil as constant as possible.
- Typically, the **moisture content fluctuates** down to a depth of 1.5 to 3.0 m.

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CONTROL OF MOISTURE CONTENT OF EXPANSIVE SOILS CONFIGURATION WITH VERTICAL GEOMEMBRANES



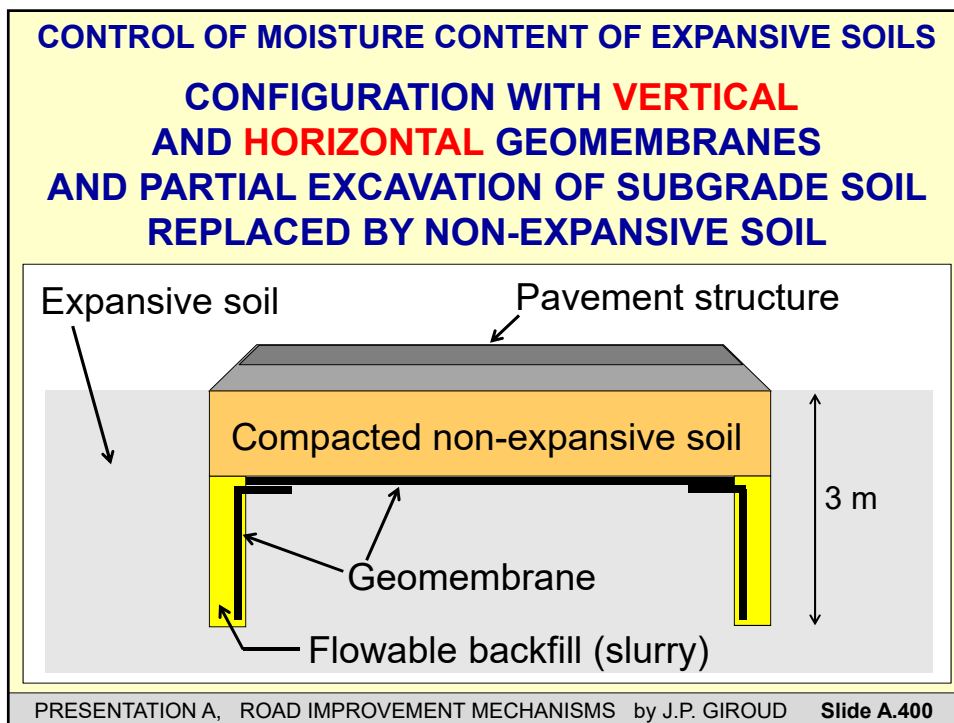
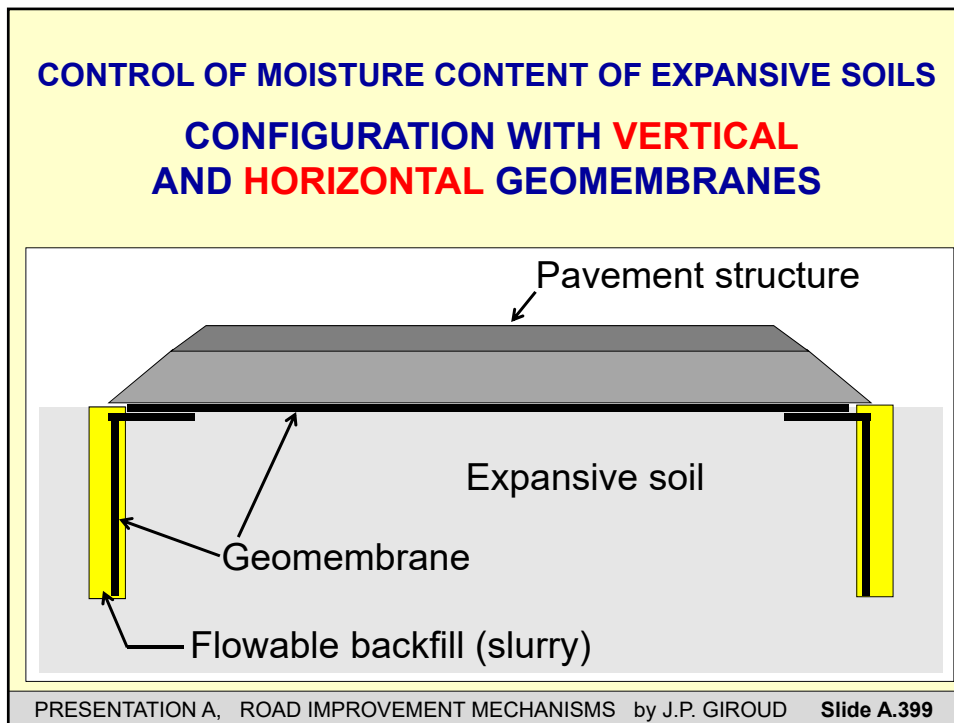
Trench depth:

1.5 m to 3.0 m
typical: 2.5 m

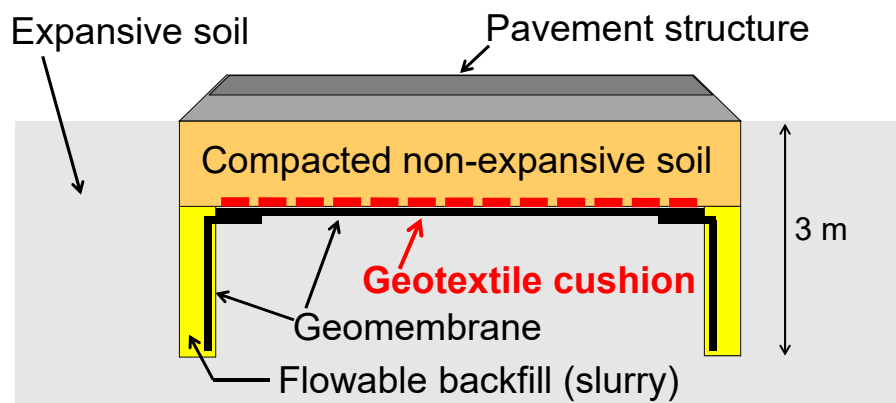
Trench width:

0.5 m backhoe
0.1 m trencher

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As shown below, a **geotextile cushion** can be added to the preceding cross section if there is a risk of damage to the geomembrane by stones of the non-expansive soil and/or by compaction-generated stresses.



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TERMINOLOGY

The technique described in the preceding three slides is sometimes referred to as "**partial encapsulation by geomembrane of expansive subgrade soil**" (where the adjective "**partial**" is essential).

Note: The phrase "*encapsulation by geomembrane of expansive subgrade soil*" (sometimes used, same as the above but without "**partial**") is misleading, because "*to encapsulate*" means "*to enclose as in a capsule*", which cannot be done with *in situ* soil.

The term "encapsulation" (alone) should be used only for a soil layer enclosed in a geomembrane. (see Slides A.209 to A.219.)

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.402

The preceding slides illustrate a mechanism that is not related to traffic (*i.e. cracking of pavement due to swelling of expansive subgrade soil*).

But, the focus of this presentation is on the behavior of roads under traffic loading.

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.403

The failure mode of **paved roads** that is related to the response of the road structure to the **traffic loads** is:

rutting, which is a symptom of **improper stress distribution** to the subgrade.

Improper stress distribution results from weakness of the base and/or sub-base.

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Base and/or sub-base are weak if:

- **They lack tensile stiffness**
and/or
- They have deteriorated over time.

Deterioration over time is due to:

- **Lack of separation**
and/or
- **Lateral spreading of aggregate.**

PRESENTATION A, ROAD IMPROVEMENT MECHANISMS by J.P. GIROUD Slide A.405

The **conclusion** of this dysfunctioning analysis
of **paved roads** is that:

- **Base and sub-base**
need **tensile stiffness**
and
- **Lateral spreading of aggregate**
must be prevented.

These are the two benefits
provided to base and sub-base
by geogrid-aggregate **interlocking**
or by soil **confinement** in geocell,
i.e. **stabilization by geosynthetic.**

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As for unpaved roads,
the “**road function approach**”
and the “**road dysfunction approach**”
lead to the **same conclusion** for paved roads:

*Use of a **geosynthetic** should provide
tensile stiffness and **lateral restraint**
to the road structure.*

Clearly, a good understanding
of the mechanisms of road **stabilization**
has been developed,
for both unpaved roads and paved roads.

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CONCLUSIONS

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FIRST CONCLUSION

The **mechanisms** associated with geosynthetics in a road structure are **complex** because the configuration is not ideal since the **load is vertical** while the **geosynthetic is horizontal**.

This configuration leads to a **variety of mechanisms**, such as:

base lateral restraint,
subgrade heave restraint,
tensioned membrane.

The complexity is increased because the loading is **dynamic** and **repeated**.

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SECOND CONCLUSION

Road **improvement by mechanical means** includes the benefits of the **stabilization** function and the **reinforcement** function.

Geosynthetic **stabilization** is beneficial to both unpaved roads and paved roads by imparting **tensile stiffness** and **lateral restraint** to the layers used in road structure.

In addition, *in the case of unpaved roads*, geosynthetic **reinforcement** provides restraint of heave of the **subgrade**, which **increases its bearing capacity**.

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THIRD CONCLUSION

In addition to road **improvement by mechanical means** discussed in the preceding slide, there is **improvement by hydraulic means**:

- **Drainage**
in both paved and unpaved roads.
- **Fluid barrier**, in some geomembrane applications and as an additional benefit of bitumen-impregnated geotextile used to delay reflective cracking.

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FOURTH CONCLUSION

Geogrids are widely used because they effectively provide **stabilization to aggregate**; and because they have practical advantages.

Geocells can provide **stabilization to a variety of soils** and can be expected to be increasingly used, in particular with low-quality fill or on-site soil.

Geotextiles are indispensable when **separation** is required (*and high-strength geotextiles can provide reinforcement*).

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**Thank
you**

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APPENDIX

**QUESTIONS
AND
ANSWERS**

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DISCUSSION OF THE ANALYSIS

The analysis presented in the preceding slides is complex, and experience shows that some **questions** are typically asked and some **comments** are sometimes made.

Important **questions** and **comments** are addressed in the following slides.

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A question sometimes asked is:

“Is a base course always necessary in unpaved roads ?”

REPLY:

An unpaved road with no base course would mean driving directly on the subgrade.

See analysis on the next slide

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A simple bearing capacity calculation shows that a soil with a CBR of 3% could support some traffic with no aggregate base.

A CBR of 3% is approximately equivalent to an undrained shear strength of 90 kPa (1800 psf).

The bearing capacity of such a soil is:

$$q = (\pi + 2)c_u = 5.14 \times 90 = 460 \text{ kPa (67 psi)}$$

This shows that this soil would support the static load of a truck (i.e. no traffic).

A low-ground pressure vehicle
could be driven slowly on this soil.

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The conclusion of the preceding calculation is that a low-ground pressure vehicle could pass directly (*i.e. with no base course*) on a soil with a CBR of 3%.

With a CBR higher than 3%,
traffic of heavier vehicles
could be considered.

Therefore, no base course is needed
in the case of a soil with high CBR,
depending of axle load and traffic.

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A frequent comment is:

*“One may wonder why
the **tensioned membrane effect**
has a negligible impact
on unpaved road performance
(as shown in some previous slides),
whereas
the **inverted tensioned membrane effect**
drastically increases
the load that can be carried by the subgrade
(as shown in other slides).”*

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SUMMARY OF THE COMMENT

*Negligible tensioned membrane effect
versus effective inverted tensioned membrane effect*

REPLY:

Due to the **shape of the pressure-deflection curve**,
a relatively small increase in the surcharge
(thanks to the inverted tensioned membrane effect)
drastically decreases the subgrade deflection.

As a result, the subgrade can be loaded
up to its **ultimate bearing capacity**,
rather than be loaded to the **elastic limit**,
hence an increase of the **load that can be carried**,
increase by 64% (geotextile) and by 82% (geogrid).

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Negligible tensioned membrane effect
versus *effective inverted tensioned membrane effect*

REPLY (continued):

Essentially, we only use
the **inverted** tensioned membrane effect
to control deflection.

In contrast, we use
the **direct** tensioned membrane effect
to carry part of the wheel load,
which is harder to achieve than controlling deflection,
hence the difference in effectiveness
between **direct** and **inverted**
tensioned membrane effects.

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A question can be described as follows:

*“It has been indicated in the analysis that the
restraint of the subgrade heave
due to the geosynthetic
is equivalent to a surcharge
increasing the bearing capacity of the subgrade.*

*What about the surcharge
provided by the **weight of the base** ?*

Should it be taken into account ?”

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SUMMARY OF THE QUESTION

*What about the surcharge
provided by the weight of the base ?*

REPLY:

The pressure due to the weight of the base
does provide a surcharge.

However, this pressure is also present
in the stress distribution angle under the wheels.

These two pressures cancel each other out,
as shown by Giroud & Noiray (1981).

*Note: Geotechnical engineers understand that
this demonstration is possible only because
the subgrade soil is assumed to be frictionless.*

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EXPLANATION OF THE PRECEDING NOTE

In the case of a subgrade soil **with friction**,
the bearing capacity equation is such that,
the surcharge is multiplied
by a factor N_q greater than one.

Therefore, the weight of the base course
has more impact on the subgrade bearing capacity
than the weight of base material
included in the load distribution angle.

In other words, the two do not cancel out,
as they do in the case of **frictionless** subgrade soil
where $N_q = 1$.

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The following comment
is sometimes made:

*“A benefit of stress distribution is not only to decrease the load on the subgrade, but also to apply the load over a **larger area**, thereby increasing the bearing capacity of the subgrade.”*

REPLY IN THE NEXT TWO SLIDES

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SUMMARY OF THE COMMENT

*“ . . . apply the load over a **larger area**, thereby increasing the bearing capacity of the subgrade.”*

REPLY:

This comment is **not compatible with the assumptions** that the subgrade soil is a low-permeability saturated soil subjected to rapid loading (i.e. a soil subjected to **undrained conditions** and, therefore, having a **frictionless** behavior), with an undrained shear strength, c_u , that is **constant with depth**, because, with such a subgrade, the bearing capacity does not depend on the loaded area, a well-known result of the theory of plasticity.

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Indeed, in the case of a frictionless soil, with c_u constant with depth, the equation $p_{ult} = N_c c_u + q$ shows that the subgrade bearing capacity **does not depend** on the **size of the loaded area**.

The bearing capacity of the subgrade soil **depends on the size of the loaded area**:

- in the case of a frictionless soil if the undrained shear strength, c_u , increases with depth; or
- in the case of a soil with friction through the famous coefficient N_γ used routinely in foundation design.

See Slides A.184 to A.187

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The following comment is sometimes made:

*“In the analysis presented in the previous slides, the classical **bearing capacity factors** used are for a **two-dimensional** situation.*

*Would it be more appropriate to use bearing capacity factors for an **axi-symmetrical** situation ?*

And would the bearing capacity factors values be very different ?”

REPLY IN THE NEXT TWO SLIDES

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TWO-DIMENSIONAL BEARING CAPACITY OR AXI-SYMMETRICAL BEARING CAPACITY

The bearing capacity factors used in the analysis presented herein, and used in the Giroud-Han design method, are for a **two-dimensional loading situation**.

It may be argued that a **two-dimensional situation** prevails in case of **rutting**.

It may also be argued that **wheel loading** can be considered approximately **axi-symmetrical**.

The actual situation is in between.

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2-D and Axi-symmetrical Bearing Capacity Factors
are not very different.

Shear stresses	2-D	Axi-symmetrical	Ratio	Difference
Outward (*)	2.57	3.07	1.19	
Zero (geotextile)	5.14	5.69	1.11	11%
Inward (geogrid)	5.71	6.04	1.06	6%

The elastic limit (3.14) is the same for 2-D and axi-symmetrical.

The **axi-symmetrical bearing capacity factors** are **slightly higher** (6 to 11%) than the 2-D factors.

The Giroud-Han design method uses the 2-D case, which is slightly conservative (less than 6% to 11%).

(*) *The outward shear stress case is an unrealistic case shown for completeness.*

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The following questions are often asked:

*“ What is the importance
of geogrid tensile strength
in the performance
of geogrid-reinforced unpaved roads ?*

*Is it appropriate to specify a geogrid
with a very high tensile strength ? ”*

A complete reply requires three slides.

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Field measurements on a
geogrid-reinforced unpaved road
with rut depths between 40 and 80 mm
indicate that **subgrade heave restraint**
can generally be achieved
with **small strains** (e.g. 1 to 2%) in the geogrid.
(Giroud & Han 2006; Watts et al. 2004).

This is **consistent with the result of calculations**
using the tensioned membrane theory
for a rut depth of 75 mm (Giroud & Noiray 1981).

*These calculations are applicable
to all types of geosynthetics.*

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Based on the data
provided in the preceding slide,
if an unpaved road is designed
for a **rut depth of 75 mm (3 in.)**
and if tensile strength is specified,
it should be the **tensile strength**
measured at a small strain (e.g. 1 or 2%)
(*i.e. approximately the mobilized tensile strength*)
not the ultimate tensile strength.

But,

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But, for punched-and-drawn geogrids,
it may not be appropriate
to specify *excessively high tensile strength*,
because it could be related to **high rib stiffness**,
which may not be beneficial,
or even **may be detrimental**.

Indeed, based on the discussion on interlocking,
it is possible that there is
an **optimum rib stiffness** for interlocking.

Above that **optimum stiffness**,
interlocking may be less effective.

*It is not known if this is applicable to geogrids
other than punched-and-drawn geogrids.*

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The following question is often asked:

*“ What precautions should be taken
if the base course of a paved road
is used as an access road
during construction ?”*

A reply illustrated using a case history

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REPLY:

Indeed, a frequent situation occurs
during the construction of a paved road:
**a section of the paved road
is used temporarily as an unpaved road.**

Then, the paved road is constructed
in that section.

The **unpaved road base** can be eventually used
as the **paved road base** or **sub-base**
only if it has **not** undergone
excessive deformation.

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In this case,
bases with geogrid and high-quality aggregate
and good geogrid/aggregate **interlocking**
are recommended, because
mobilization of interlocking
does not require significant displacement
and, as a result, the base does not undergo
excessive deformation.

*Bases with geotextile tend to deform more
than bases with geogrids,
because friction requires displacement
to be mobilized.*

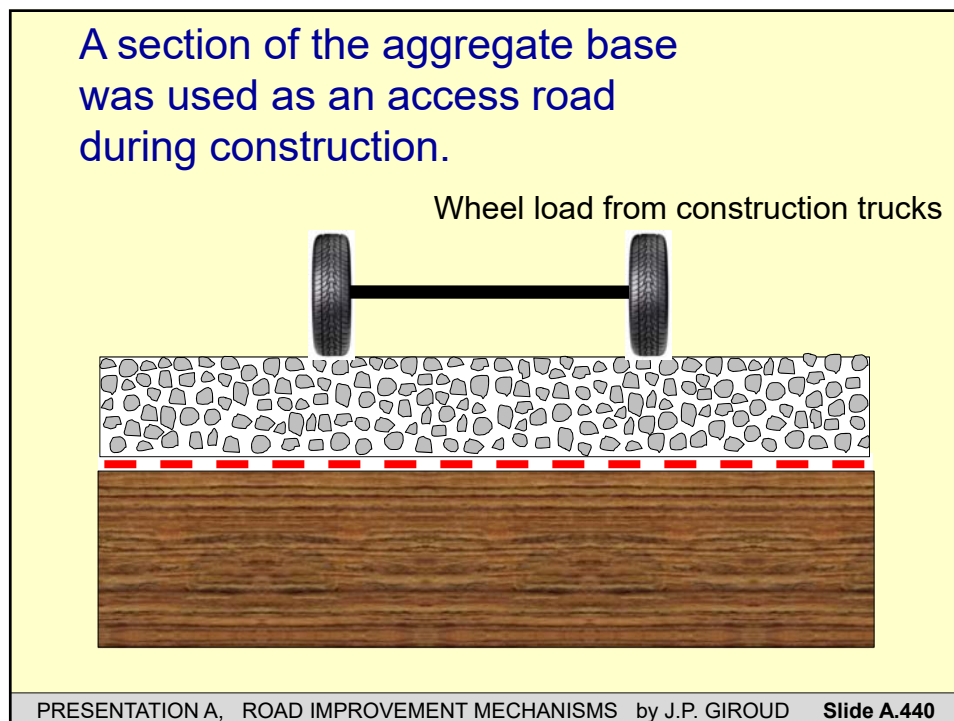
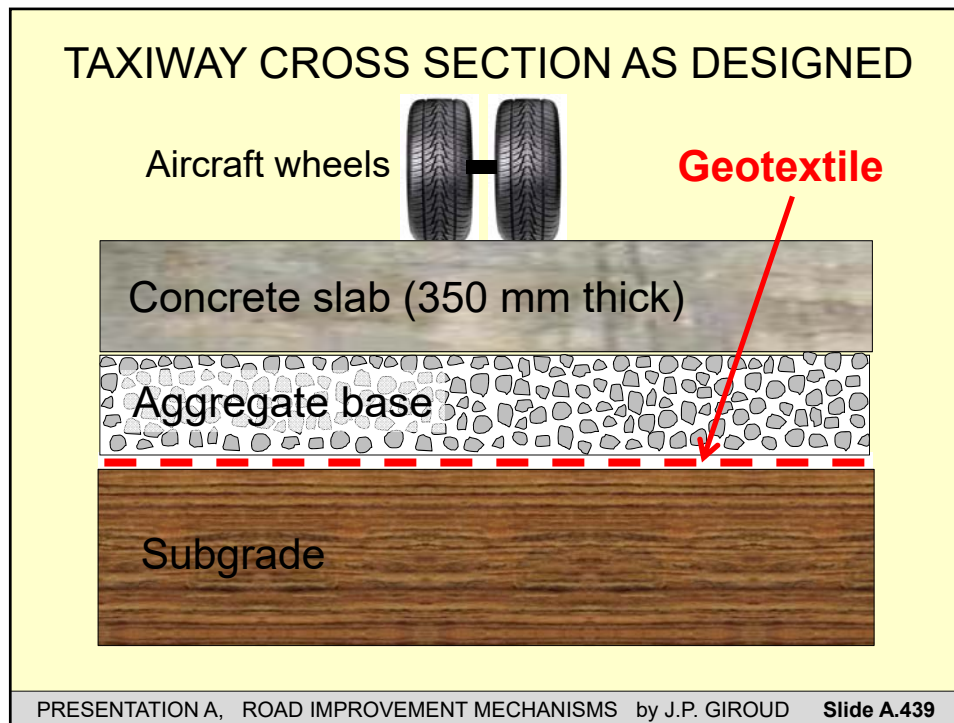
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This is illustrated by
the following case history.

**CASE HISTORY OF PROBLEM
DURING CONSTRUCTION
OF A TAXIWAY
AT A MAJOR AIRPORT
IN THE UNITED STATES**

1979

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The access road carried a large number of trucks and **performed well**.

Then, it was time to place the concrete slab on the aggregate base.

It was then realized that the **elevation** of the top of the aggregate **was too high**.

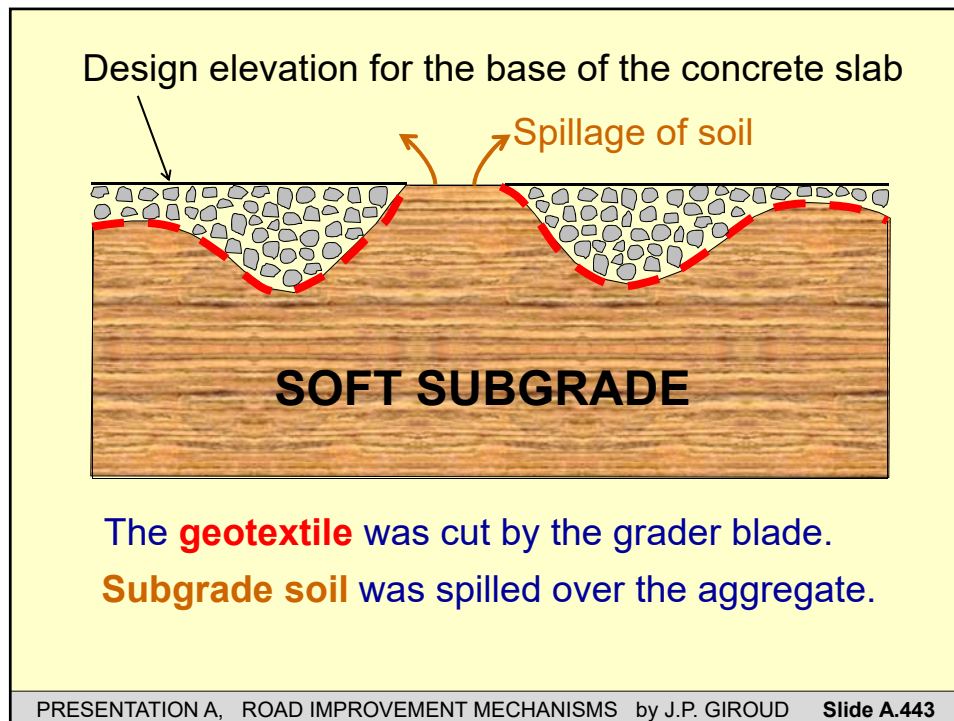
A grader was used to remove the excess aggregate and **the geotextile was cut**.

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The next slide shows the **situation** in the field **after the geotextile was cut** by the grader

(i.e. after the grader had removed the aggregate that was above the elevation where the concrete slab was to be placed).

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Construction work was interrupted.

The contractor, who was using a geotextile for the first time (1979), concluded that **geotextiles do not work.**

The design engineer and the geotextile supplier did not know what to do.

I was asked to go to the site immediately.

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I came. I saw. I said:

- The access road performed well, which indicated that the **geotextile had worked well**.
- But, to work on a soft subgrade, the **geotextile had to deform** which caused rutting.
- As a result, it was necessary to add aggregate to fill the ruts.

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It was confirmed by the contractor that *aggregate had been periodically added*.

As heavy truck traffic continued, more rutting took place causing **more deformation** of the geotextile.

As **more aggregate** was placed to fill the ruts, the **elevation** of the top of the aggregate exceeded the design elevation.

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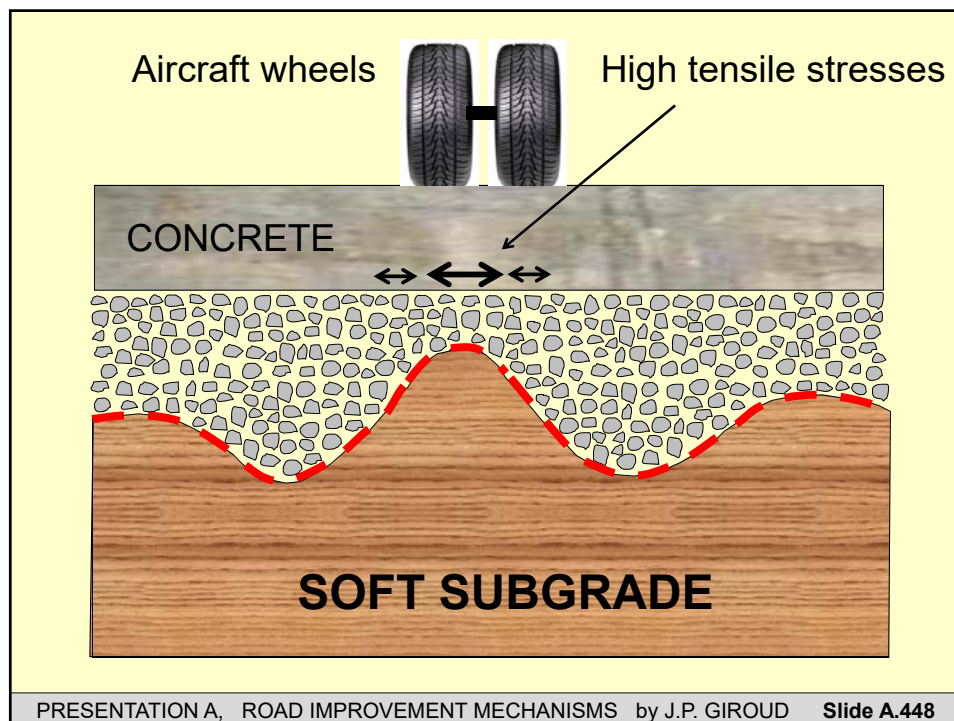
I concluded on a positive note saying that
the incident was very fortunate.

Why ?

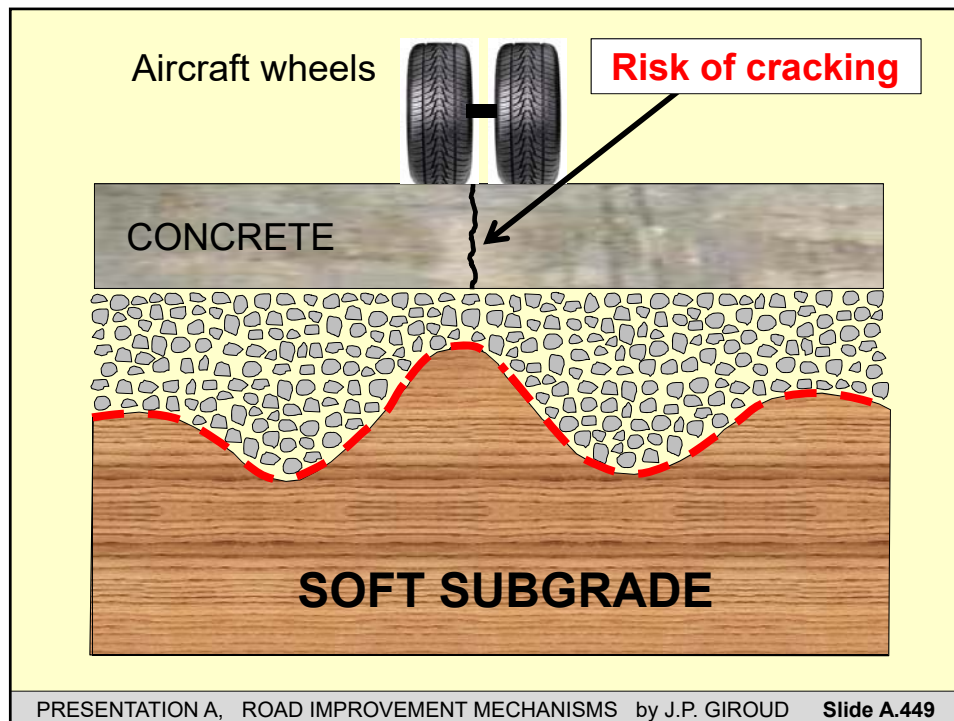
Because, if the geotextile had not been cut,
the concrete slab would have been installed
on a **base** with a **non-uniform thickness**.

As a result, the concrete slab
would have been subjected to
excessive tensile stresses.

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THE SOLUTION

Clearly, it was **impossible** to use the unpaved road as a base for the concrete slab, **including in places where the geotextile had not been cut.**

The solution consisted in excavating and regrading the subgrade to construct an aggregate base with a **uniform thickness.**

Two lessons can be learned,
one for **design**, the other for **construction**:

- If an unpaved road is to be paved at a later stage, the geosynthetic should be **selected** to **minimize deformation**.
- Prior to constructing the pavement, the **base thickness** should be checked.

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The following question is often asked:

“ What geosynthetic should be selected if the subgrade soil is so soft that it is not possible to start the construction of a road ?”

REPLY: In such cases, several types of geosynthetics can help and the best choice may be to use the geosynthetic that happens to be available at the site.

A geogrid with high bending stiffness may be an adequate solution. Indeed, workers can walk on a geogrid with high bending stiffness to install it.

More on the next slide

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Geotextiles are more difficult than geogrids to install on soft soil. However, they provide reinforcement through the tensioned membrane effect especially high-modulus woven geotextile. This is helpful if significant traffic of construction equipment is expected.

However, the **deep rutting** associated with the tensioned membrane effect may be **detrimental** in the case of a paved road, as shown in the preceding case history.

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The following question is often asked:

“ Is it necessary to anchor a geogrid at the edges of an unpaved road ?”

REPLY:

A geosynthetic that performs the **stabilization function** does not need to be anchored laterally, whereas a geosynthetic that performs the **reinforcement function** (as in the case of the tensioned membrane effect) needs to be anchored laterally.

More on the next slide 

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The **required anchorage length** increases with increasing values of the tensile modulus of the geosynthetic that performs the reinforcement function.

As a result, **the tensioned membrane effect is small** in the following cases:

- If the geosynthetic **modulus is low**, the tensioned membrane effect is low.
- If the geosynthetic **modulus is high**, the required anchorage length is huge and cannot be achieved with practically all road configurations.

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If necessary, an **anchorage system** can be considered at the **edges of a road**, for example:

- by wrapping a geosynthetic around aggregate or compacted soil at the edges of the base;
or
- by attaching the geosynthetic to concrete blocks or concrete curbs at the edges of the base.

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The following question is often asked:

“ Is channelized traffic required in the case of a geosynthetic-stabilized unpaved road ?”

REPLY: Channelized traffic is required to impart tension in the geosynthetic, when the geosynthetic provides **reinforcement**, to improve bearing capacity (and, in case of deep rutting, to carry part of the load through the *tensioned membrane effect*).

When the geosynthetic provides **stabilization**, channelized traffic is not required *per se*, but limited rutting, associated with lateral restraint mobilization, may be beneficial by maintaining the locked-in stresses that ensure aggregate confinement by the geosynthetic.

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The following question is often asked:

“ What is the difference between geogrids and geocells regarding confinement and lateral restraint of the base material ?”

REPLY:

A detailed reply is provided on the following slides.

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First comment:
confinement and lateral restraint are the same thing.
So the question can be summarized as follows:
which is most effective ?

- **Closed confinement**
in the case of geocells ?
or
- **Open confinement**
in the case of geogrids ?

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Fundamental considerations with geocells

Fundamental advantages of geocells:

- All of the material in the geocell is confined, so the confinement thickness is known: it is the geocell thickness.
- All types of soils can be confined in a geocell.

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Fundamental considerations with geocells

Fundamental disadvantages of geocells:

- The geocell imposes its geometry to the infill material, which may be a drawback if aggregate is used, because the aggregate **may not achieve its densest arrangement**.
- Unless the geocell walls are rough and have holes, relative displacement may occur between the infill material and cell walls, which may be detrimental to confinement.

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Fundamental considerations with geogrids:

- Drawback: The degree of confinement decreases with increasing distances from the geogrid; as a result the **thickness** of the **effectively confined zone** is not known accurately.
- Advantage: Triaxial geogrid promotes the **densest arrangement** of aggregate (*i.e. the hexagonal arrangement*).

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Practical considerations for the geocell / geogrid comparison:

- INSTALLATION
 - Installation of geocell is labor intensive.
 - Installation of geogrid is easy.
- COMPACTION
 - Aggregate compaction in geocell is not easy.
 - Aggregate compaction with geogrid is easy.

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In conclusion:

- In roads (paved or unpaved), where **high quality aggregate** is used, the preceding discussion leads to the conclusion that **geogrids are the material of choice.**
- However, a **growing use of geocells** can be predicted due to the **decreasing availability of high-quality aggregate**, and the possibility of using a variety of materials in geocells, in particular local materials.

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If **sand** is the **only material available** to construct the road base (beach, desert area), a geocell is the geosynthetic of choice.

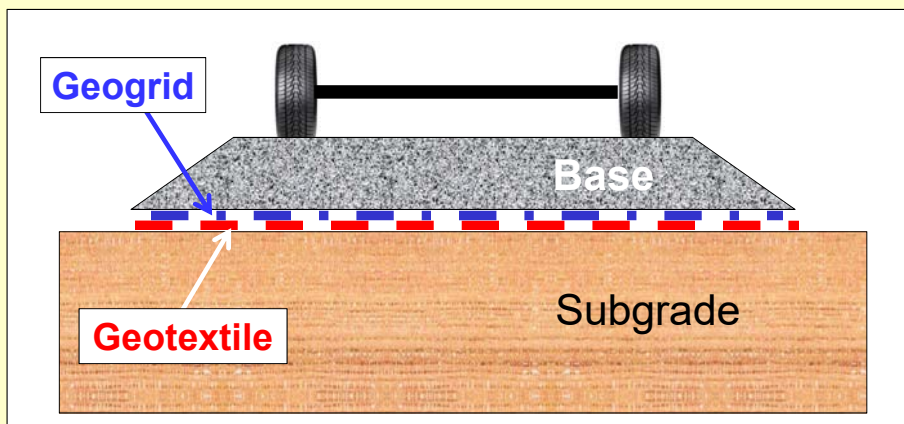


Courtesy
GeoGlobe
Europe
Arik Rosen

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The following question is often asked:

“ What bearing capacity factor should be used in the case of a geogrid underlain by a geotextile ? 5.14 or 5.71 ? ”



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REPLY:

If a **geogrid** is underlain by a **geotextile**,
*which is recommended if there is
a risk of inter-mixing
of base aggregate and subgrade soil,*
the **bearing capacity factor**
is **5.14** rather than **5.71**
because stresses
between geotextile and subgrade
tend to be normal
*(as in the case of a geotextile alone
between the base and the subgrade).*

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The following question is often asked:
*“Is geosynthetic reinforcement effective
against collapse of a road into a cavity ?”*



Courtesy M. Dobie

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REPLY:

Extremely strong geosynthetic reinforcement, typically using several layers of geosynthetic, may effectively **bridge a cavity**, depending on the size of the expected cavity.

This type of reinforcement is beyond the scope of this presentation: it is relevant to embankment reinforcement and is different from the geosynthetics used for road stabilization.

This leads to the following comment applicable to road stabilization.

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IMPORTANT BENEFIT

Geosynthetic reinforcement in road applications (i.e. under embankments or in road structures) improves the structure behavior by distributing stresses and bridging weak areas in the case on **non-uniform soils**.

This benefit is difficult to quantify, but it is real as it results from a **combination of mechanisms** such as depression bridging, load distribution, tensioned membrane, etc.

This is an important benefit because non-uniform soils are frequent and unpredictable.

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