Pavement Design Systems and Pavement Performance models

Mechanistic Models for Road Design

NordFoU 2007-2009

Anders Huvstig
SRA
SE 405 33 Göteborg
SWEDEN
Tel: +46 31 63 50 80
Cell: +46 70 563 50 80
Email: anders.huvstig@vv.se

Anders Huvstig

Swedish Road Administration (SRA)

Rutting and unevenness in roads have been a problem in many thousand years

And still, rutting and unevenness in roads are great problems today

If we could predict future rutting and unevenness, when a new road is ready, it would give a great help to minimize these problems!

Background

Road building

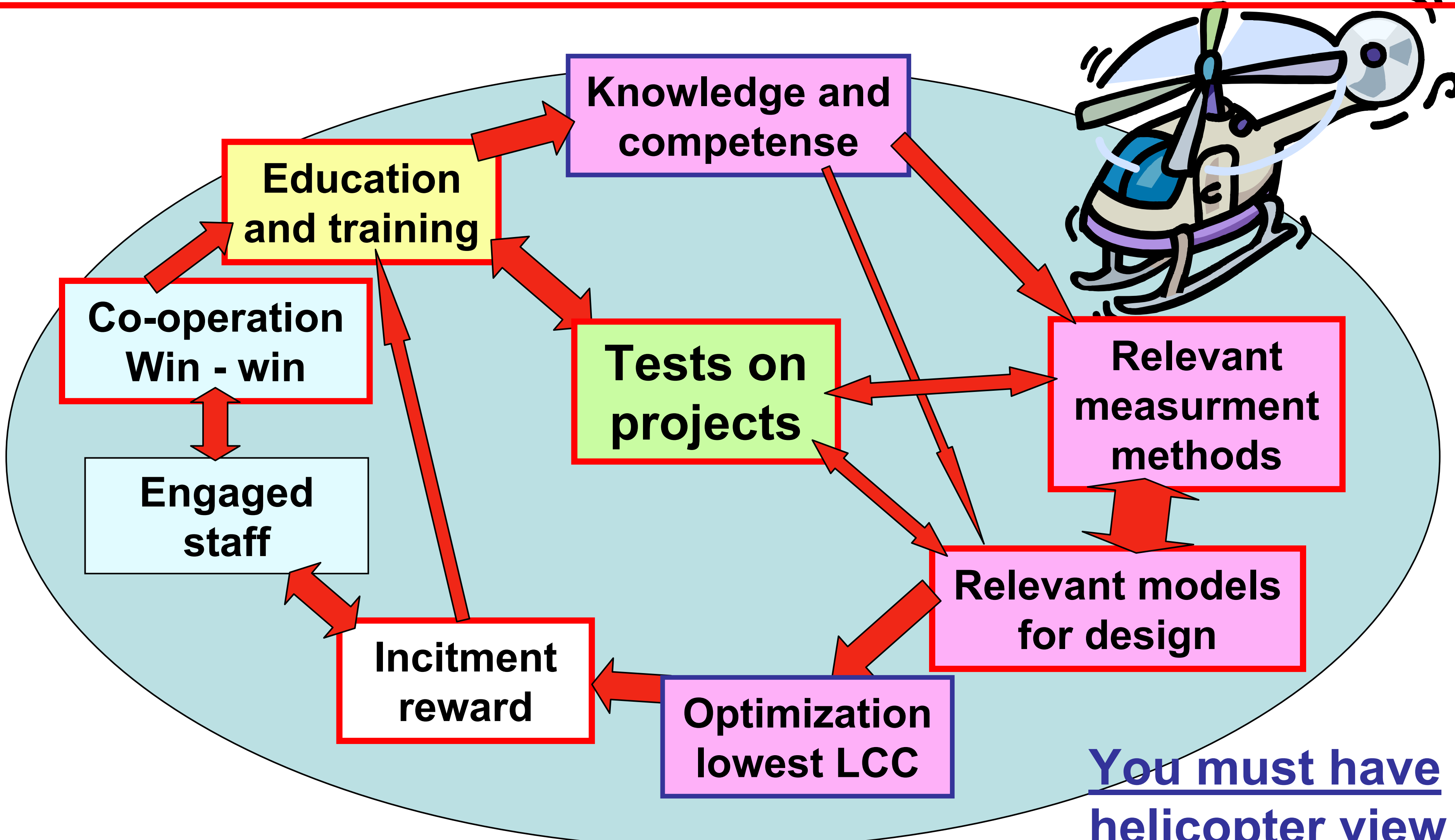
Investment cost	New technique 3 % per year or 15 % in 5 years	System costs 5%	Unnecessary costs 10 %	Error costs 10 %

Investigation from Chalmers University of Technology

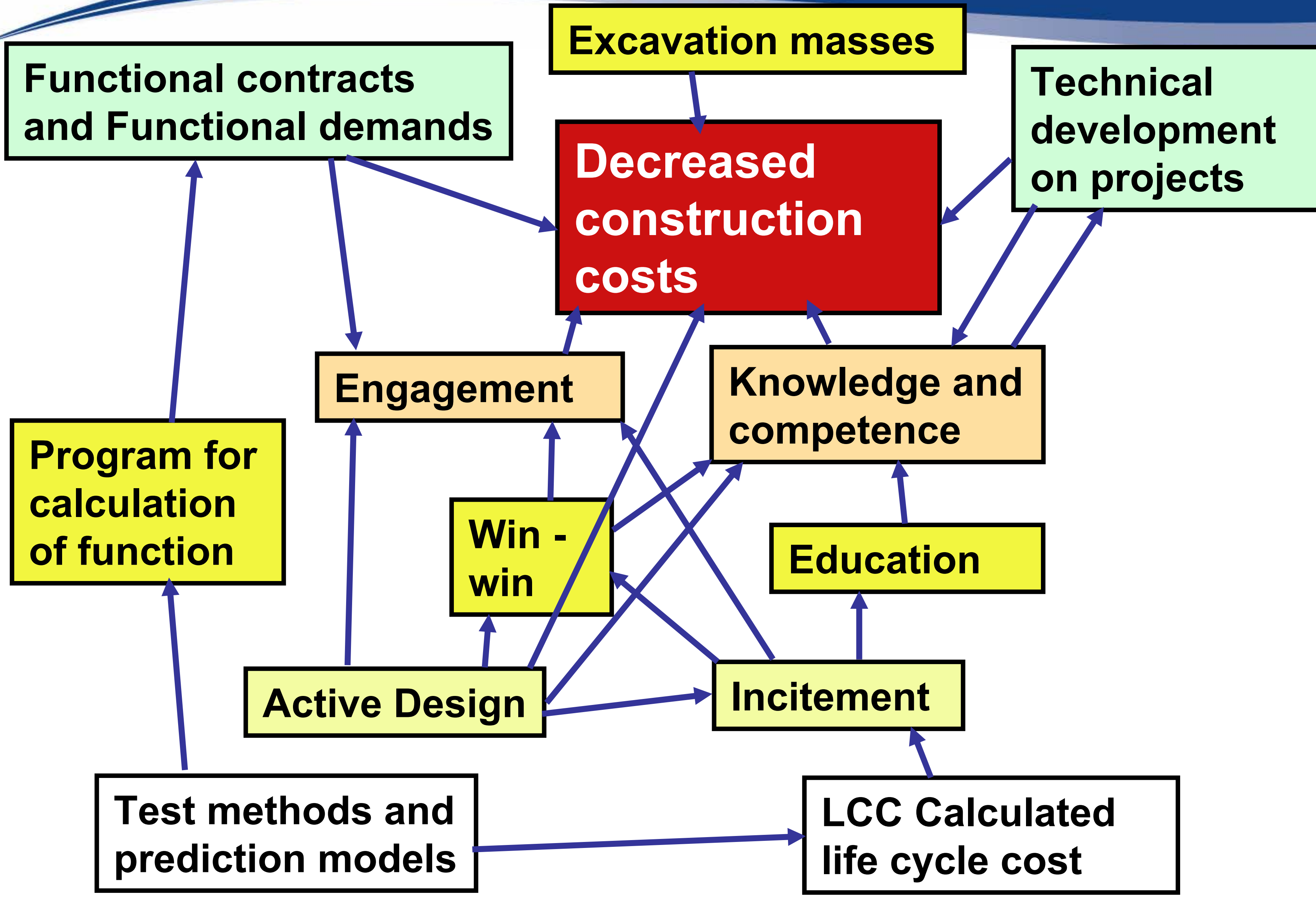
saving POTENTIAL (inside 5 years) 40 %!

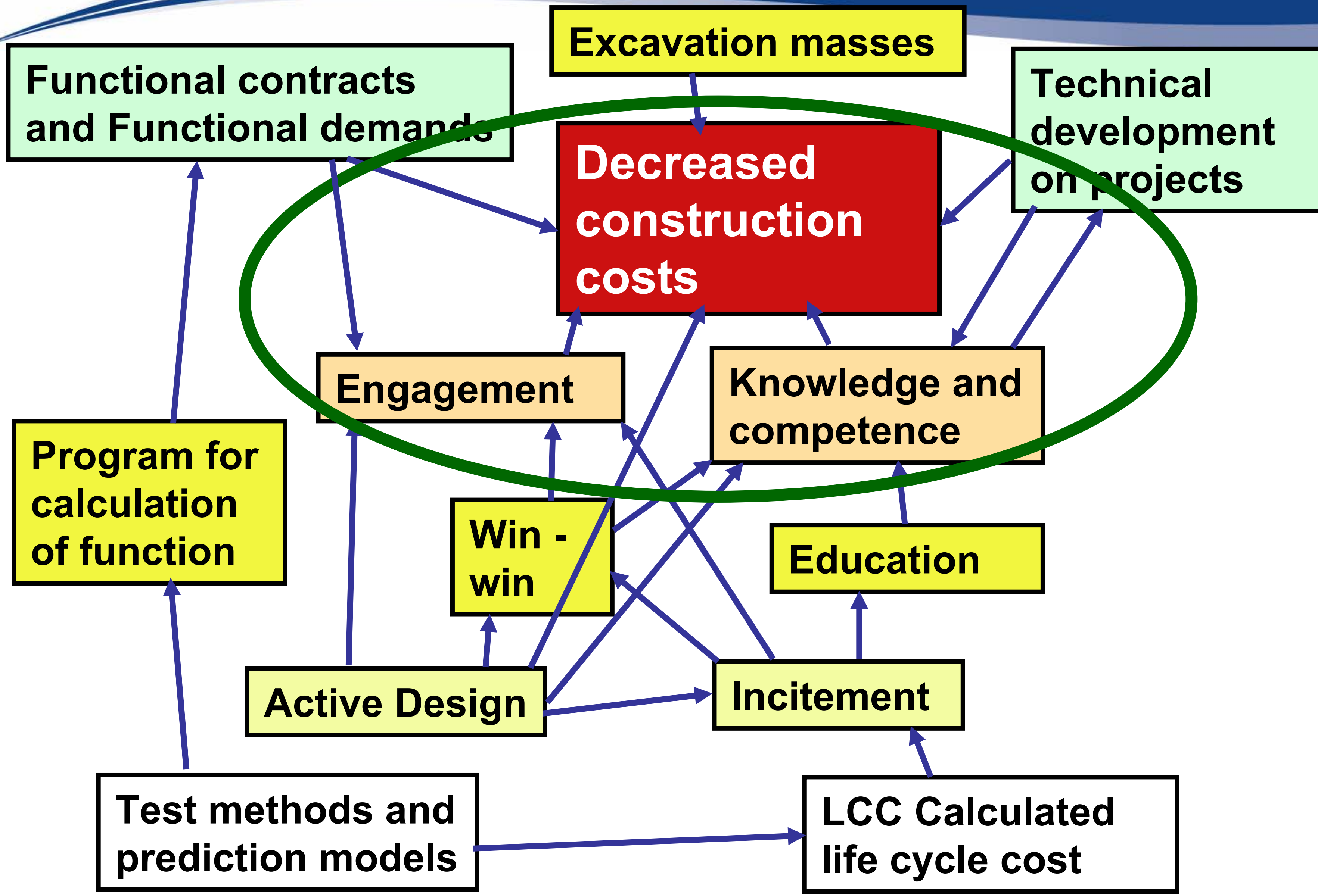
Vägverket

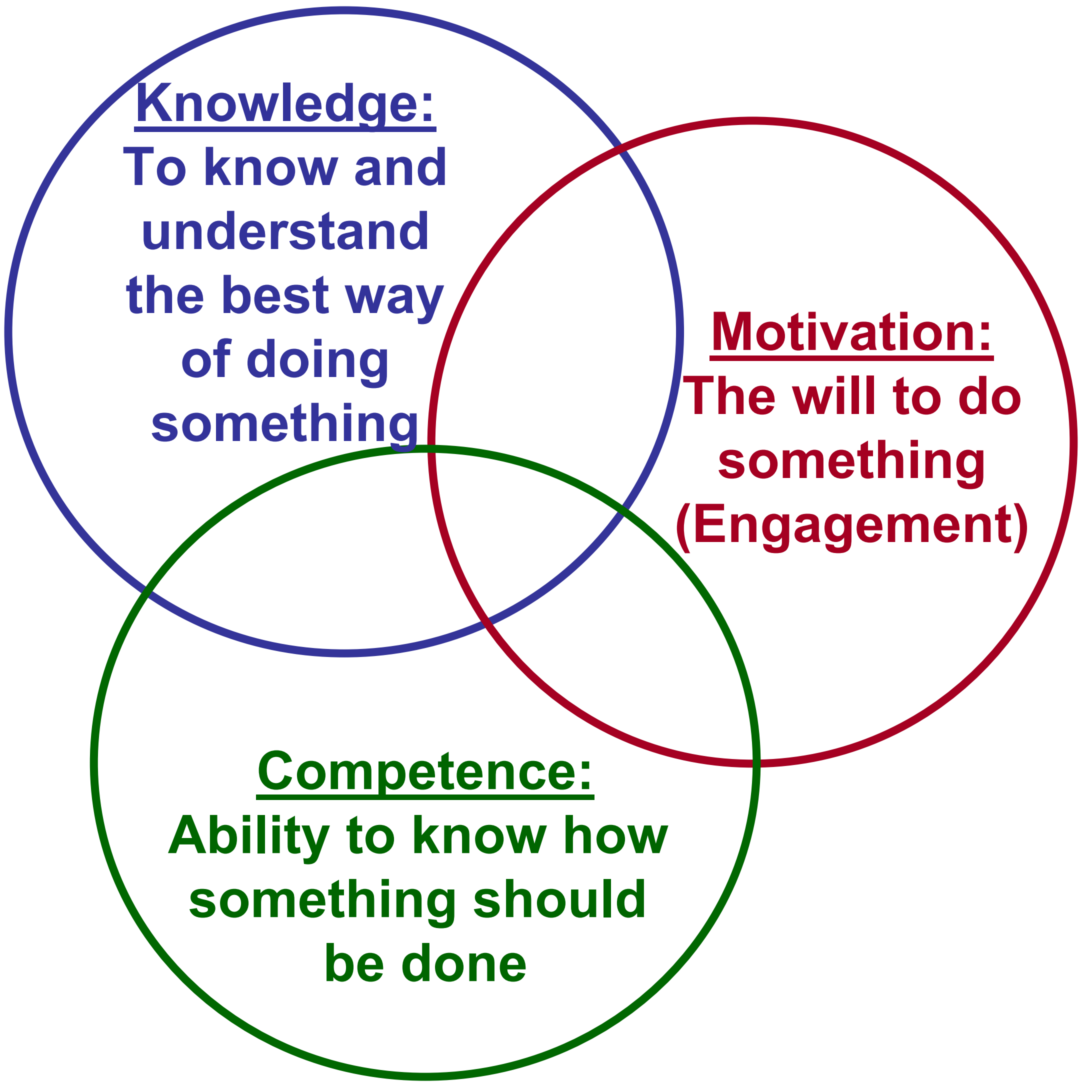
Necessary measures in order to succeed with implementation of research results



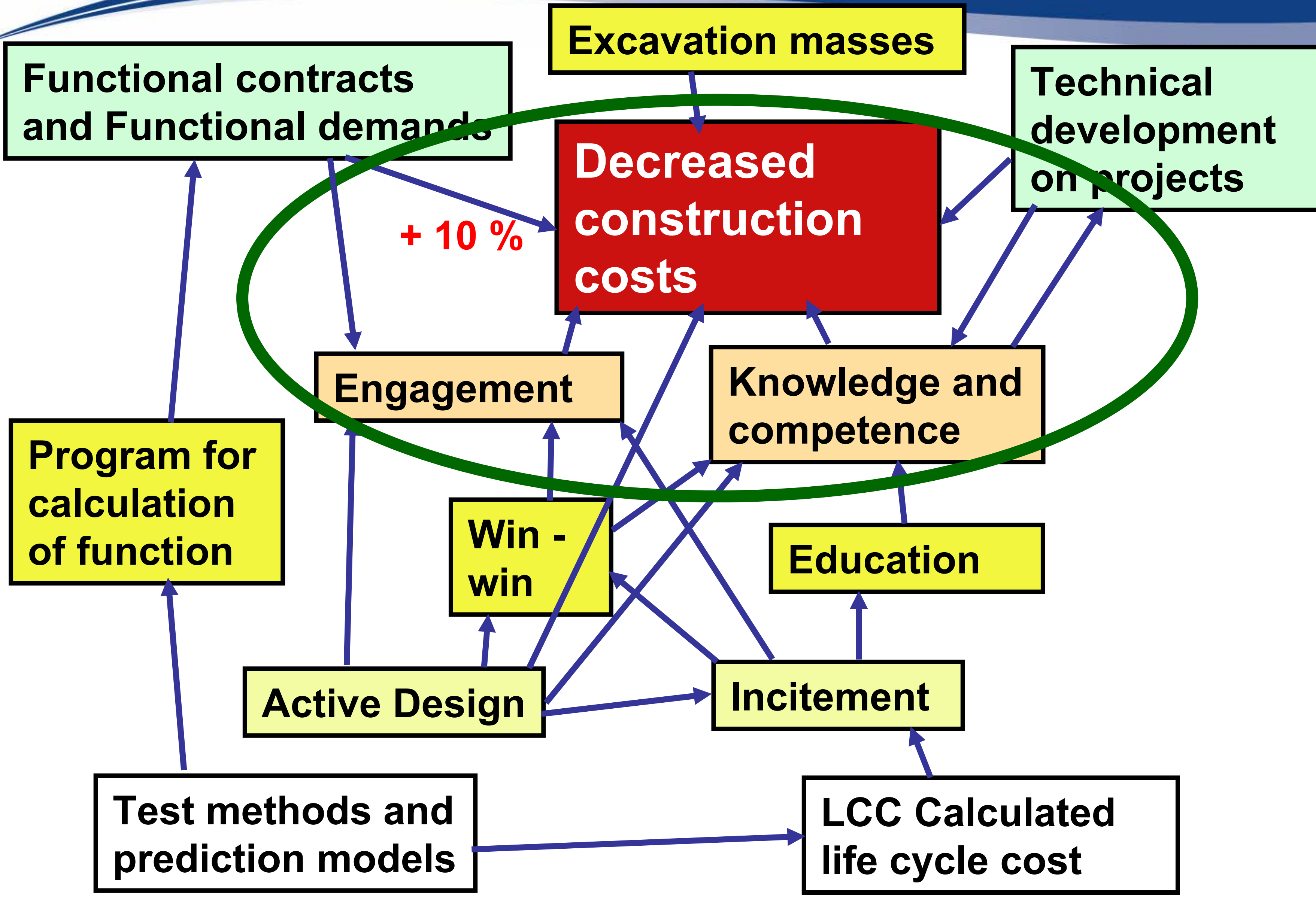
You must have helicopter view

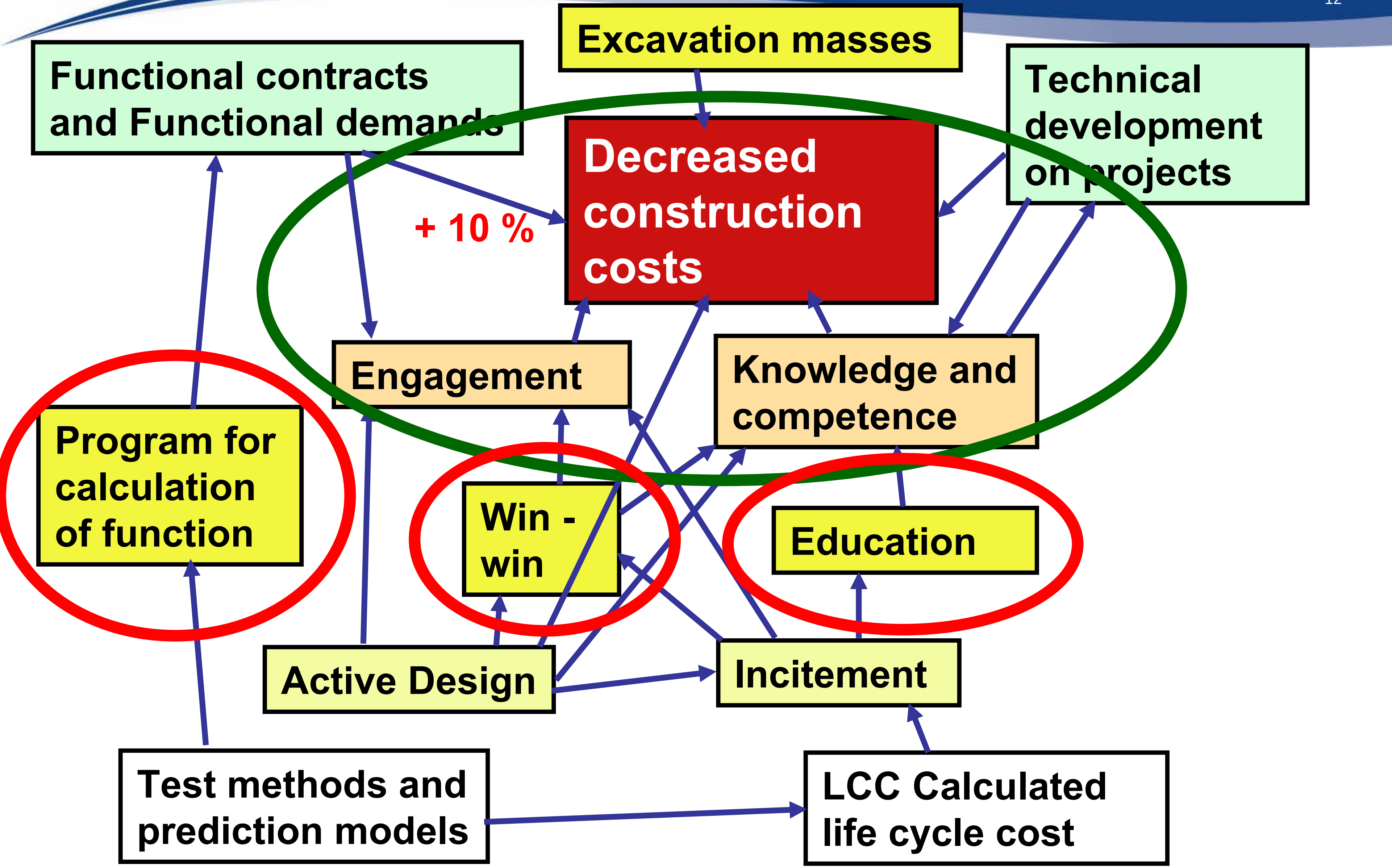

Excavation masses
Functional contracts and Functional demands
Decreased construction costs
Technical development on projects
Engagement
Knowledge and competence
Program for calculation of function
Win - win
Education
Active Design
Incitement
Test methods and prediction models
LCC Calculated life cycle cost

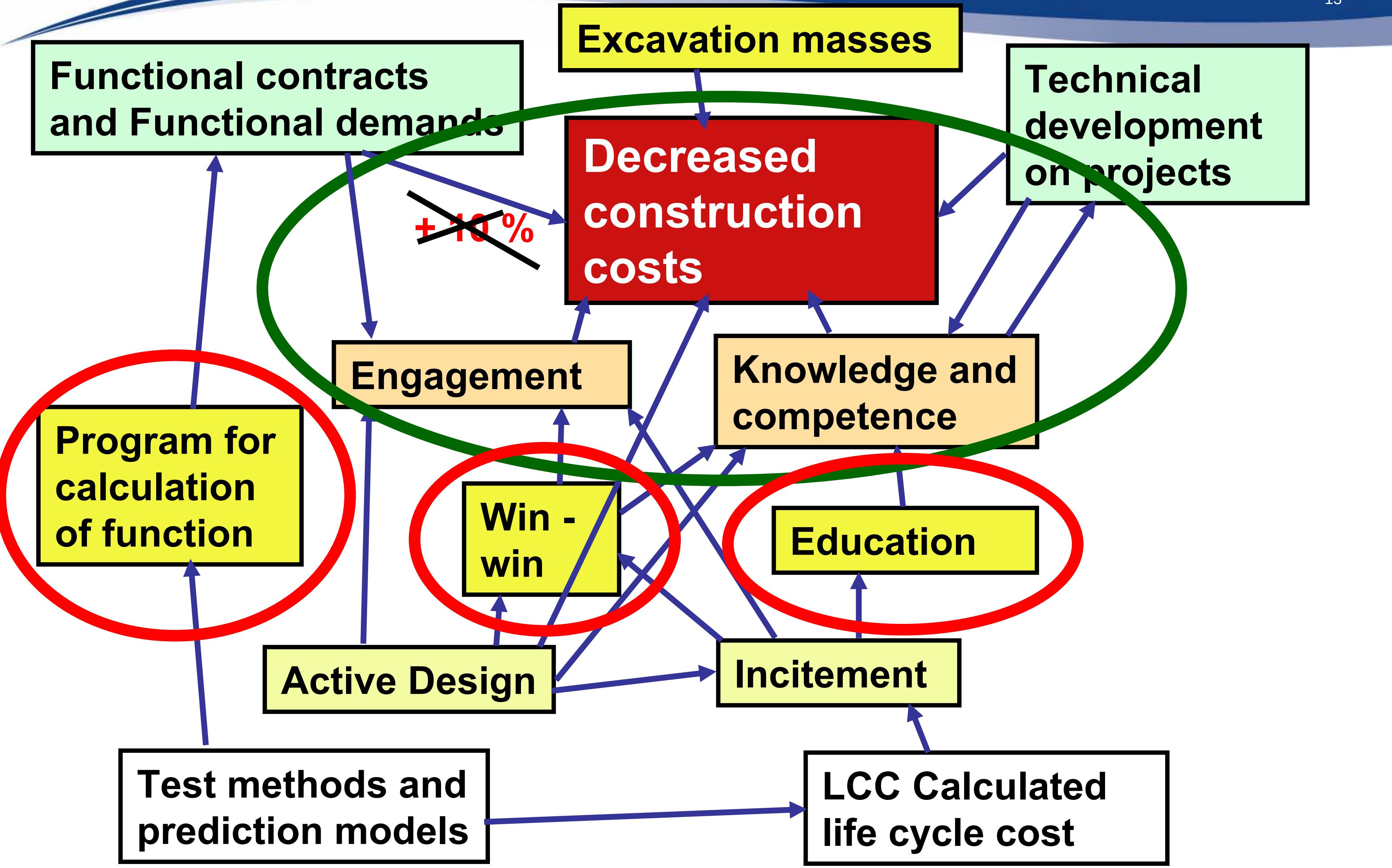

Excavation masses
Functional contracts and Functional demands
Decreased construction costs
Technical development on projects
Engagement
Knowledge and competence
Program for calculation of function
Win - win
Education
Active Design
Incitement
Test methods and prediction models
LCC Calculated life cycle cost

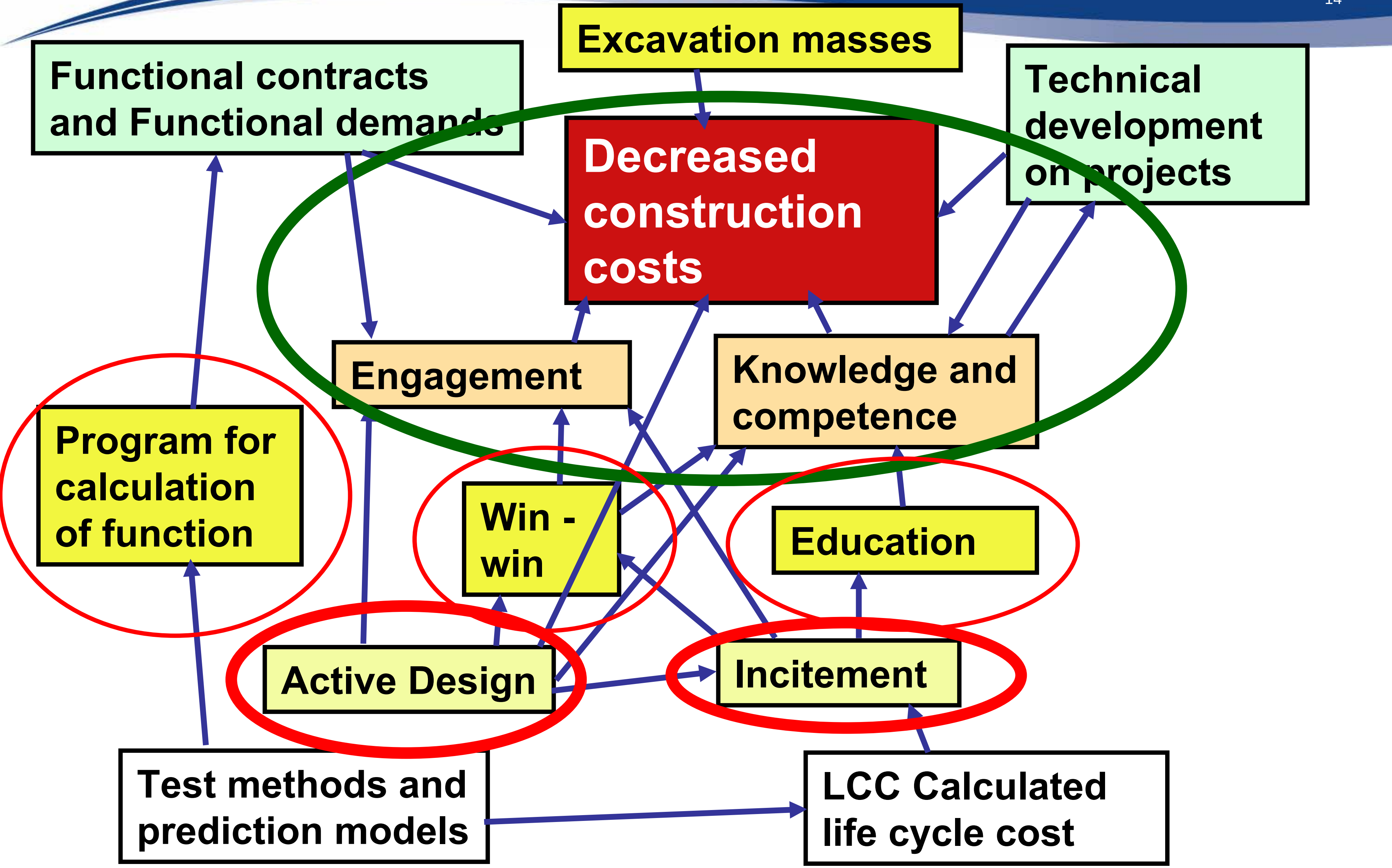


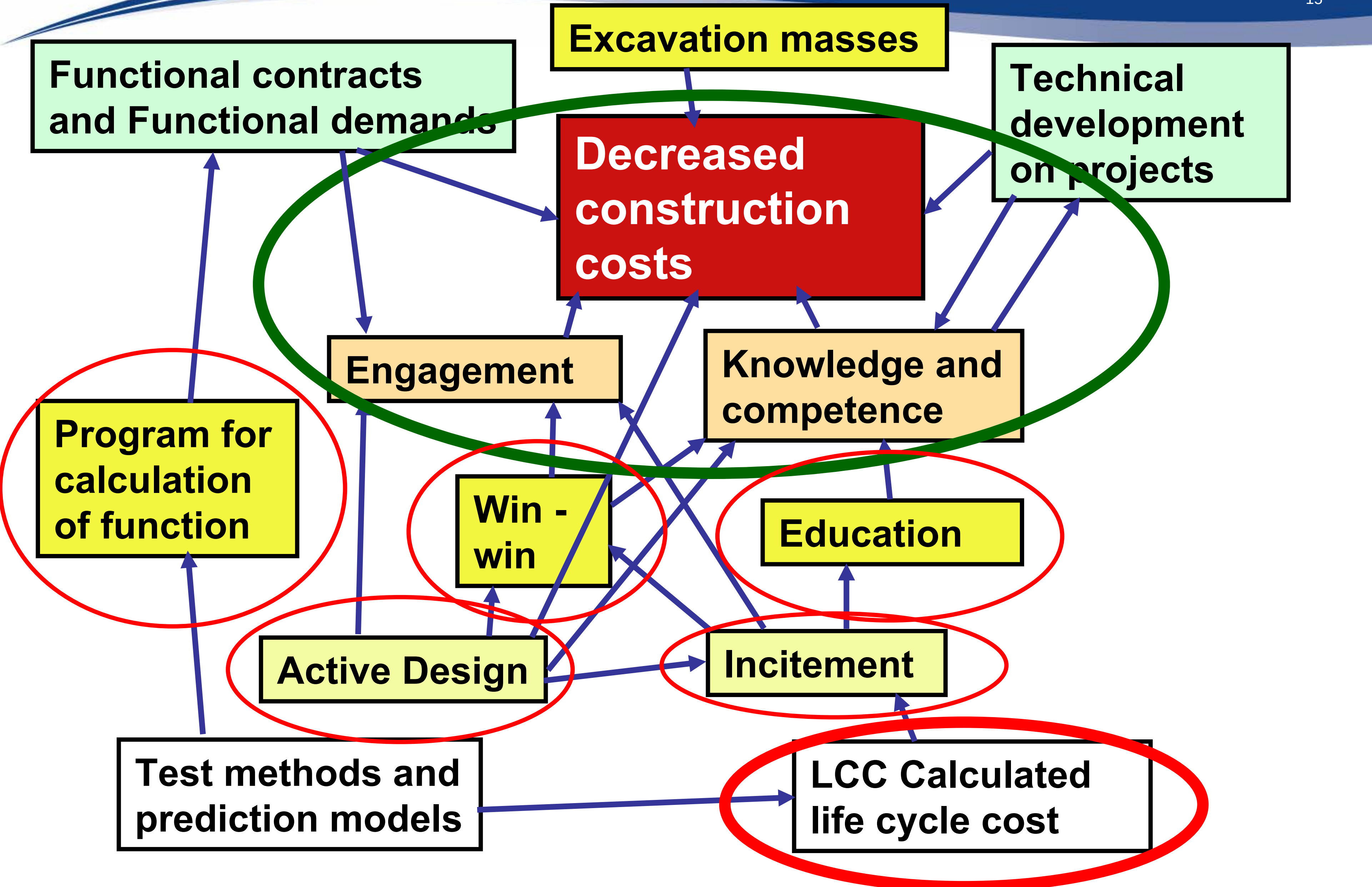
All these three circumstances must be a reality, if it should be a habit to work with the Win – win concept. Preferably for all persons who are working in a project

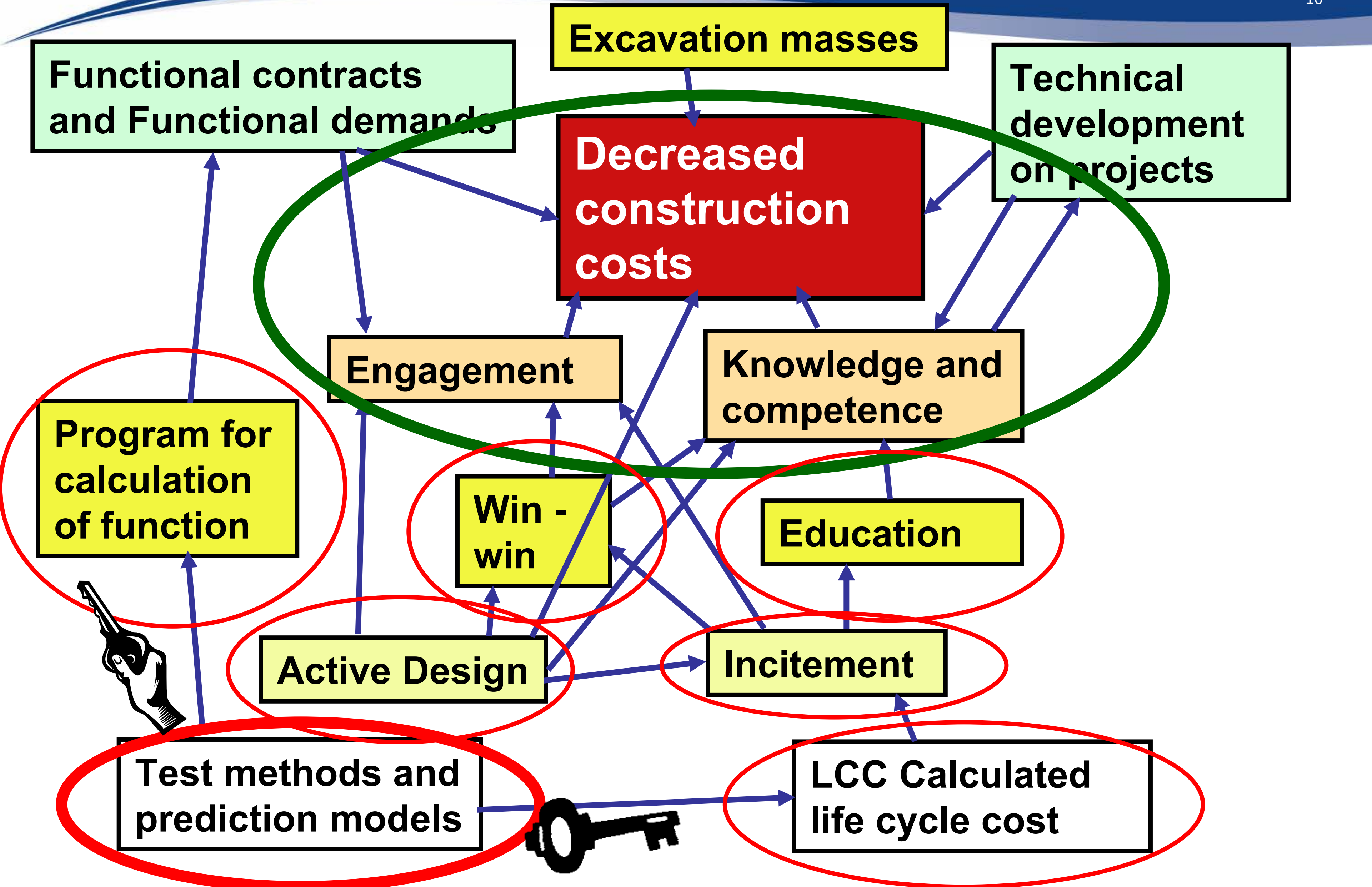

Vägverket
Excavation masses
Functional contracts and Functional demands
Technical development on projects
Decreased construction costs
+ 10 %
Engagement
Knowledge and competence
Program for calculation of function
Win - win
Education
Active Design
Incitement
Test methods and prediction models
LCC Calculated life cycle cost


Excavation masses
Functional contracts and Functional demands
Technical development on projects
Decreased construction costs
+ 10 %
Engagement
Knowledge and competence
Program for calculation of function
Win - win
Education
Active Design
Incitement
Test methods and prediction models
LCC Calculated life cycle cost


Excavation masses
Functional contracts and Functional demands
Decreased construction costs
Technical development on projects
+ 10 %
Engagement
Knowledge and competence
Program for calculation of function
Win - win
Education
Active Design
Incitement
Test methods and prediction models
LCC Calculated life cycle cost

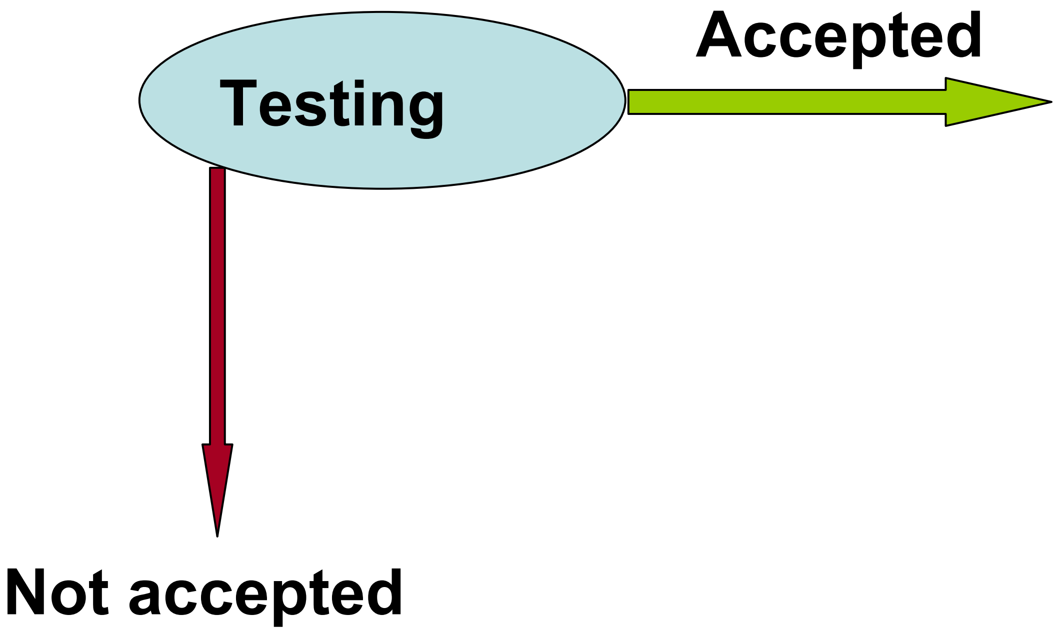

Excavation masses
Functional contracts and Functional demands
Decreased construction costs
Technical development on projects
Engagement
Knowledge and competence
Program for calculation of function
Win - win
Education
Active Design
Incitement
Test methods and prediction models
LCC Calculated life cycle cost


Excavation masses
Functional contracts and Functional demands
Technical development on projects
Decreased construction costs
Engagement
Knowledge and competence
Program for calculation of function
Win - win
Education
Active Design
Incitement
Test methods and prediction models
LCC Calculated life cycle cost

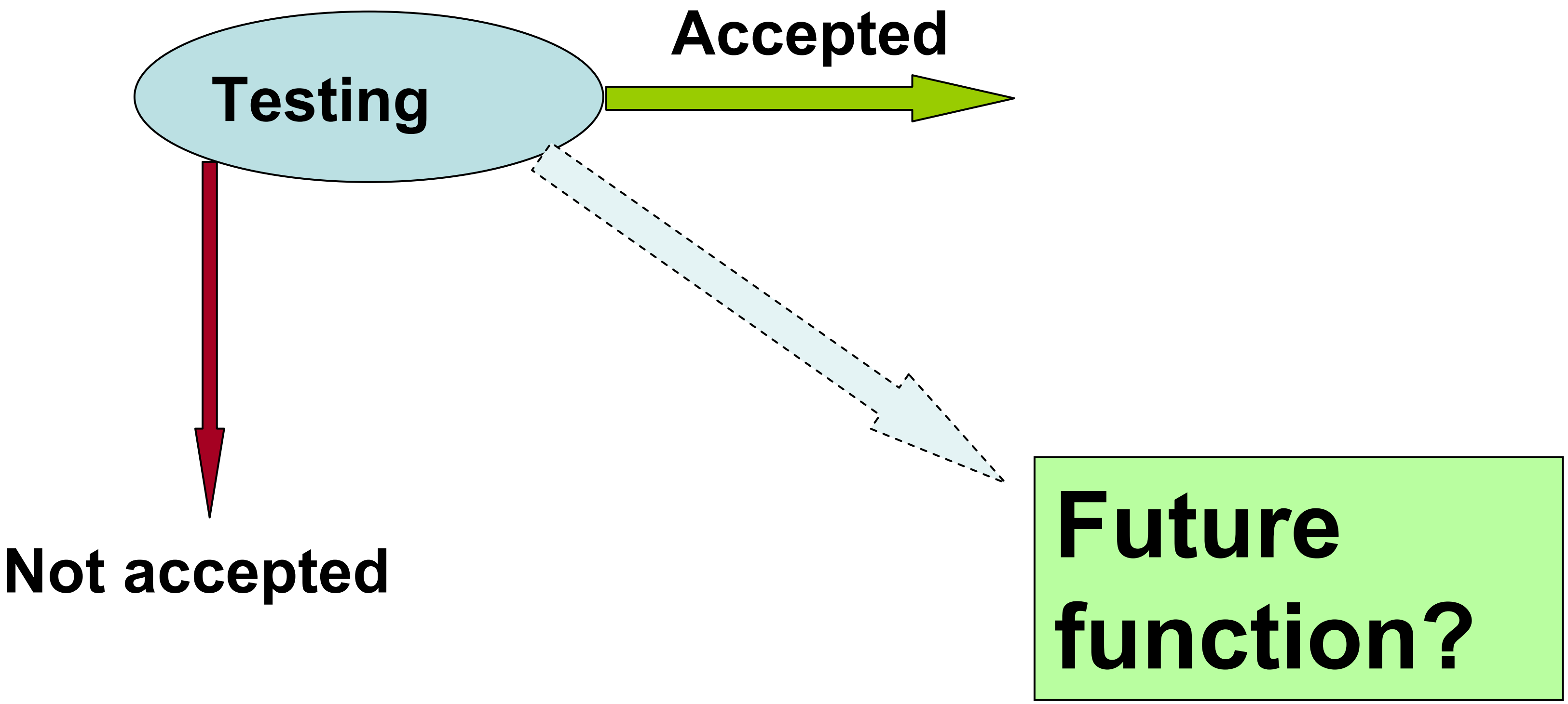

Excavation masses
Functional contracts and Functional demands
Decreased construction costs
Technical development on projects
Engagement
Knowledge and competence
Program for calculation of function
Win - win
Education
Active Design
Incitement
Test methods and prediction models
LCC Calculated life cycle cost

Implementation of new technique

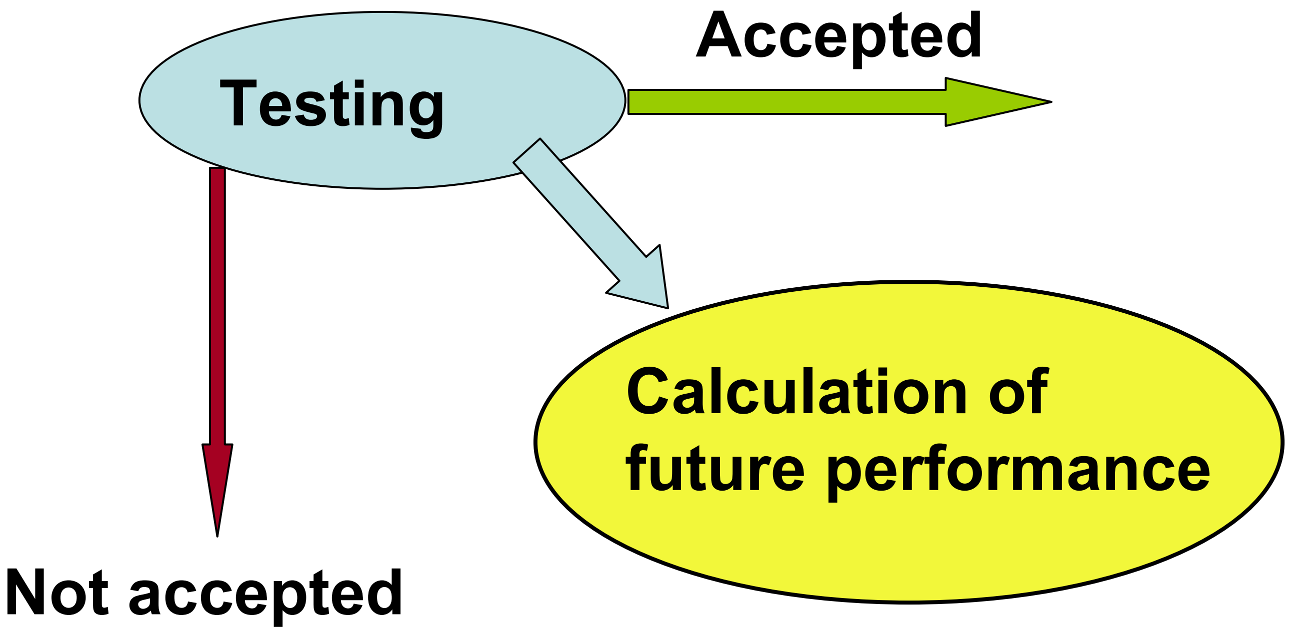
Normal rules today



Normal rules today

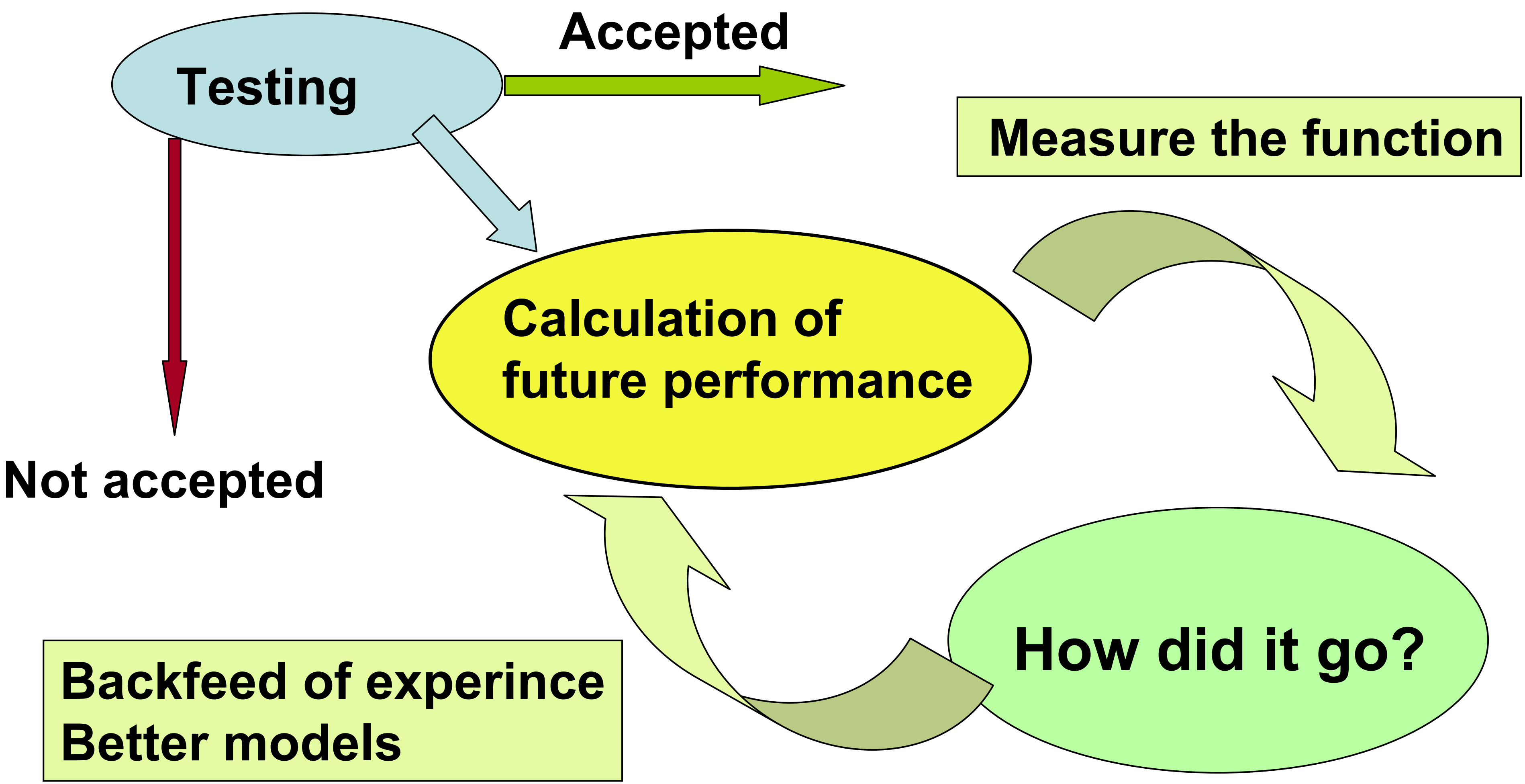


It is possible to work like this today!

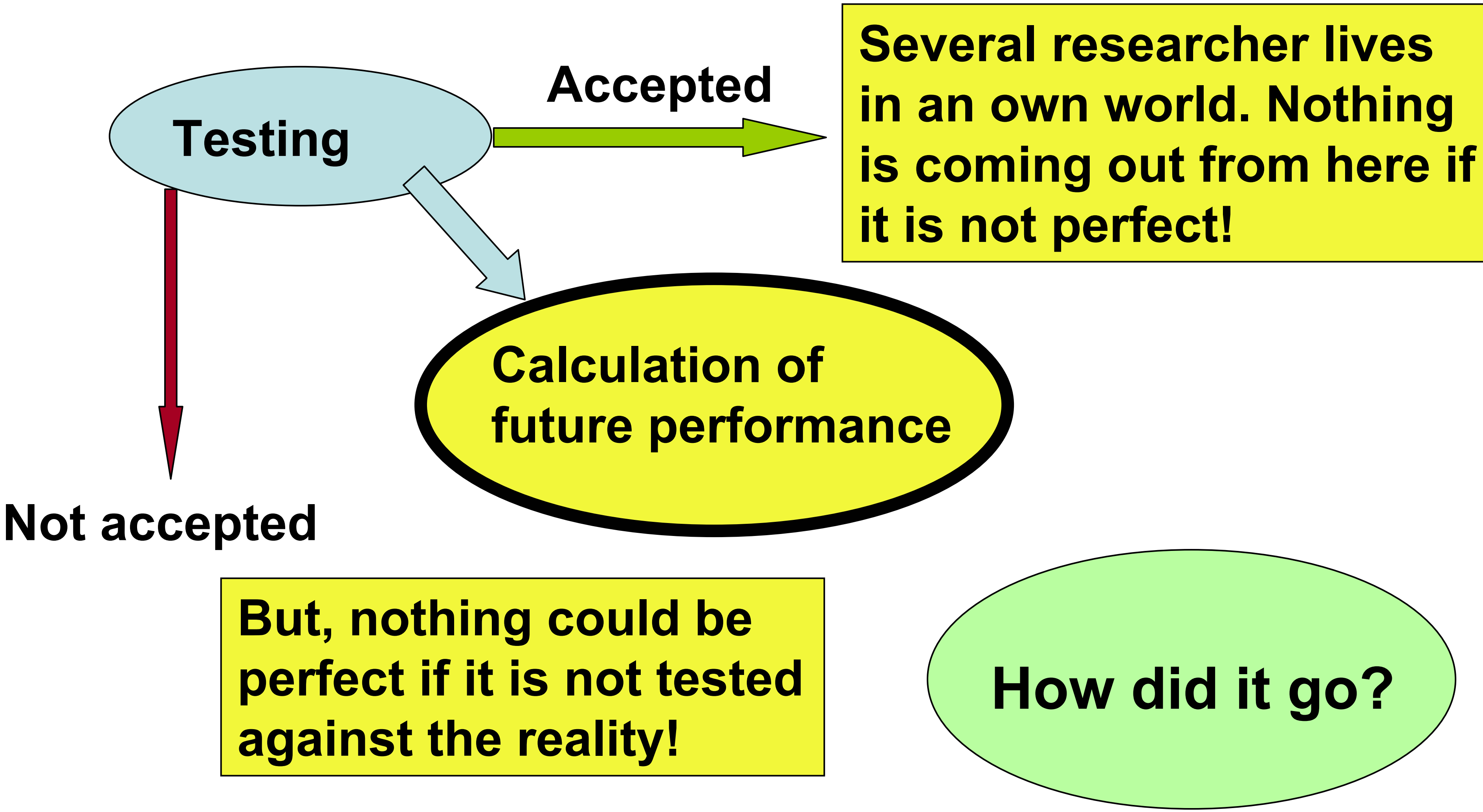


Test results, material characteristics or quality on execution, are used together with values on traffic, climat and moisture in order to calculate future function

An ideal way of working!



Why doesn’t this work today?



What is the problem today?

Testing

Accepted

Several researcher lives in an own world. Nothing is coming out from here if it is not perfect!

Calculation of future performance

There is a need of more competens on working sites

Not accepted

But, nothing could be perfect if it is not tested against the reality!

How did it go?

Active Design

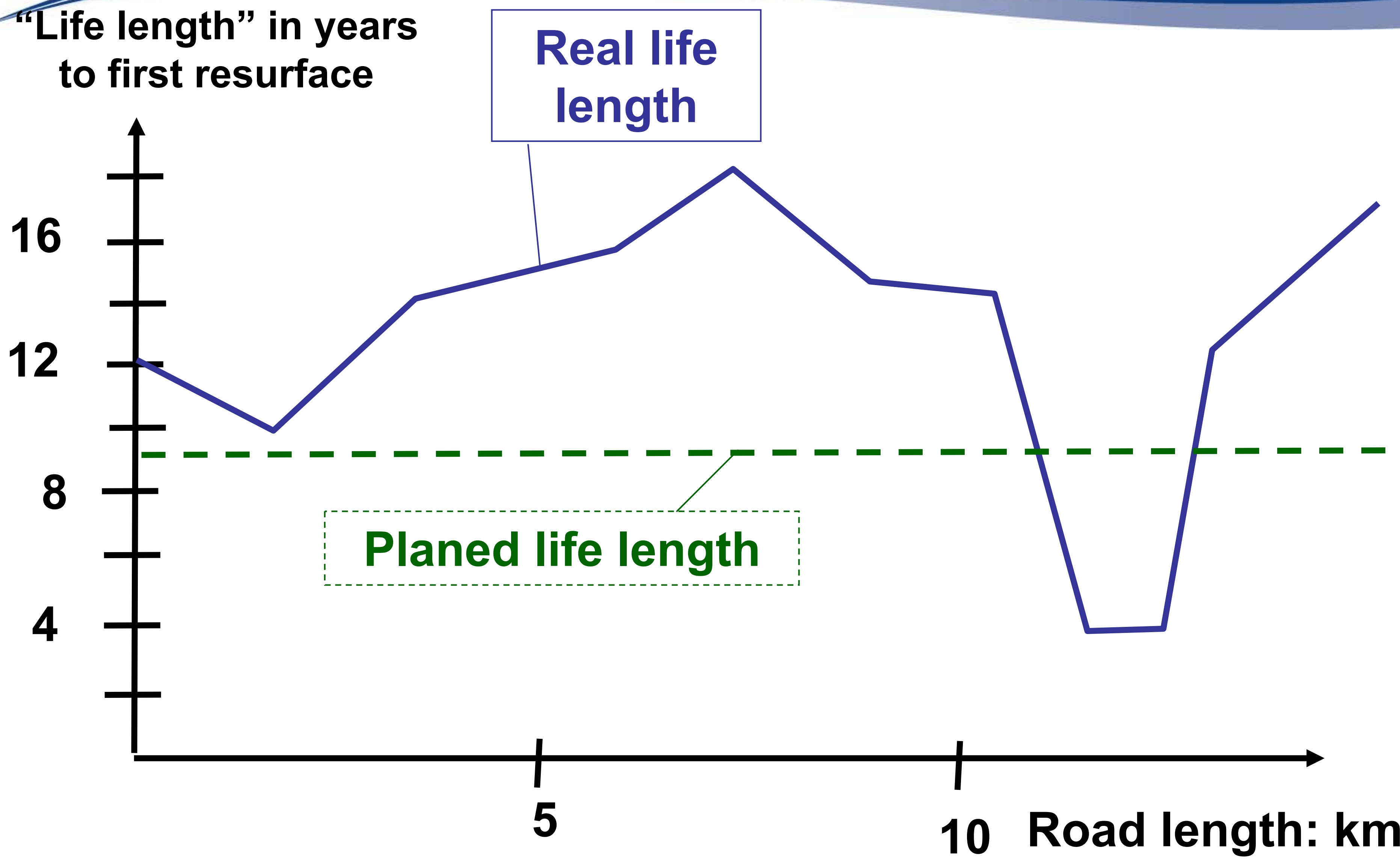
ACTIVE DESIGN

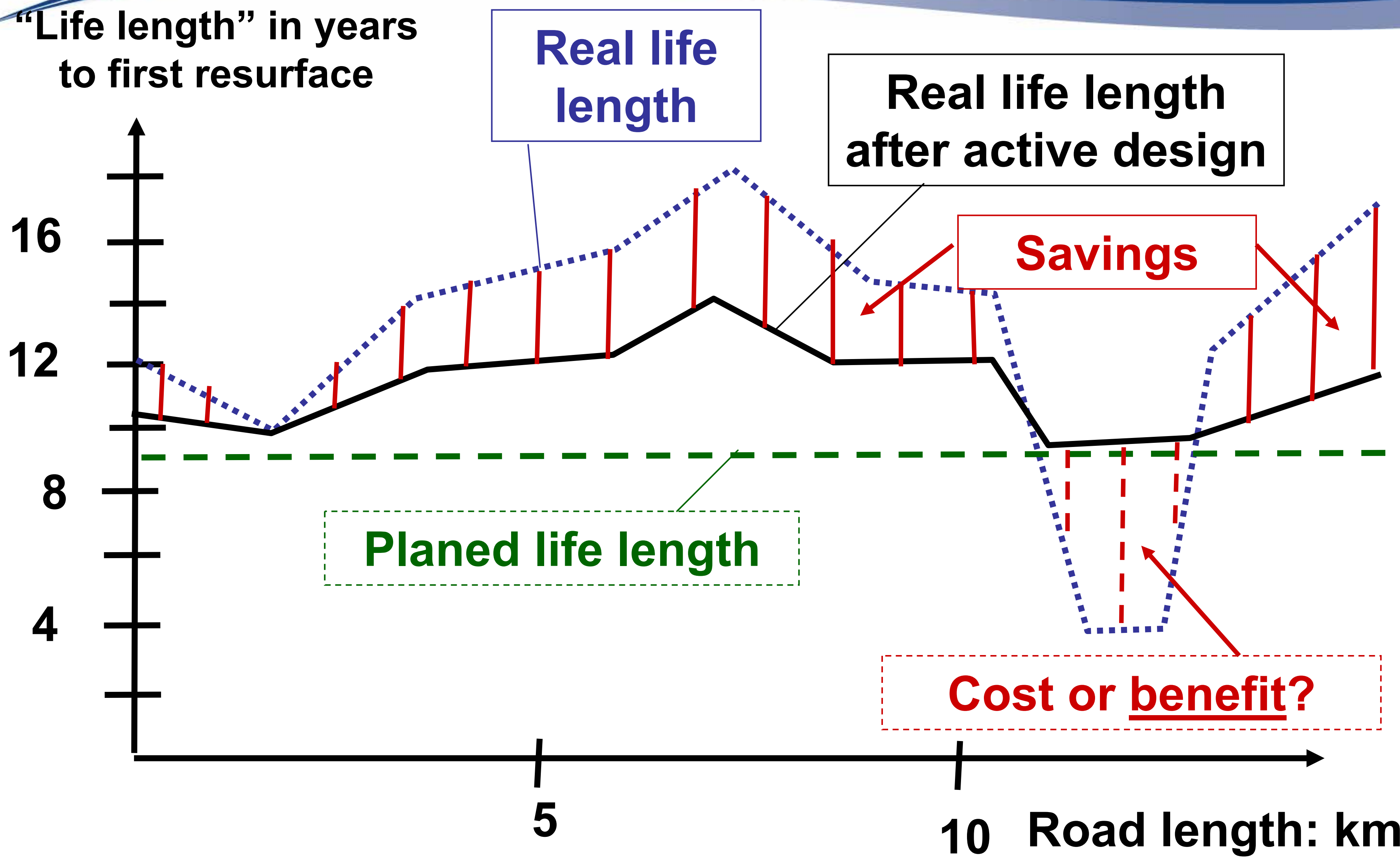
Soil and rock, used in road construction has an uneven quality: Design after real quality!

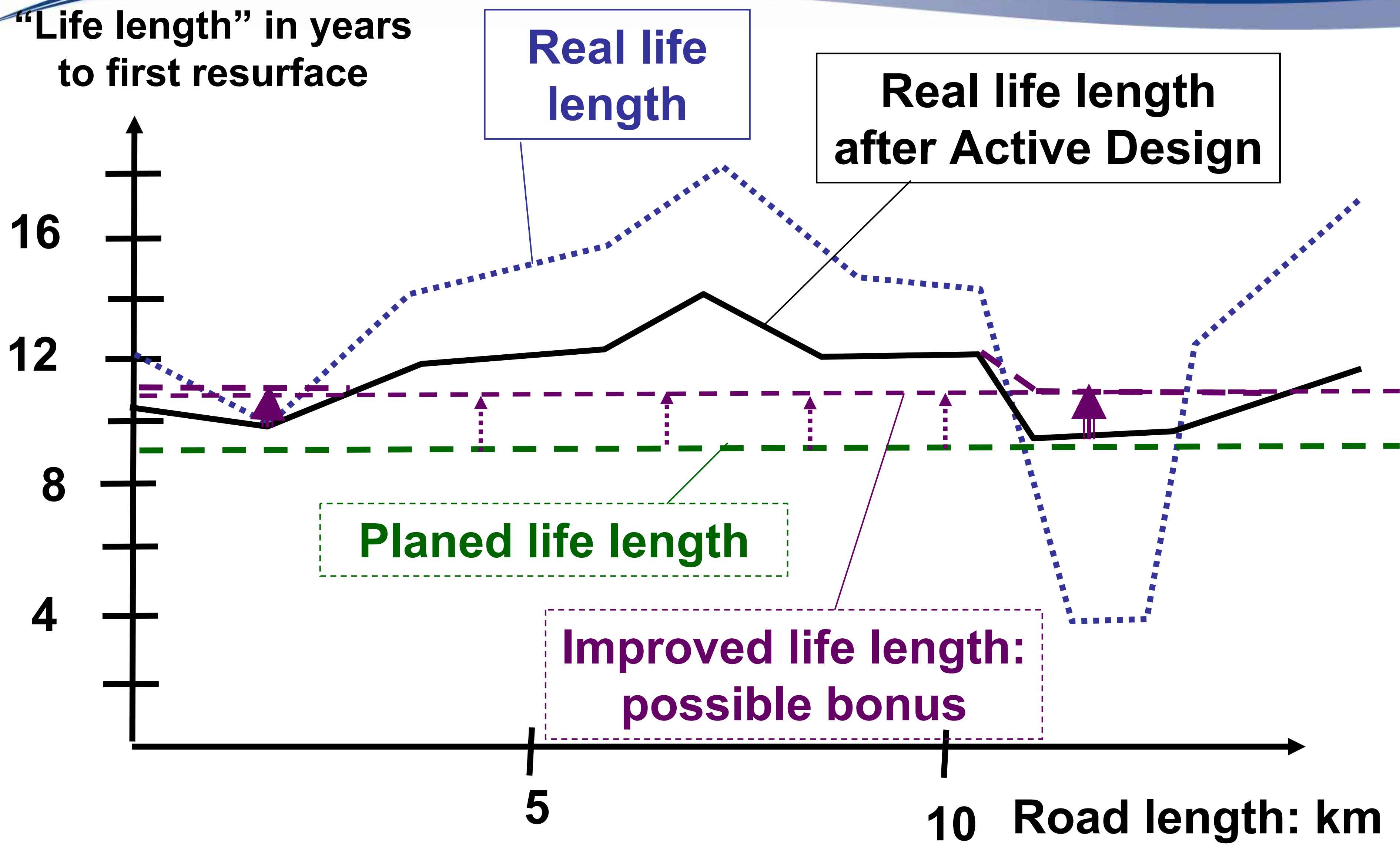
Use the best material close to the subgrade surface to get better bearing capacity

Calculate future function from test results on site in order to choose the optimal alternative

Incentive for better quality gives resources for improvement of the competence and technical development, and it also gives a strong motivation to produce with an improved quality

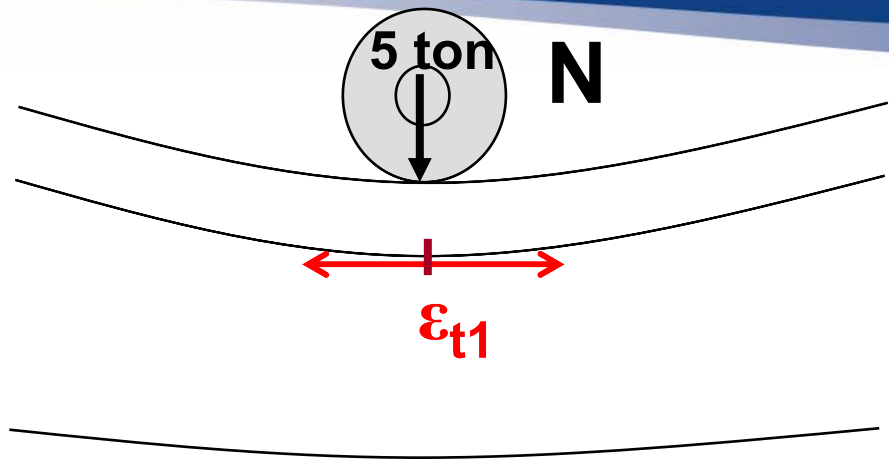

"Life length" in years
to first resurface
Real life
length
16
12
8
4
Planed life length
5
10
Road length: km


"Life length" in years
to first resurface
Real life length
Real life length after active design
Savings
16
12
8
4
Planed life length
Cost or benefit?
5
10
Road length: km


"Life length" in years
to first resurface
Real life
length
Real life length
after Active Design
16
12
8
4
Planed life length
Improved life length:
possible bonus
5
10
Road length: km

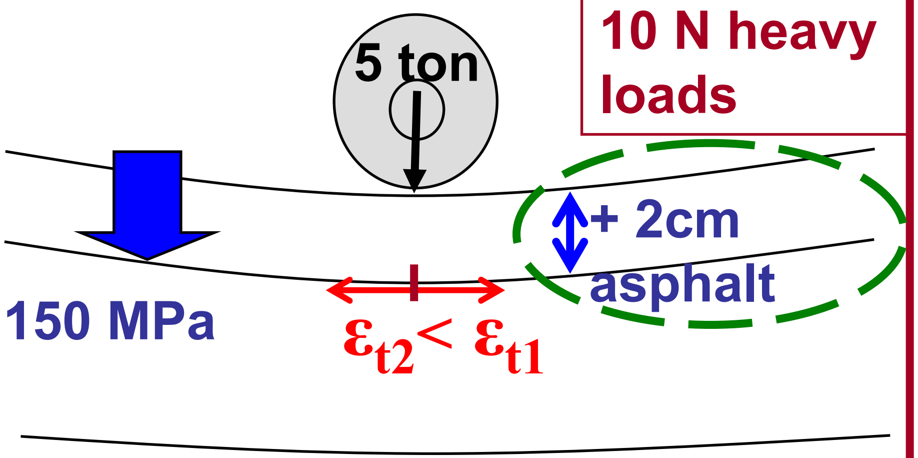
FATIGUE OF PAVEMENT

Improved life length; lower ε_{t1} to ε_{t2}



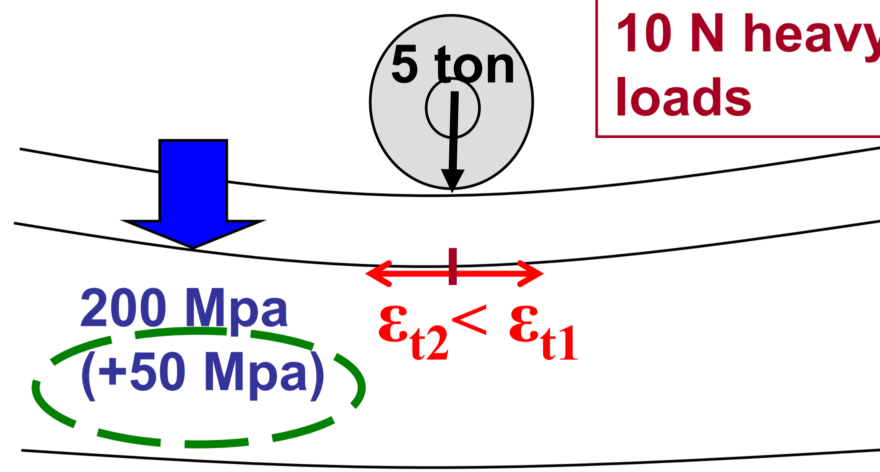
N heavy loads

ε = strain in bottom of asphalt



10 N heavy loads

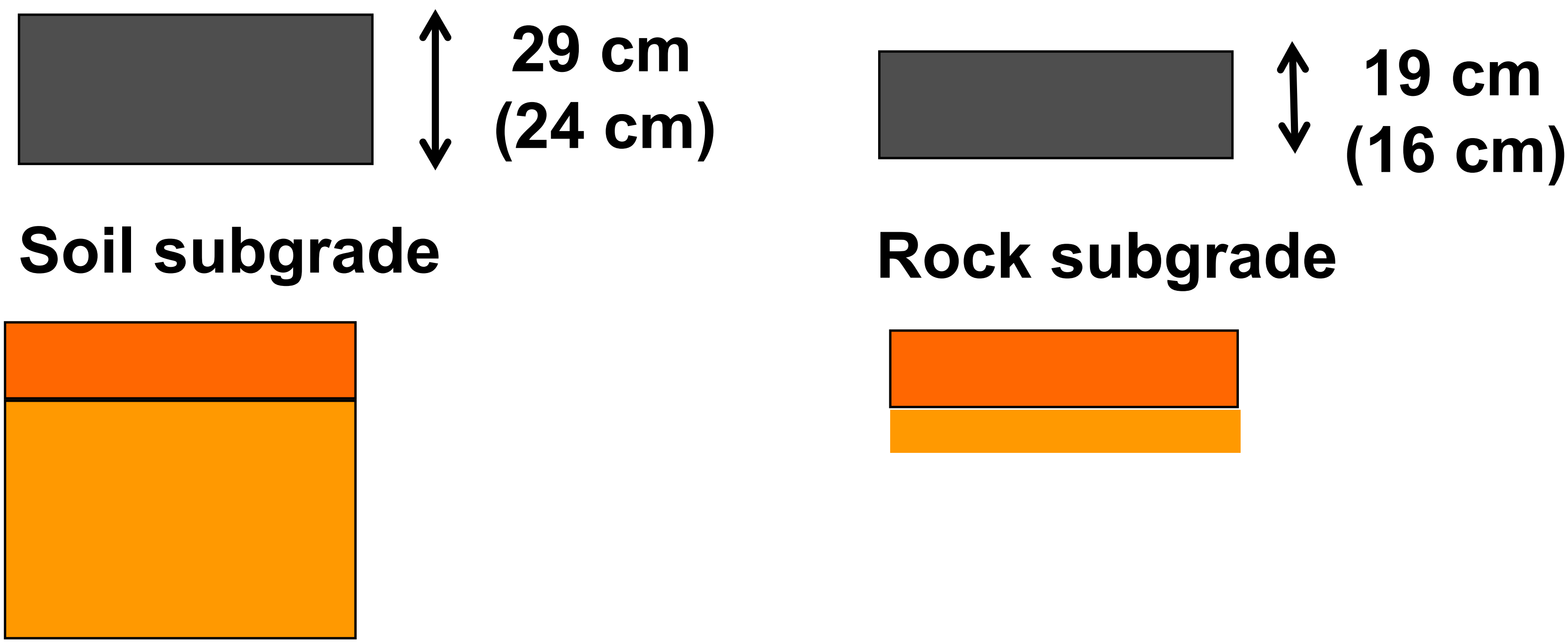
Alt 1: Thicker pavement, 2 cm, cost ca 2 Euro/m^2



10 N heavy loads

Alt 2: Extra compaction, cost ca 0,2 – 0,4 Euro/m2

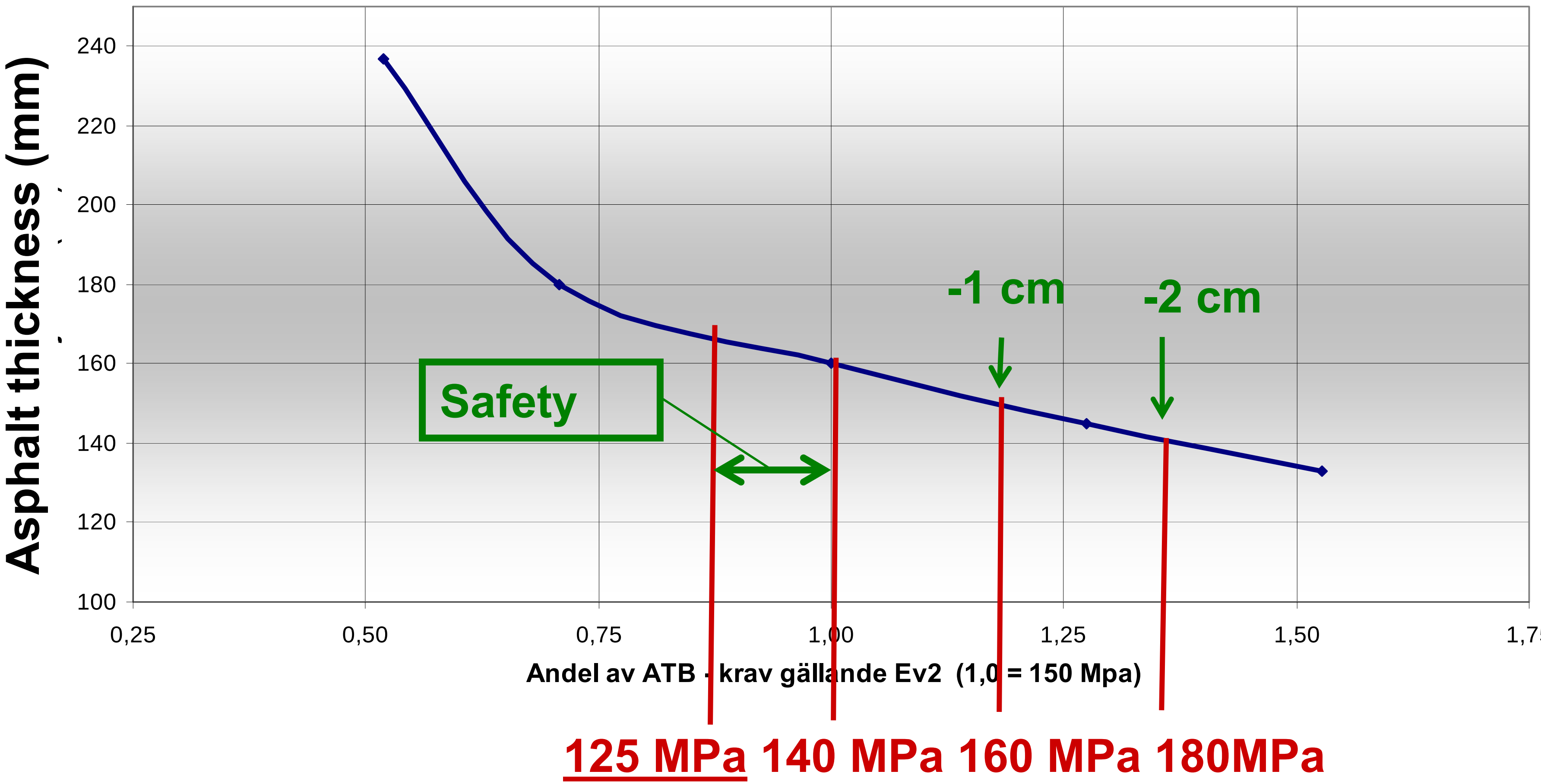
Swedish standard before 1974



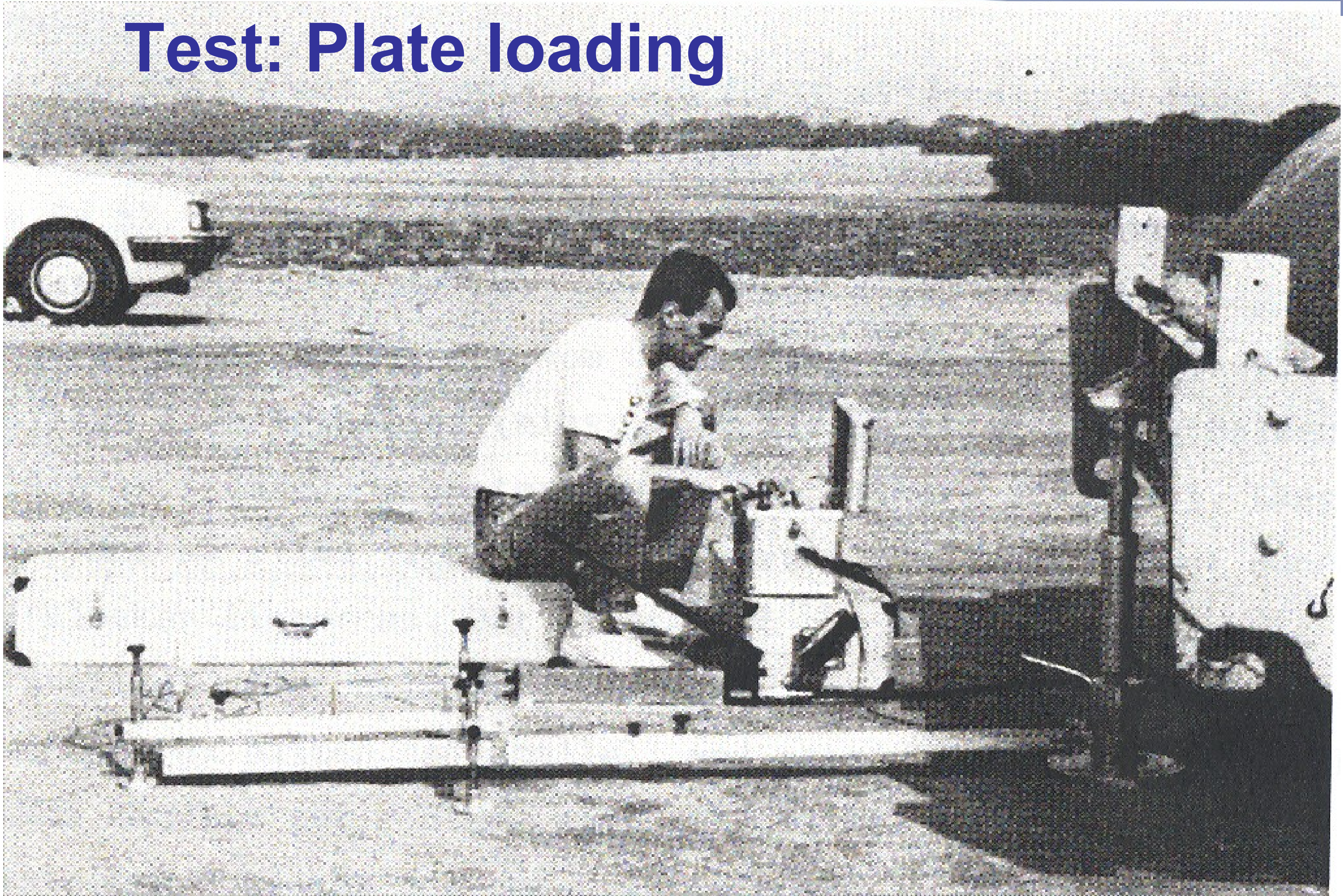
Thickness highest class
(second highest class)

QUALITY LEVELS

Change in pavement thickness with surface covering measurement on the compactor

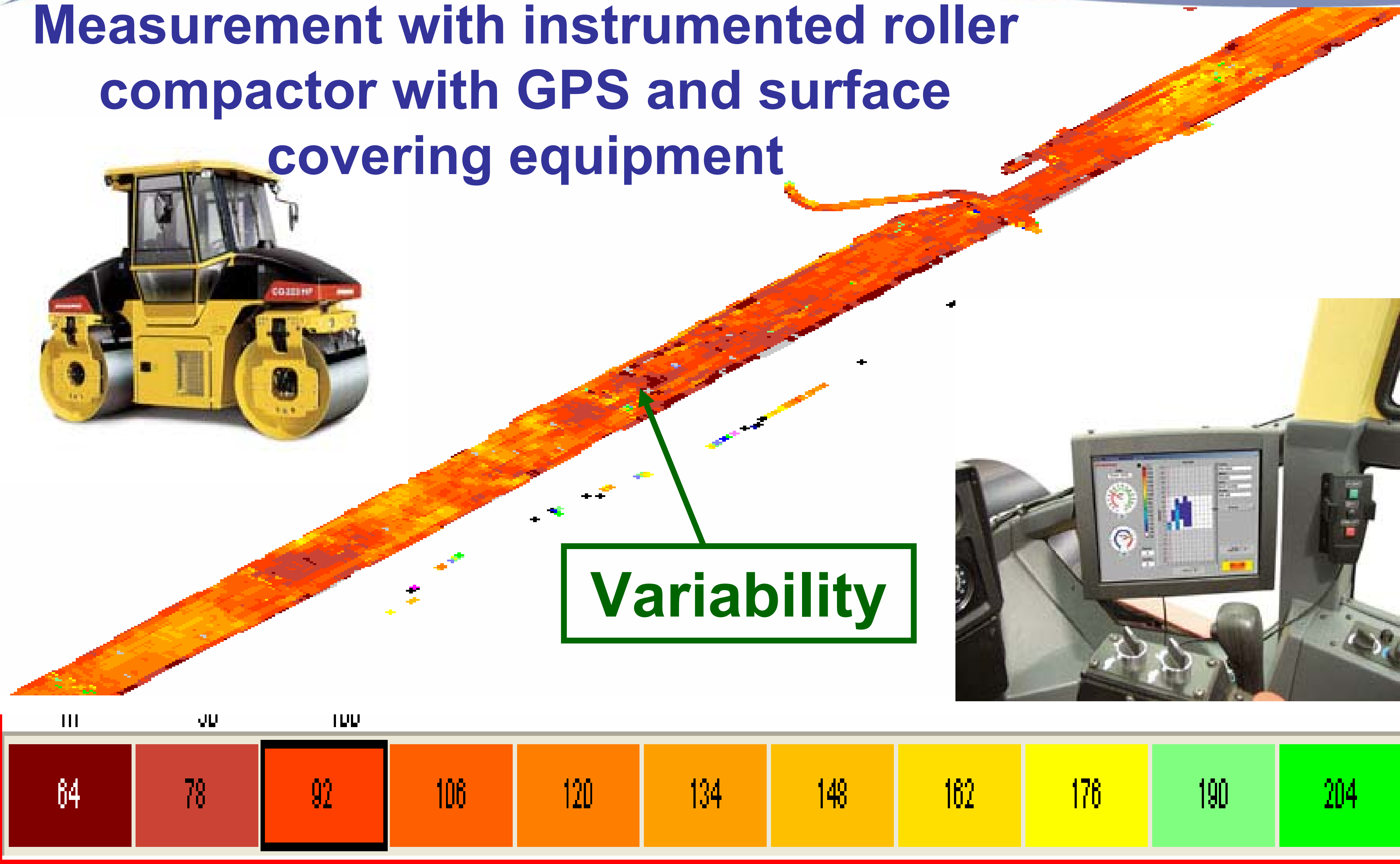


Test: Plate loading

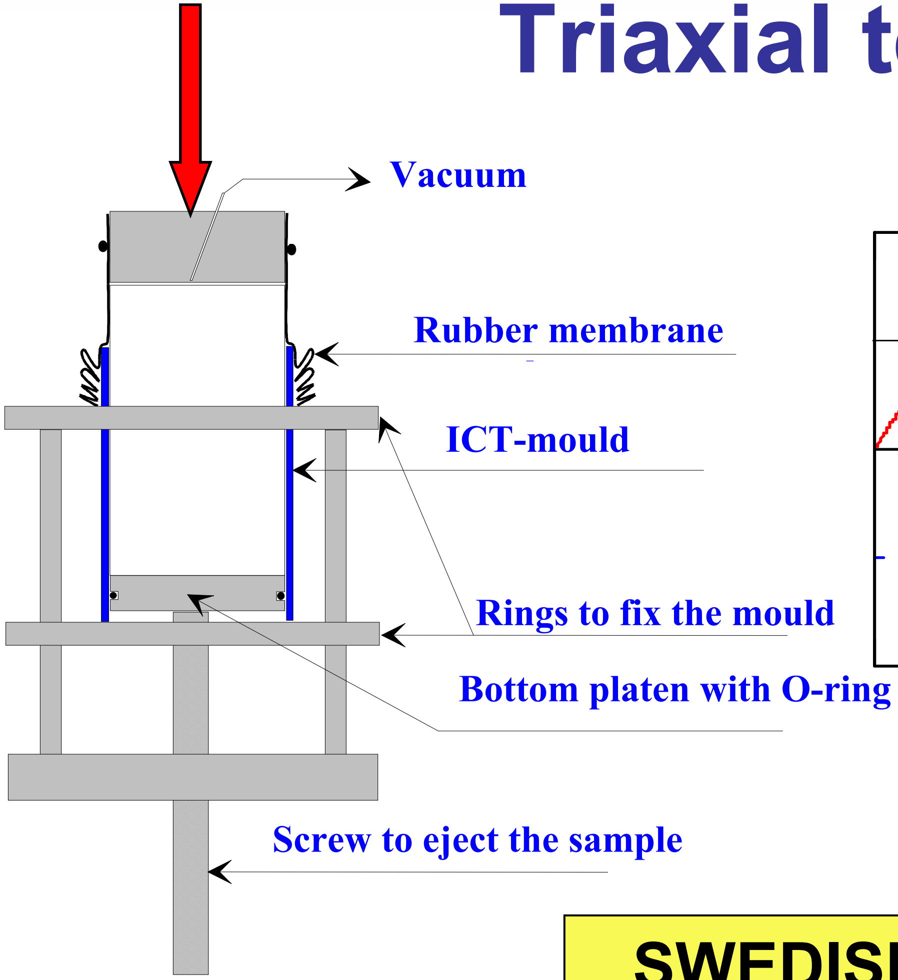


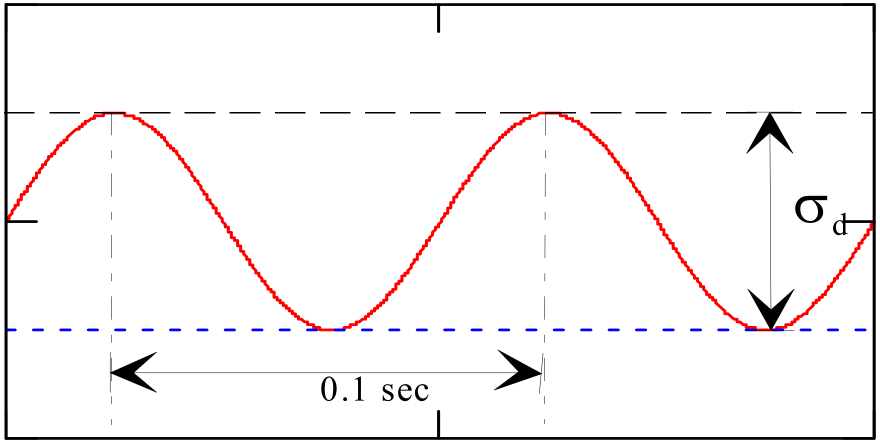
Equipment for measuring bearing capacity with plate loading

Measurement with instrumented roller compactor with GPS and surface covering equipment



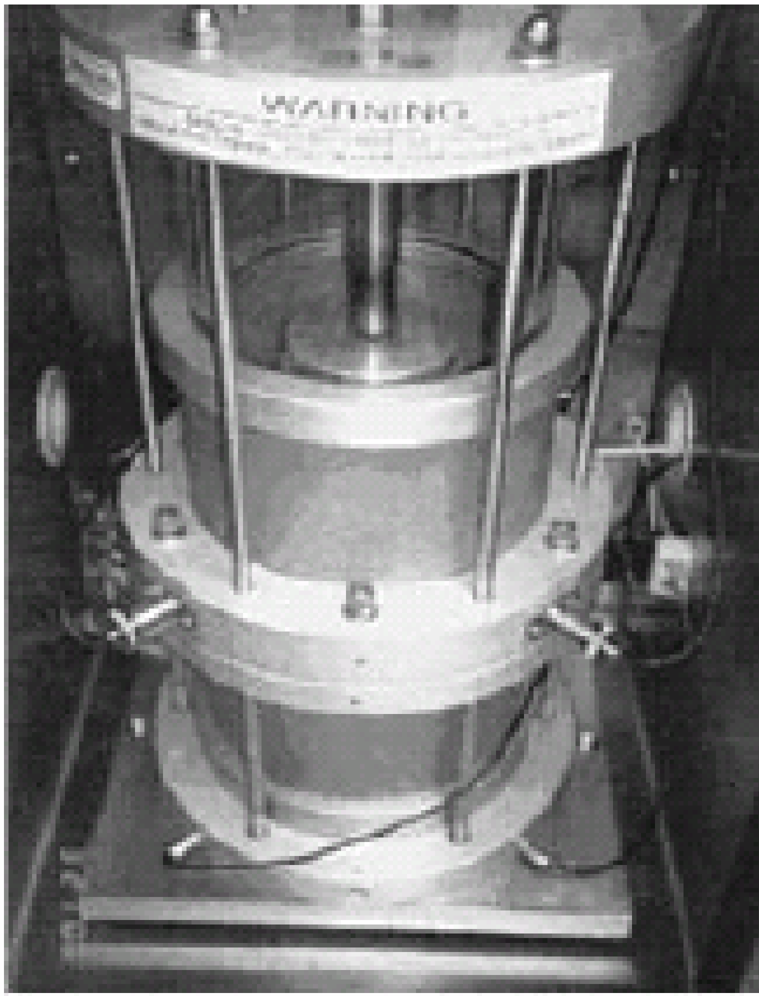
Triaxial test

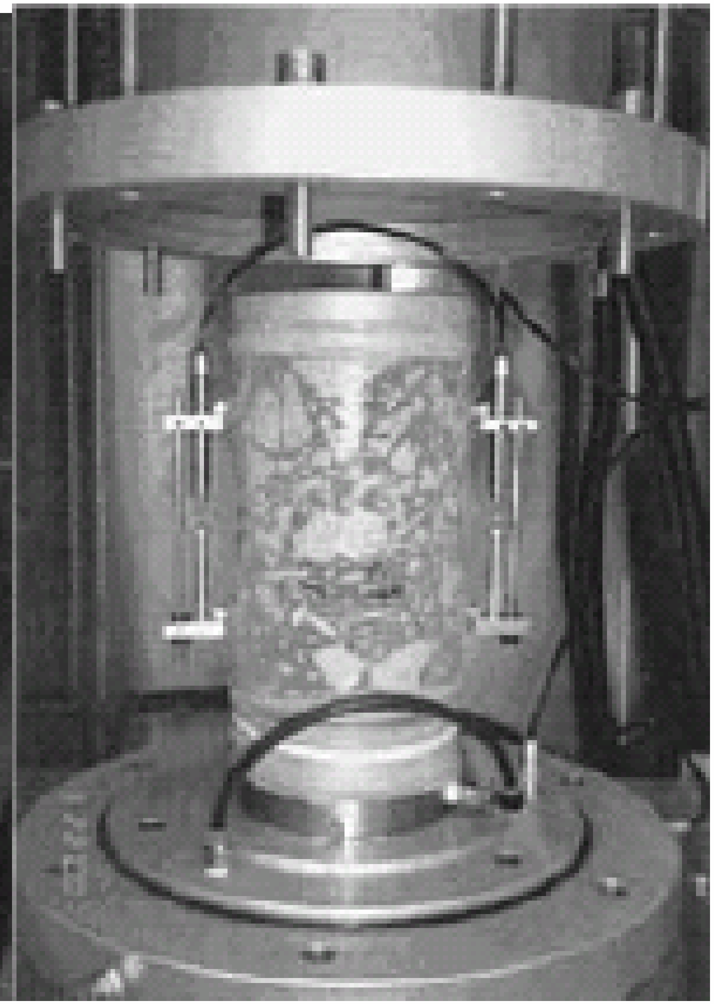




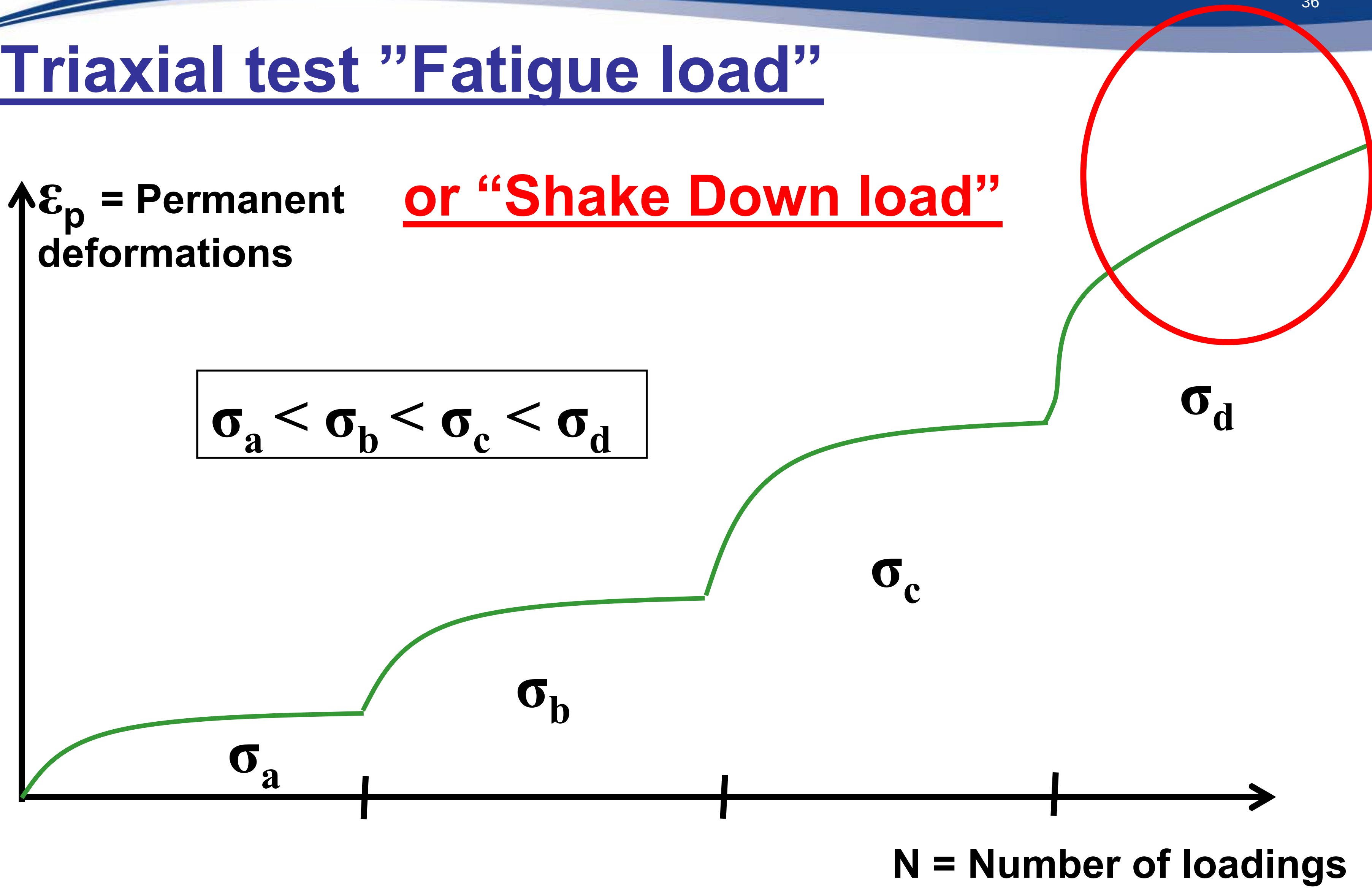
SWEDISH STANDARD
SS-EN 13286-7:2004
Appointed 2004-02-13

Equipment for Triaxial tests





Triaxial test "Fatigue load"



Triaxial tests on unbound layers

Gives following data / material characteristics:

- Unlinear static elasticity modulus (resilient modulus)
- Unlinear dynamic elasticity modulus (resilient modulus)
- Fatigue strength (”Shake Down” load)
- Input data for calculation of permanent deformations

In the project "Active Design" SRA co-operates with the contractors (SBUF) and consultants in order to use new knowledge for mechanistic design.

This knowledge is taken from research in Sweden and other countries above all from SAMARIS and Design Guide

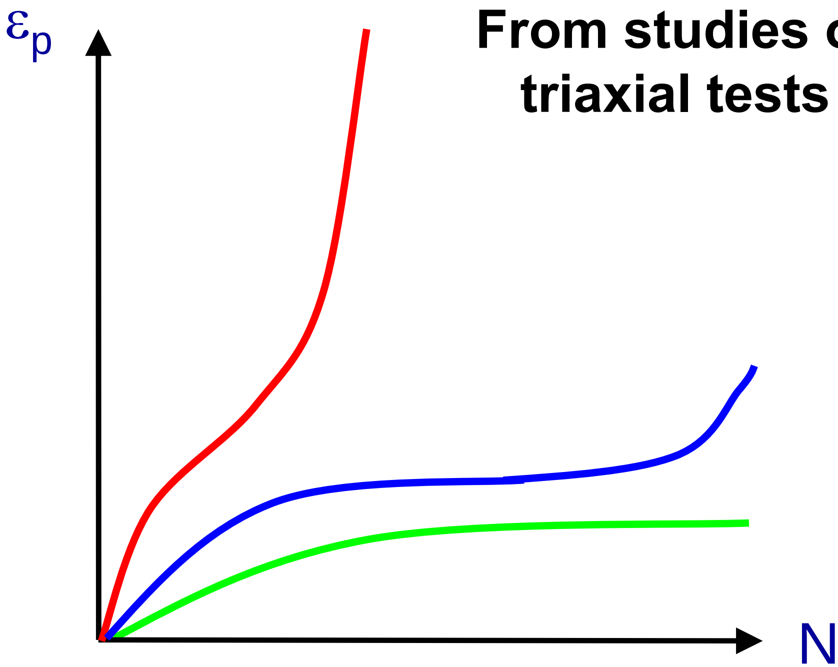
MATERIAL MODELS
Rutting in unbound materials

Shake Down load
(Dresden)

Decision of critical stress conditions in unbound layers

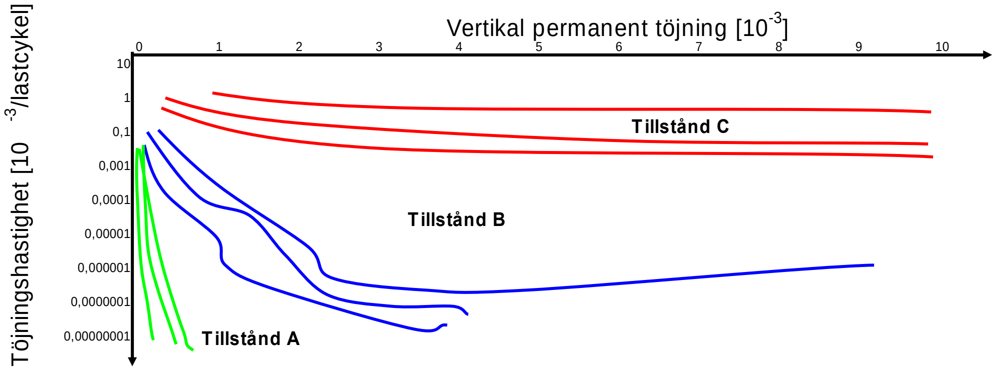
- Shakedown concept
  - Stable state (little rutting)
  - Unstable state (severe rutting)

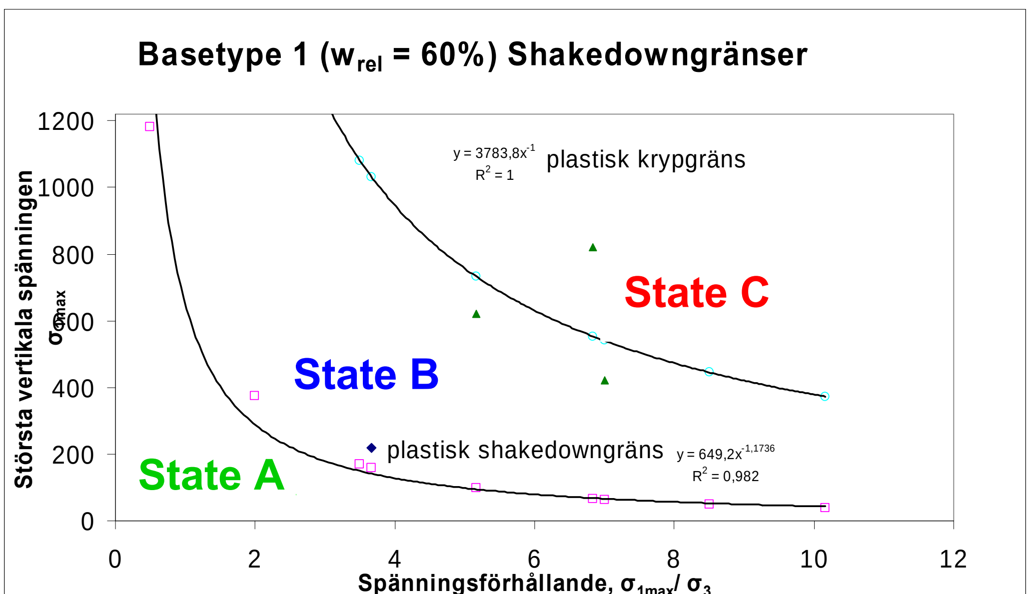
- State A (stable behaviour)
- State B (unstable behaviour)
- State C (collapse)



From studies of triaxial tests

The Shake Down concept

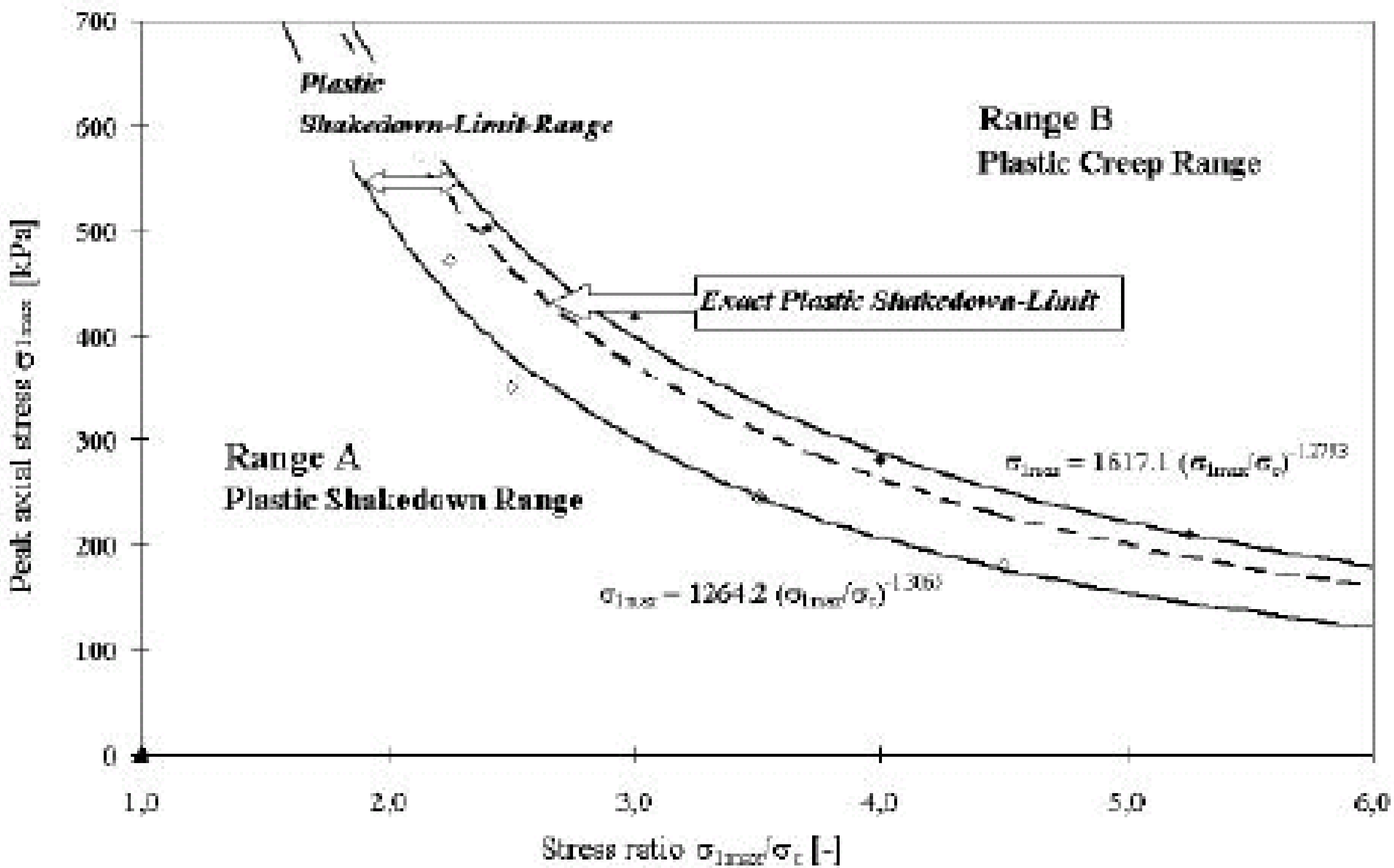




$$\sigma_{1,\max} = \alpha \cdot \left(\frac{\sigma_{1,\max}}{\sigma_c} \right)^{\beta}$$

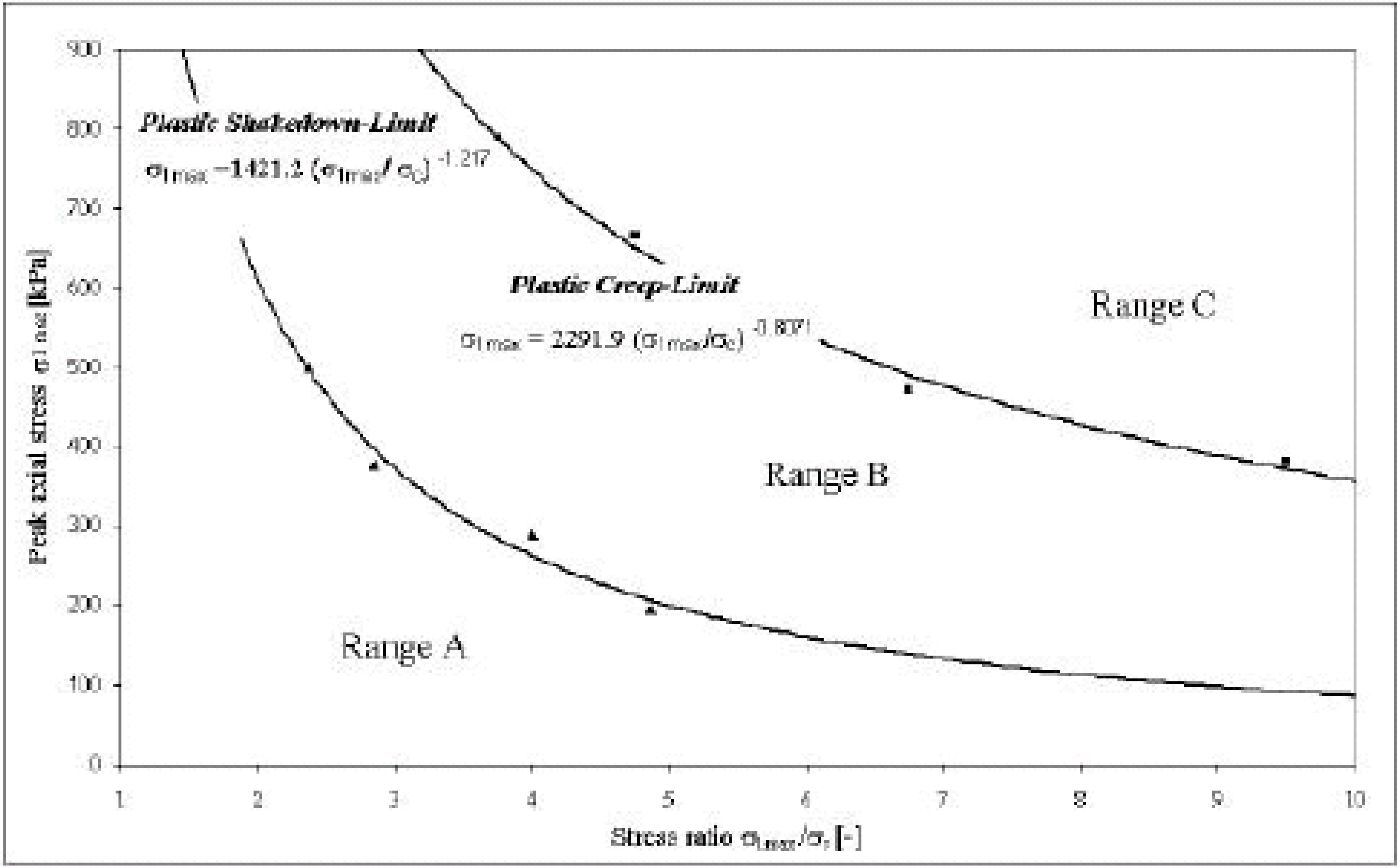
Shake down load

From Sabine Werkmeister doctor thesis

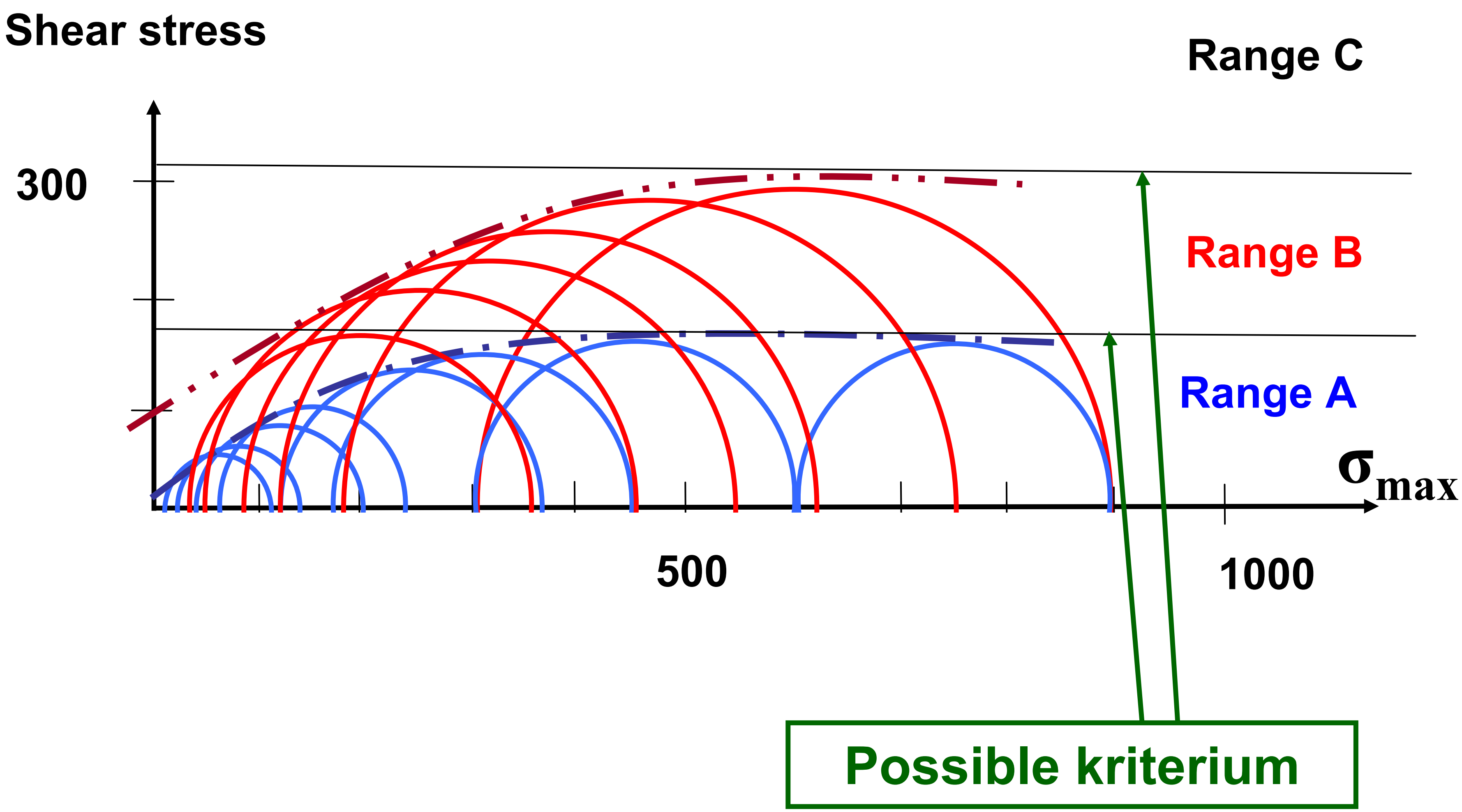


Shake down load

From Sabine Werkmeister doctor thesis



Shake down load



Permanent deformations, depending on shear stress (tests from SAMARIS)

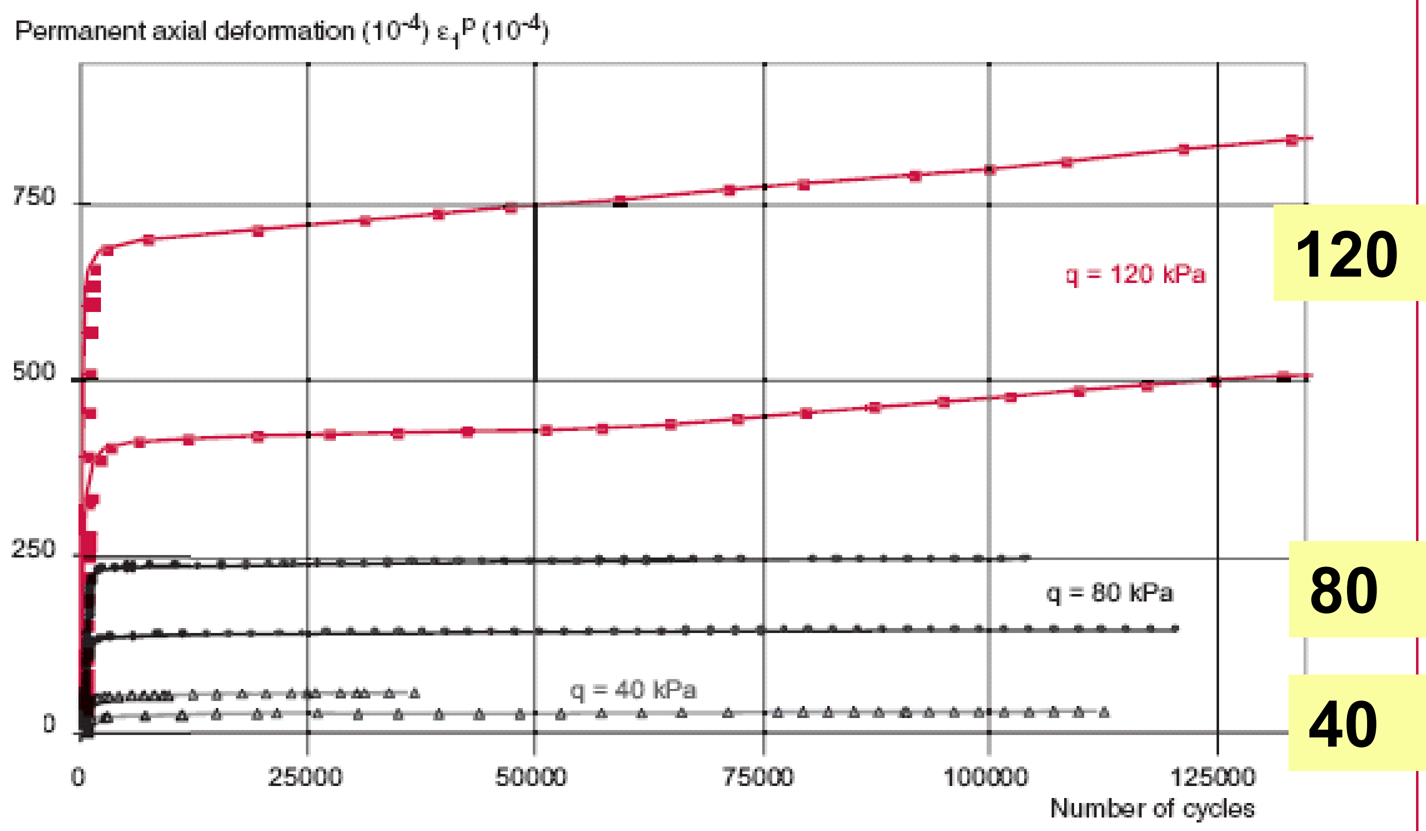


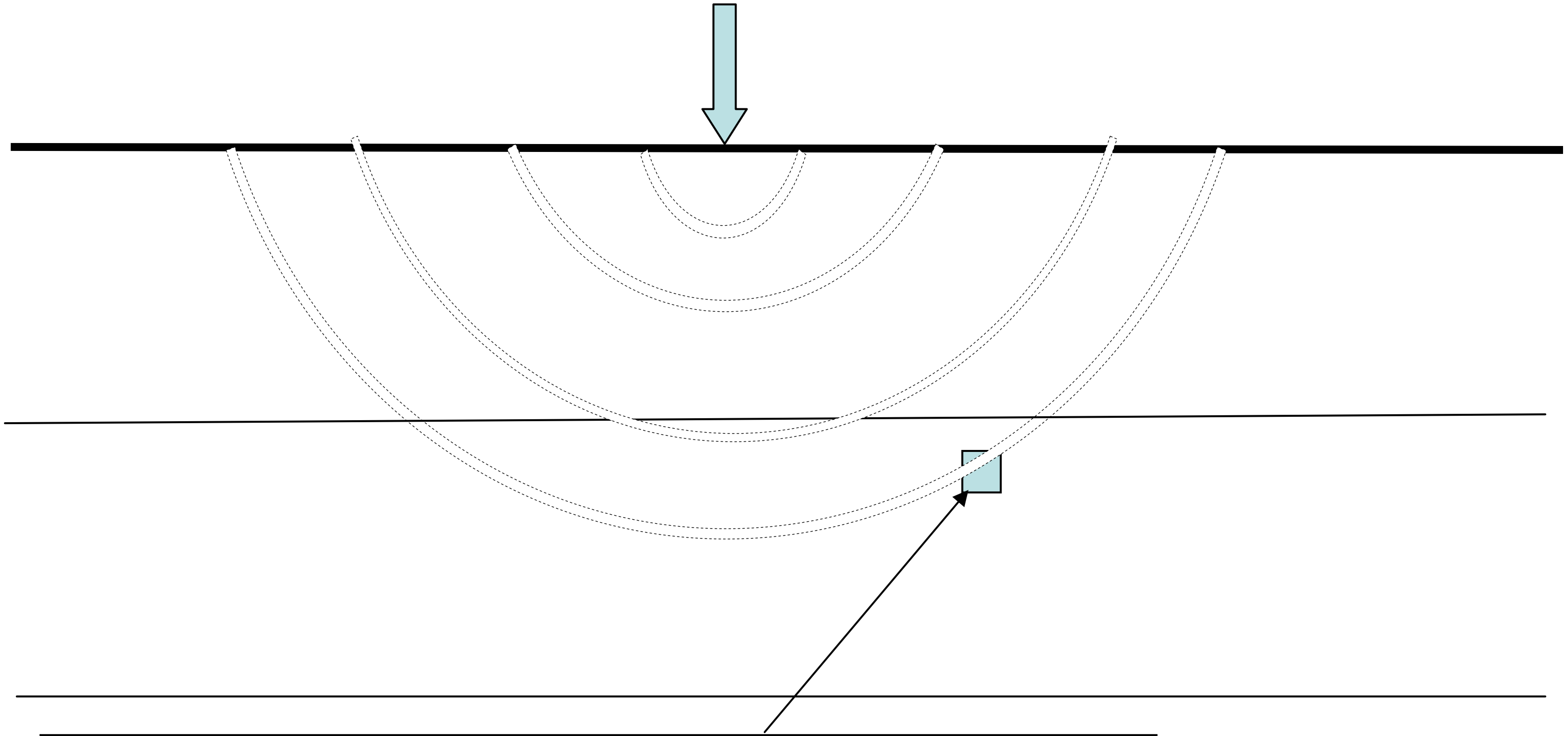
Fig. 3 - Influence of the number of loading cycles (after Martinez [14]).

Mechanistical background

TABLES

Number/Amount/Quality Thickness	Heavy traffic	Amount of frost	Subgrade material	Other
Asphalt				
Base				
Sub base				

MULTILAYER MODELS



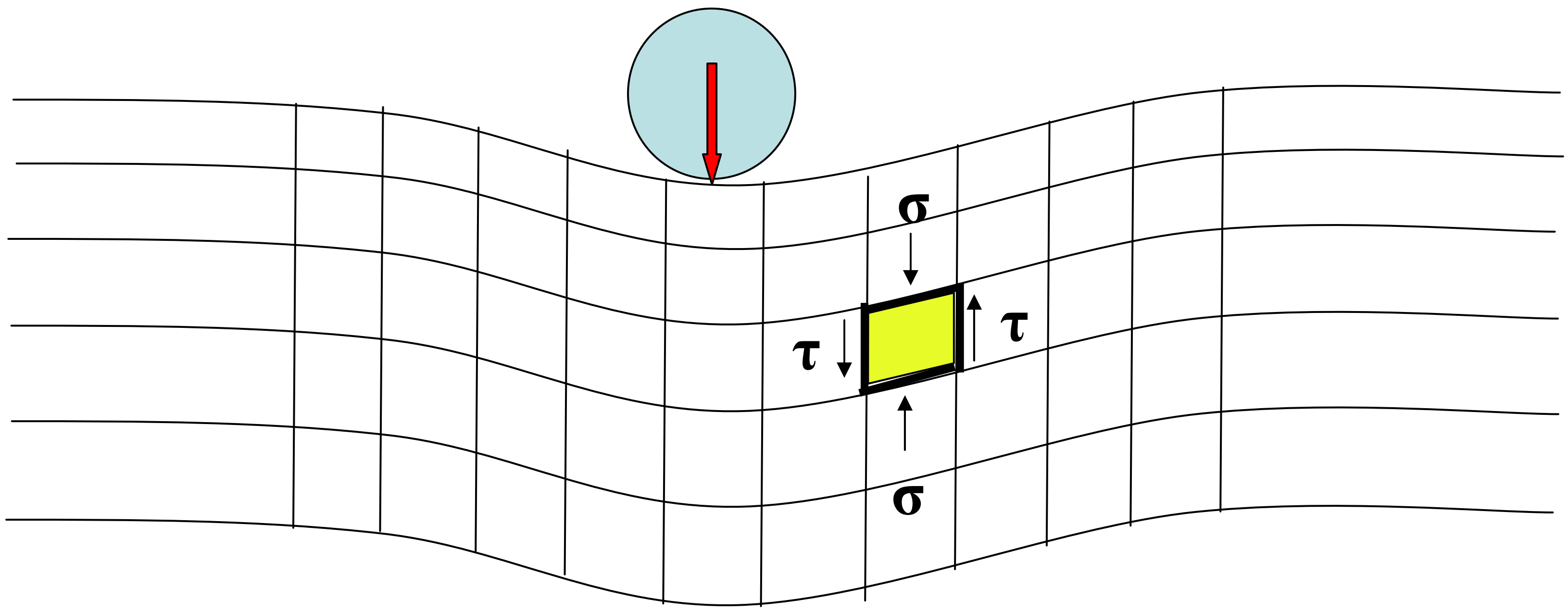
Elastic stress and strain could be calculated in different positions

MULTILAYER MODELS

Prerequisites:

- The material is linear elastic
- The material can take tensile stress, even if it is wrong (unbound material)
- The material has no weight
- The material has infinite extension in all directions

FINIT ELEMENT MODELS (FEM)



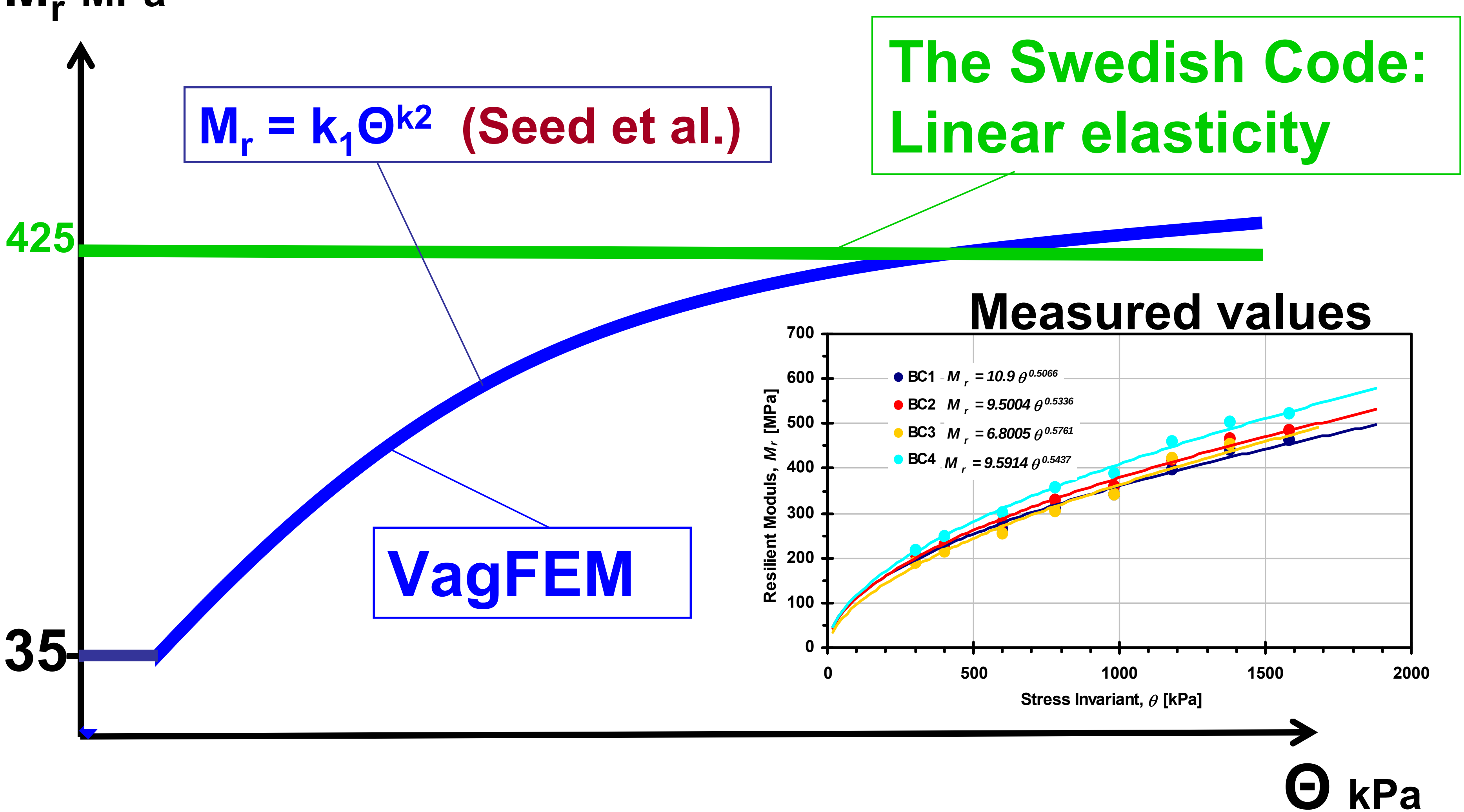
Every little part must be in stress equilibrim and deform in such a way that all pieces fits together.

FINIT ELEMENT MODELS (FEM)

Prerequisites:

- Different material models could be used
- The material can take tensile stress or not (unbound material)
- The weight of the material could be included in the calculations
- The real geometry of the road can be simulated

Unbound layer: Simulated E-modulus



Different material gives different resilient modulus

Materiale	Resilientmodul (MPa)			
	θ=100 kPa	θ=200 kPa	θ=300 kPa	θ=400 kPa
Åndalen knust fjell 0 – 32 mm	262	390	493	662
Hedrum knust fjell 22 – 64 mm	227	328	406	532
Steinskogen knust fjell 22 – 64 mm	240	331	400	507
Åndalen knust fjell 22 – 64 mm	255	362	445	577
Hordaland knust fjell 22 – 64 mm	137	213	277	385
Åndalen knust fjell 0 – 32 mm (NGI pros.)	219	320	398	526
Åndalen knust fjell 22 – 64 mm (NGI pros.)	230	348	443	602

Exemple from Norway and Finland

Stress dependant resilient modulus

Design Guide

Why is it difficult to use Design Guide?

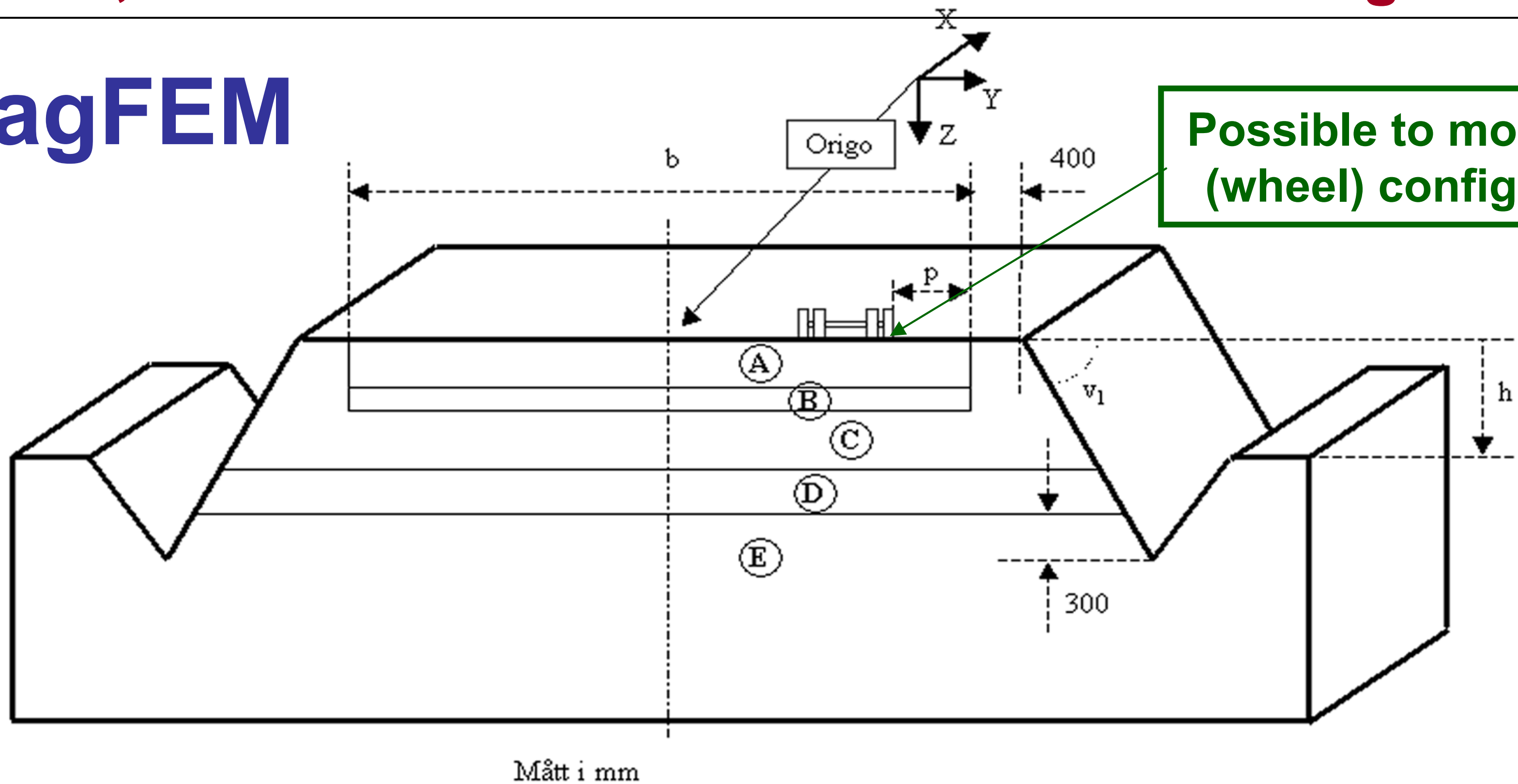
- **It do not take the real material characteristics into consideration**
- **It makes separete calculations for each month during 20 years, which means at least 280 calculations. This takes a very long time to run in a computer**

USER FRIENDLY PROGRAMS

VagFEM is a 3D finite element program, built on ABAQUS, and run in a large computer. The result is coming back as a PDF-file inside 20 minutes. The input data is very easy to handle, it could be done in 3 minutes on a working site.

VagFEM

Possible to model load (wheel) configuration



Inre släntlutning		1:2	
Höjd omgivande mark		50	[mm]
SKIKT A	Typ	Bundet linjärt	
	Tjocklek	110	[mm]
SKIKT B	Typ	Asfaltsgrus linjärt	
	Tjocklek	130	[mm]
SKIKT C	Typ	Obundet linjärt	
	Tjocklek	400	[mm]
SKIKT D	Typ	Inget	
	Tjocklek	600	[mm]
SKIKT E	Typ	Obundet linjärt	
Lasthantering		Axel med super-single hjul	
Axellast		10 ton	
Däcktryck		1200	[kPa]
Placering		600	[mm]

Fortsätt till nästa steg | Återställ | Hjälp

SKIKT A	Bundet linjärt		Tjocklek 110 [mm]
Densitet	2000	[kg/m³]	
Poissons tal	0.35	[1]	
Elasticitetsmodul	10000	[MPa]	
SKIKT B	Asfaltsgrus linjärt		Tjocklek 130 [mm]
Densitet	2000	[kg/m³]	
Poissons tal	0.35	[1]	
Elasticitetsmodul	9000	[MPa]	
SKIKT C	Obundet linjärt		Tjocklek 400 [mm]
Densitet	2000	[kg/m³]	
Poissons tal	0.35	[1]	
Elasticitetsmodul	1000	[MPa]	
SKIKT D	Inget		Tjocklek 0 [mm]
SKIKT E	Obundet linjärt		
Densitet	2000	[kg/m³]	
Poissons tal	0.35	[1]	
Elasticitetsmodul	1000	[MPa]	

Komplett resultatfil ☐

Generera fil för permanent deformation ☐

Starta beräkningen | Tillbaka till föregående steg | Hjälp

Projekt: Testprojekt

Namn på beräkningen: Ber 2

SKIKT C

Typ: Obundet linjärt

Tjocklek: 125 [mm]

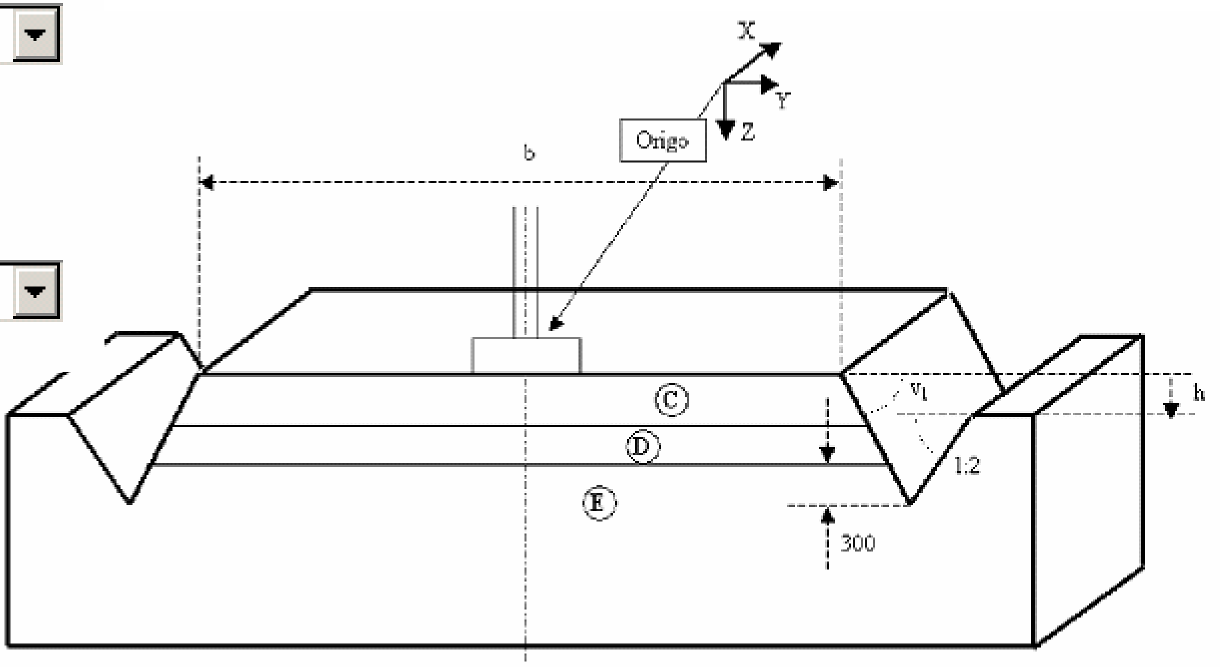
SKIKT D

Typ: Inget

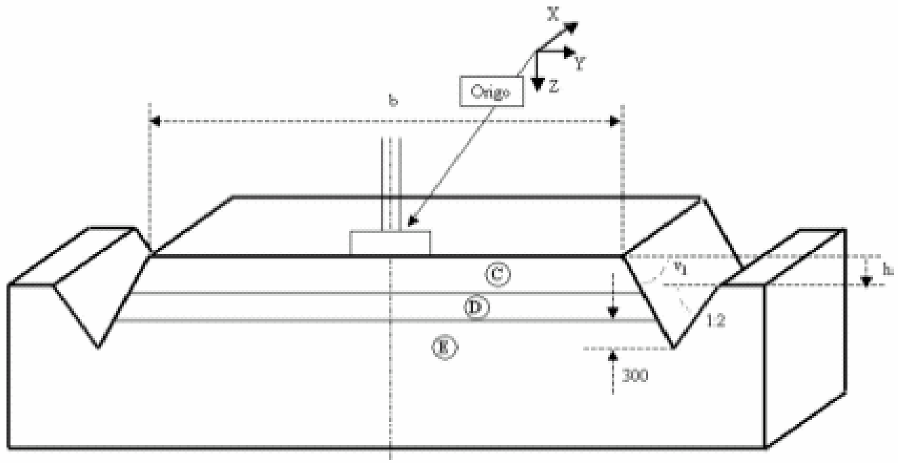
Tjocklek: [mm]

SKIKT E

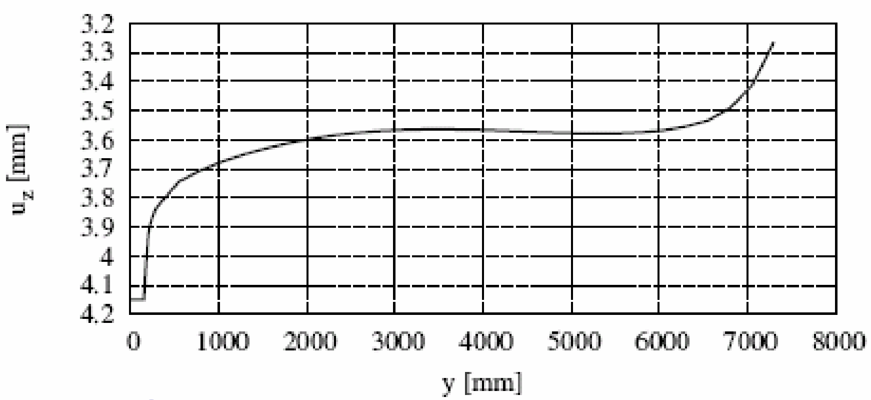
Typ: Obundet linjärt



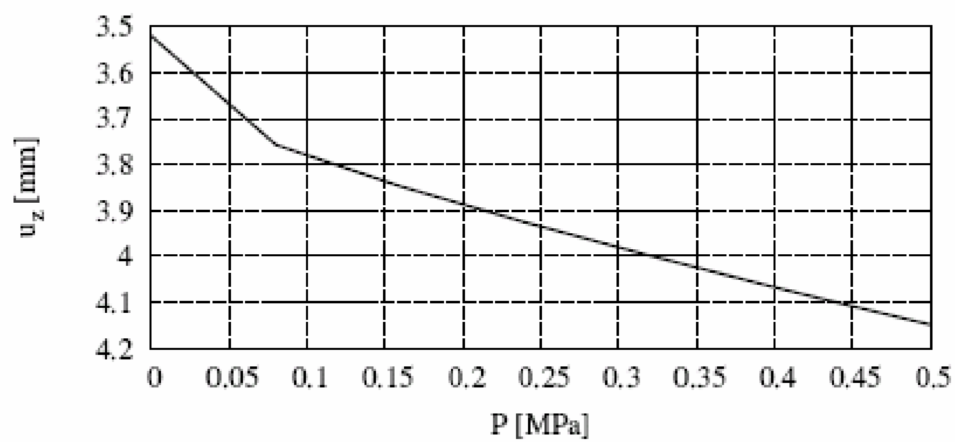
VagFEM – Plate Loading – Resilient modulus



Geometry for plate loading test

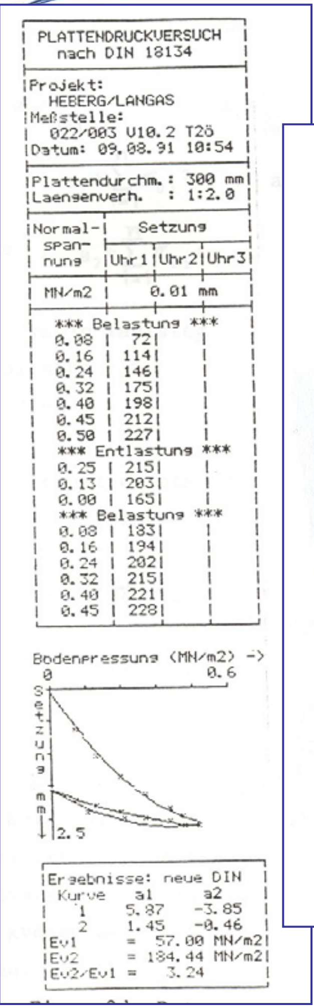


Deflection beside the plate at full load (compare FWD)



Deflection under the plate at various load steps

Test: Plate loading


PLATTENDRUCKVERSUCH
nach DIN 18134

Projekt:
HEBERG/LANGAS
Meßstelle:
022/003 V10.2 T2ö
Datum: 09.08.91 10:54

Plattendurchm.: 300 mm
Laengenverh. : 1:2.0

Normal-spannung	Setzung Uhr 1	Uhr 2	Uhr 3
MN/m2	0.01 mm		
*** Belastung ***			
0.08	72		
0.16	114		
0.24	146		
0.32	175		
0.40	198		
0.45	212		
0.50	227		
*** Entlastung ***			
0.25	215		
0.13	203		
0.00	165		
*** Belastung ***			
0.08	183		
0.16	194		
0.24	202		
0.32	215		
0.40	221		
0.45	228		

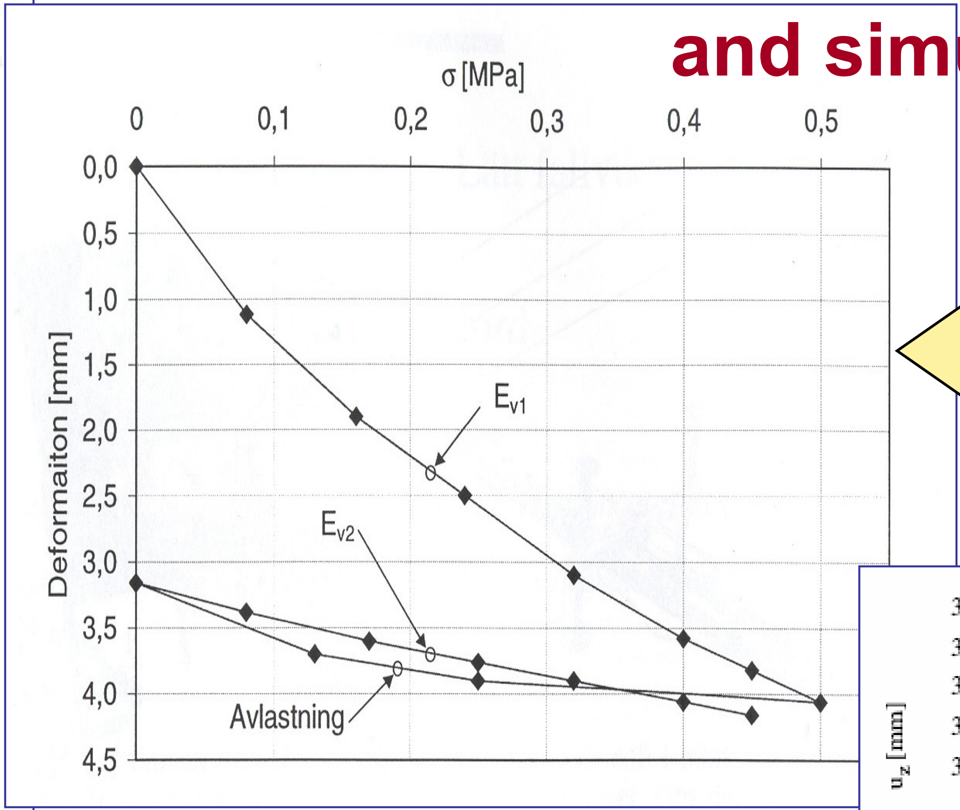
Bodenpressung (MN/m2) ->
0 0.6
Setzung mm
2.5

Ergebnisse: neue DIN

Kurve	a1	a2
1	5.87	-3.85
2	1.45	-0.46

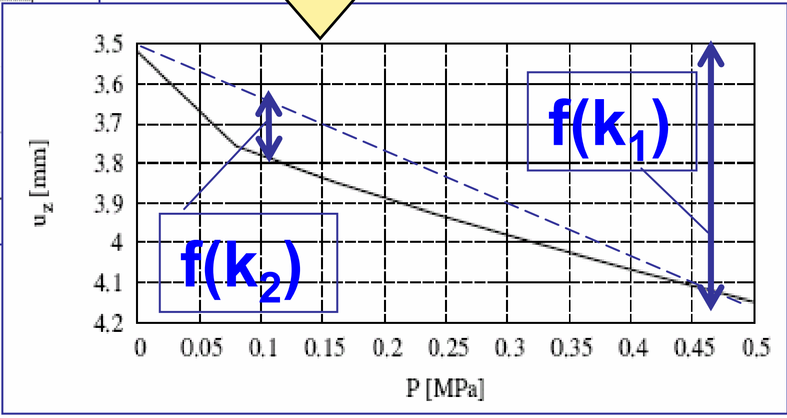
Ev1 = 57.00 MN/m2
Ev2 = 184.44 MN/m2
Ev2/Ev1 = 3.24

Result from Plate loading and simulation in VagFEM



Resilient Module

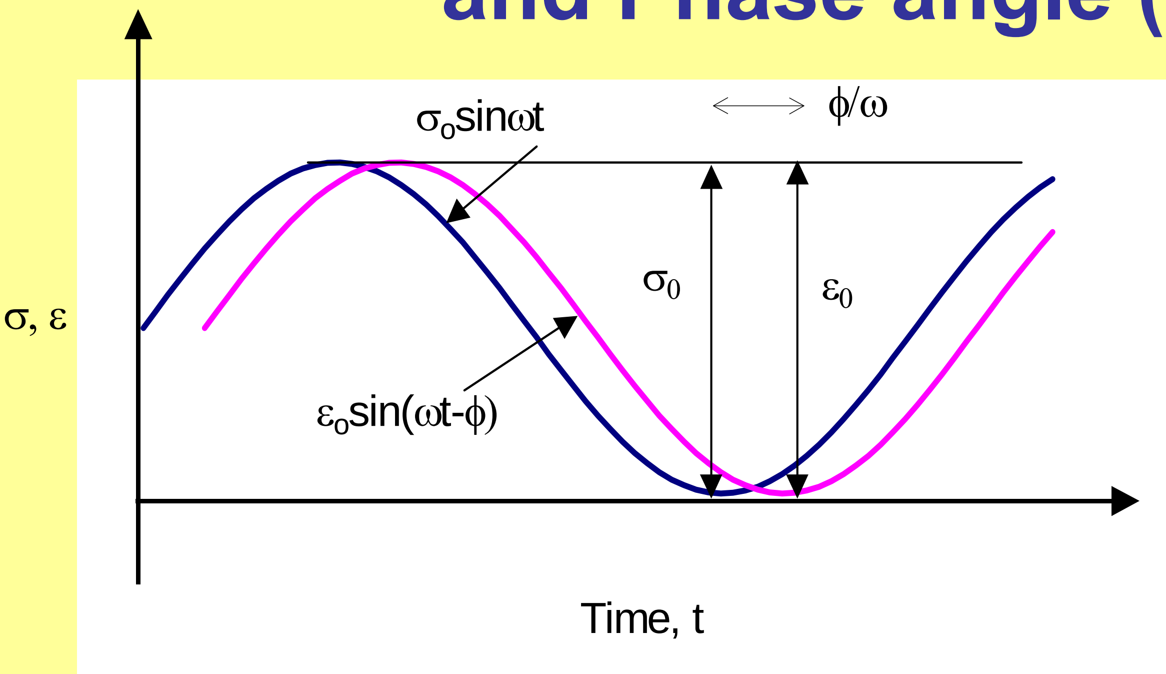
$$Mr = k_1 \Theta^{k2}$$



Measured Mr_1 in subgrade is used as input data in calculation of Mr_2 in subbase

TEST METHODS
bituminous bound layers

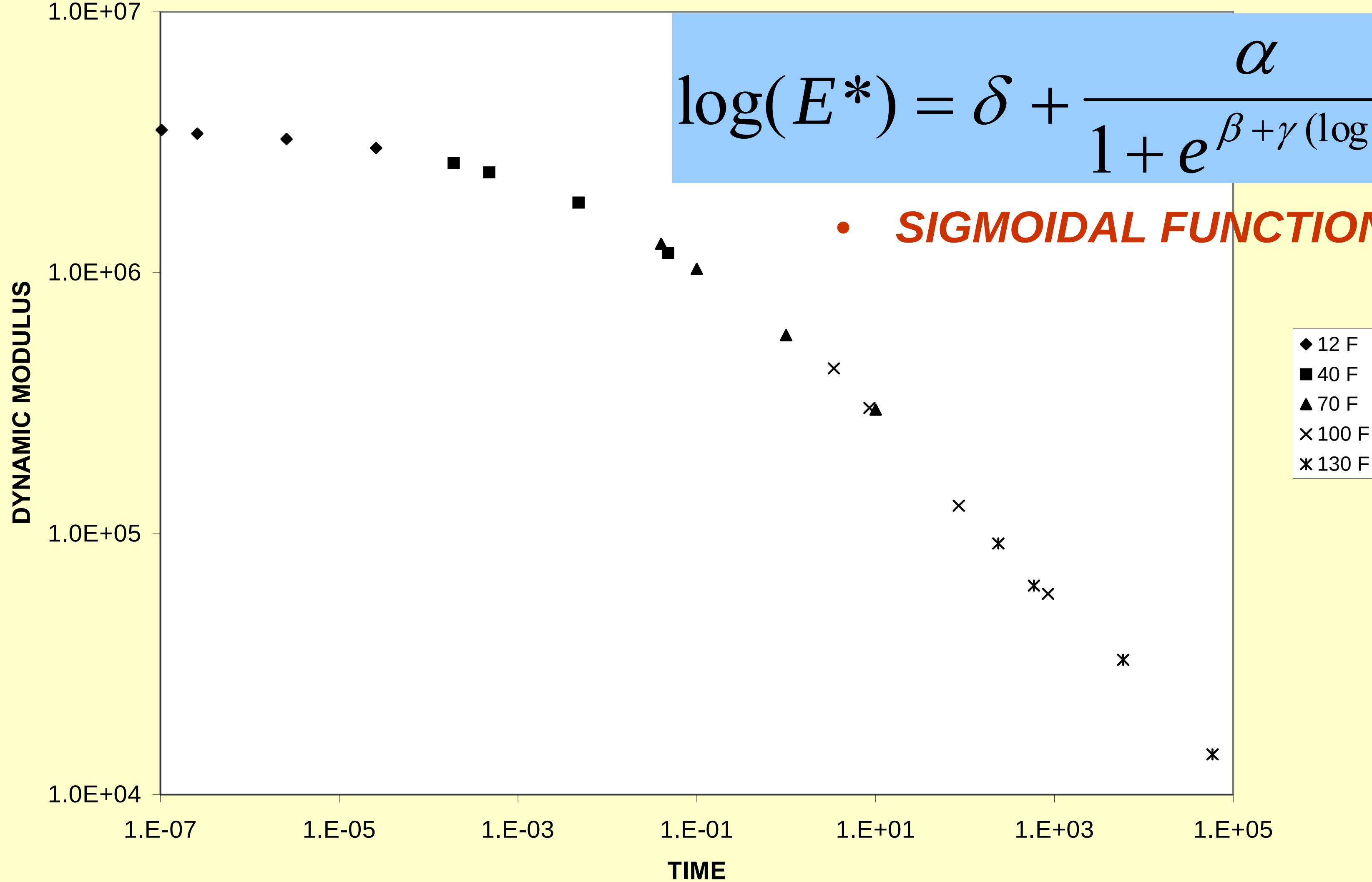
Compressive Dynamic Modulus (|E*|) and Phase angle (ϕ)



$$|E^*| = \frac{\sigma_0}{\varepsilon_0}$$

$$\phi = \omega t_i$$

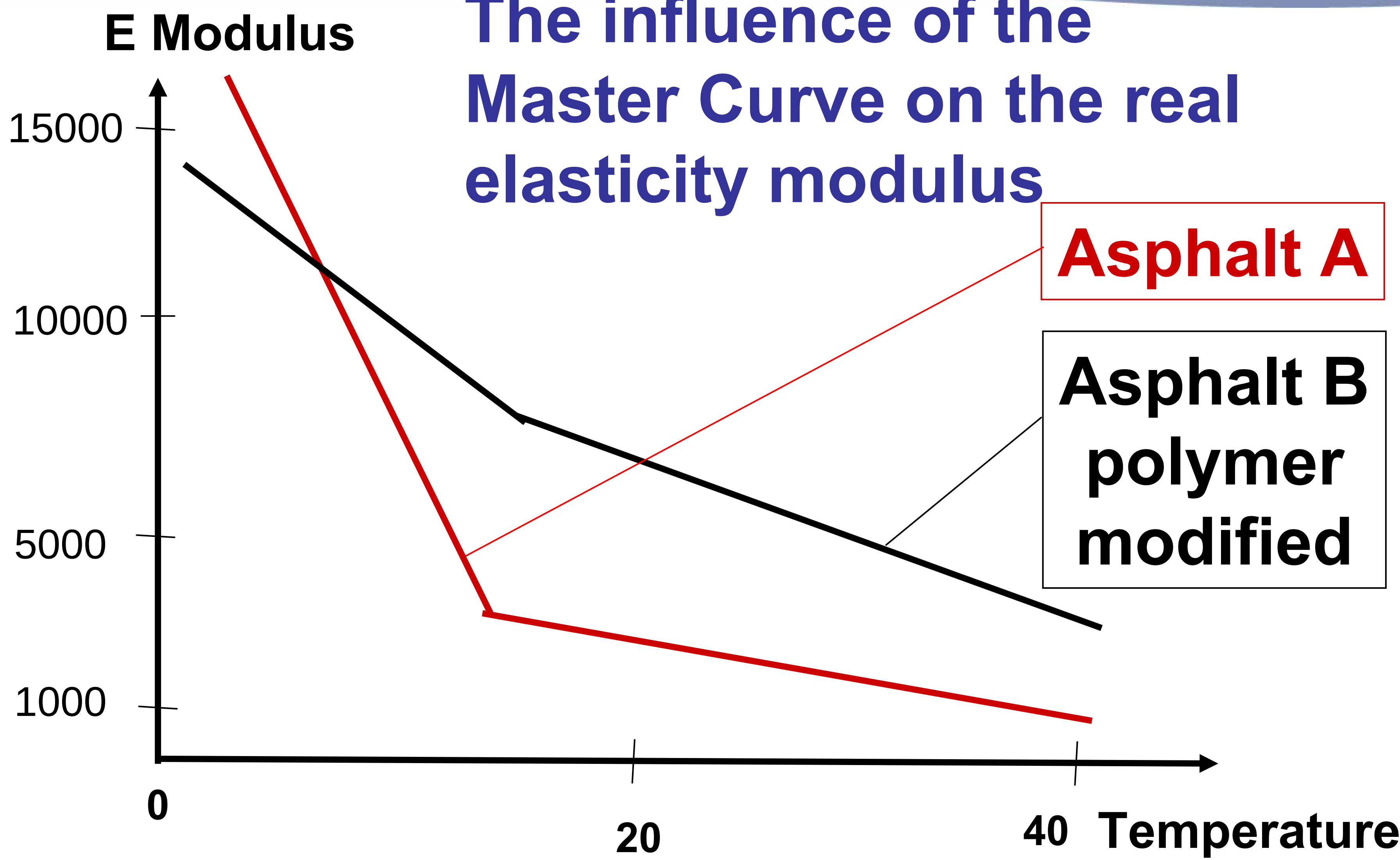
Dynamic Modulus Master Curve

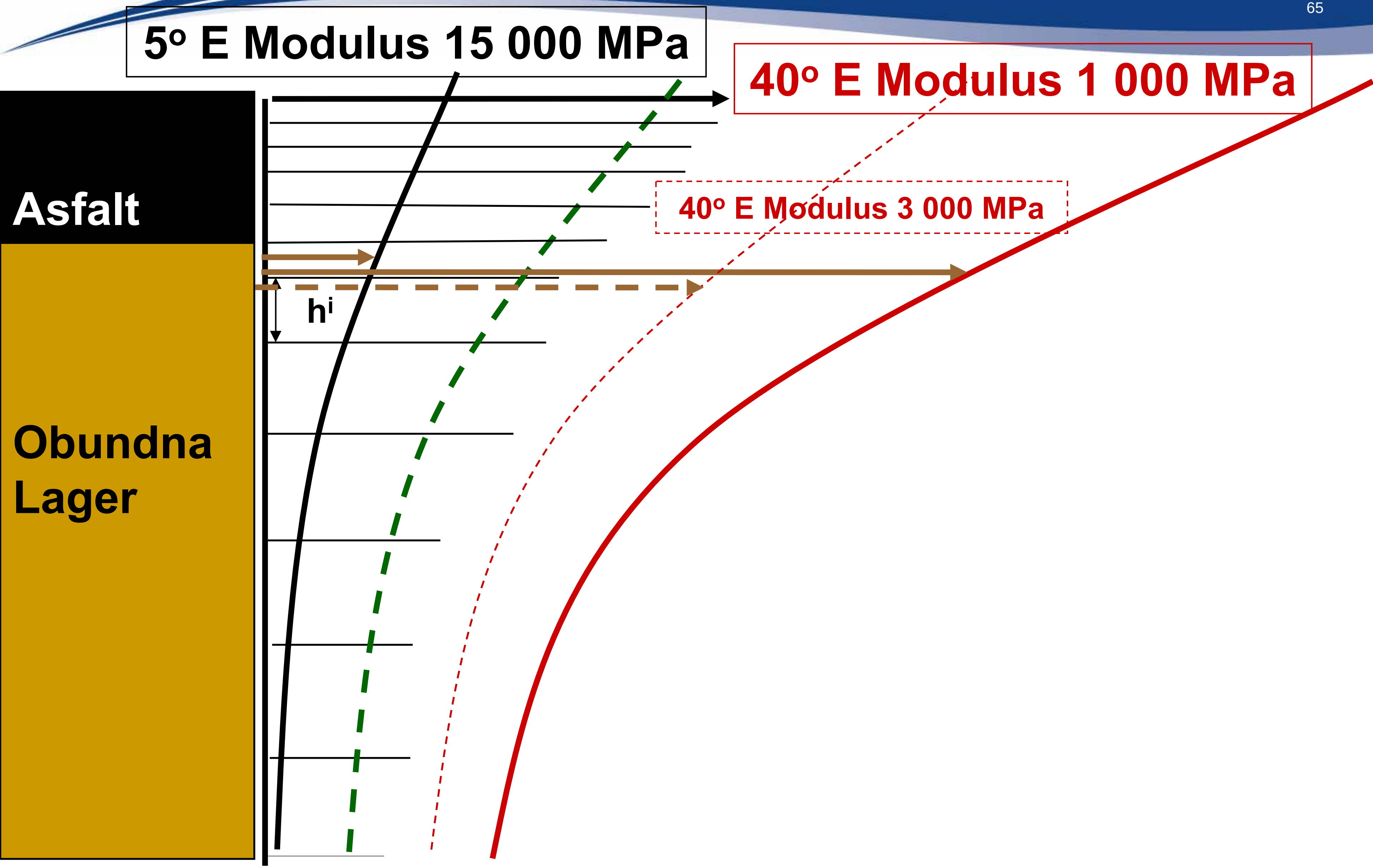


$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log t_r)}}$$

- ***SIGMOIDAL FUNCTION***

The influence of the Master Curve on the real elasticity modulus

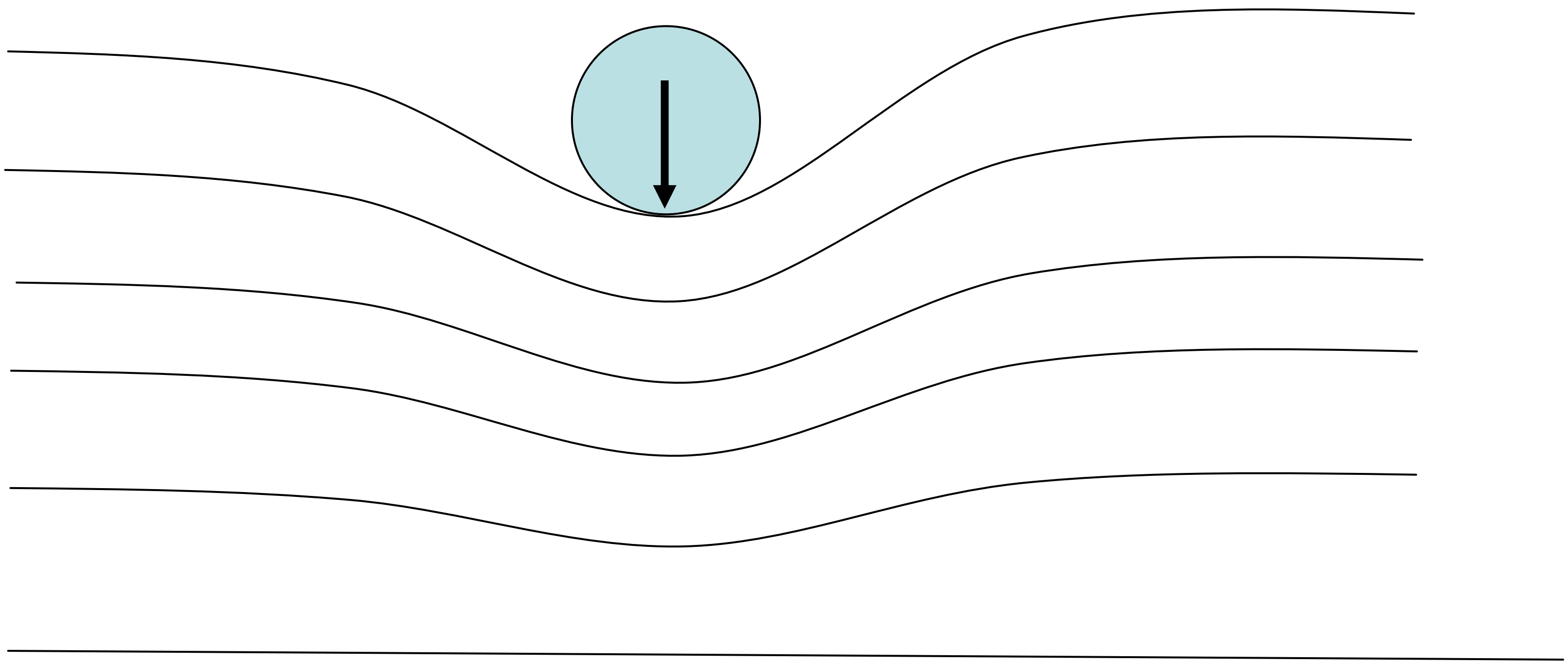



5º E Modulus 15 000 MPa
40º E Modulus 1 000 MPa
40º E Modulus 3 000 MPa
Asfalt
hi
Obundna
Lager

Calculation of rutting

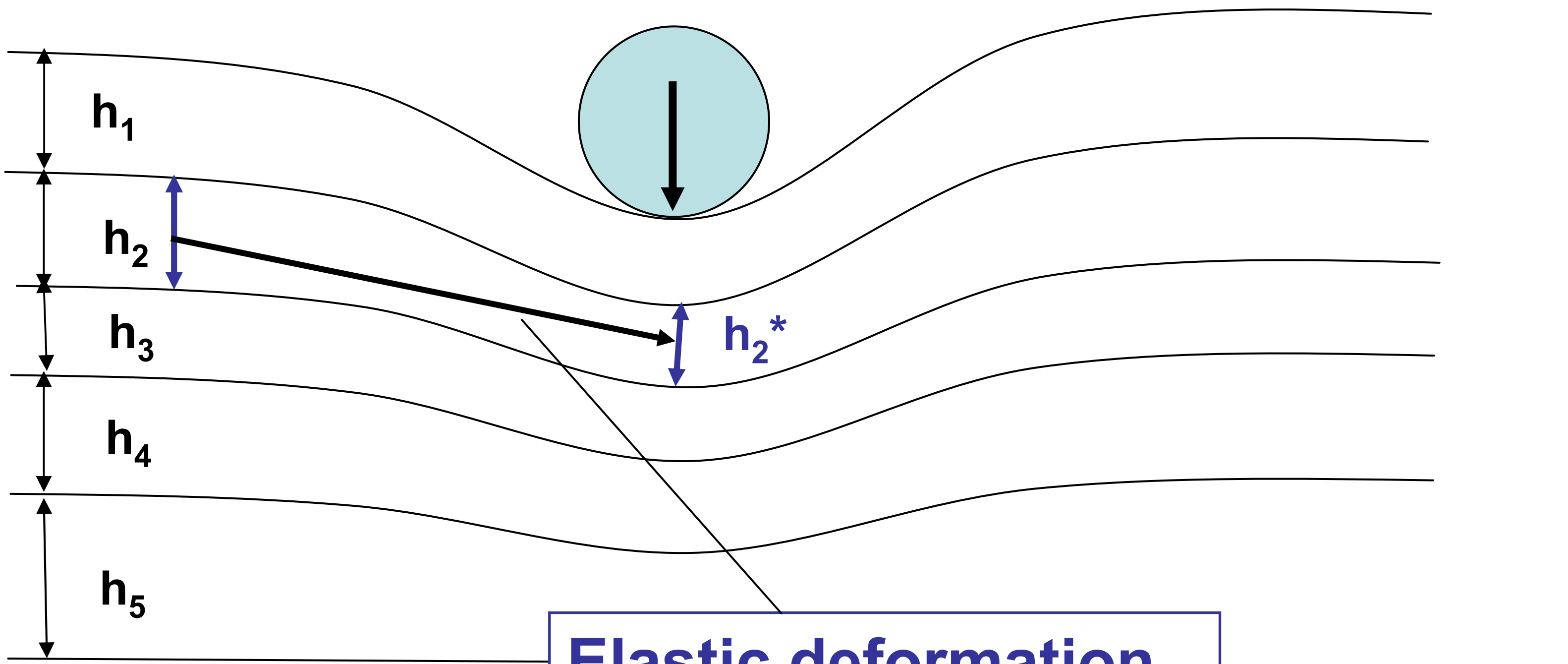
Elastic deflection from a heavy vehicle

Elastic deflection from a heavy vehicle



Elastic deflection from a heavy vehicle

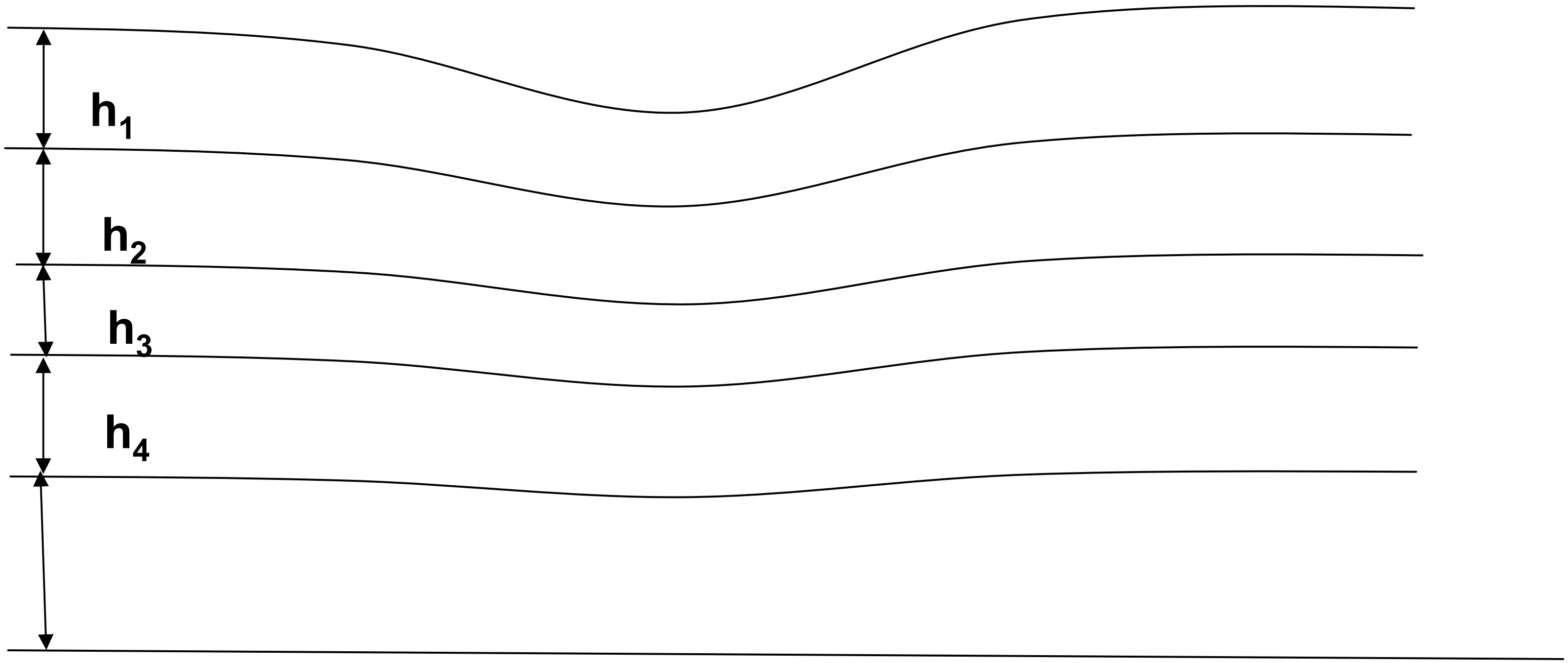
Elastic deflection from a heavy vehicle



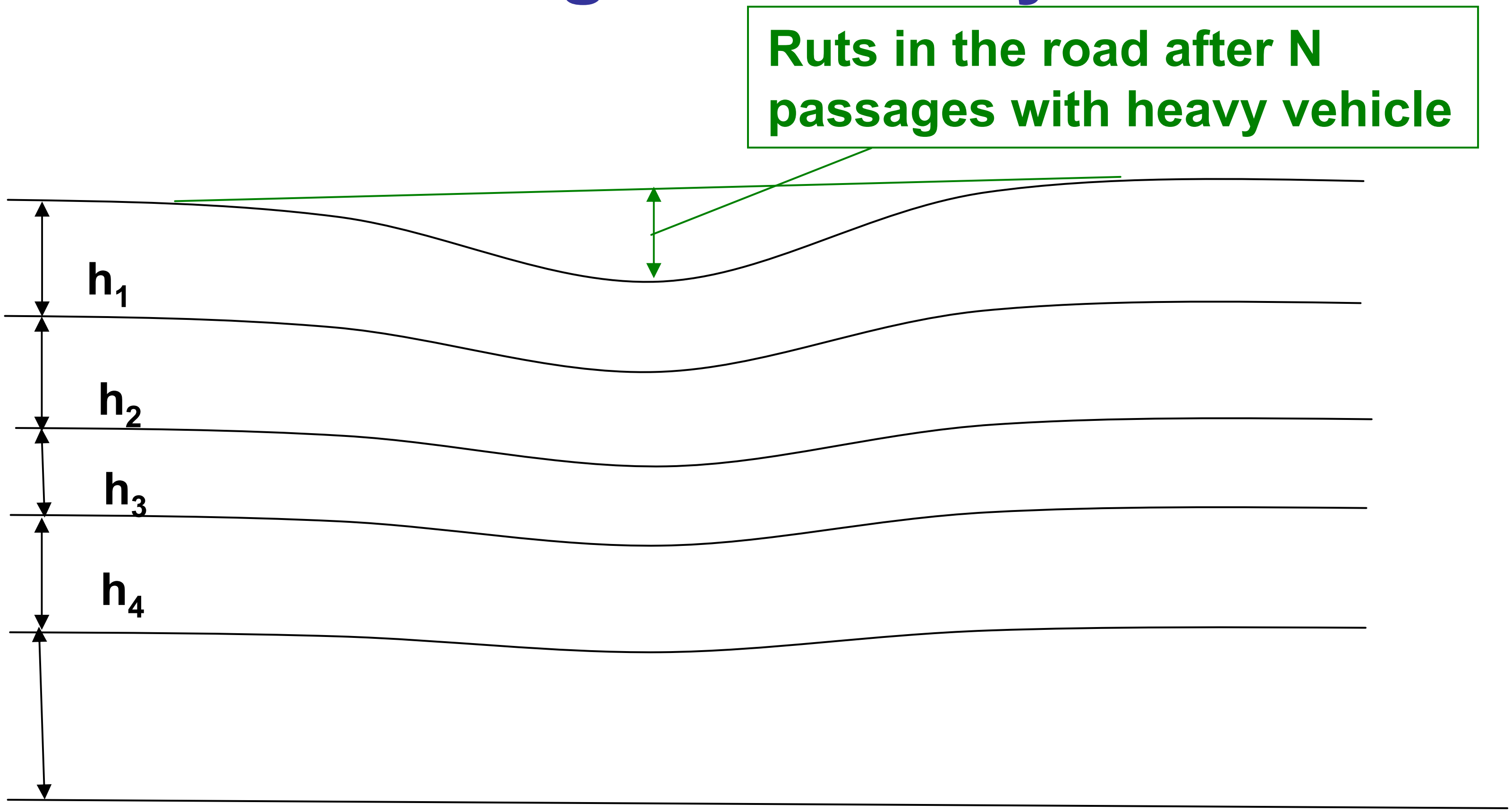
Elastic deformation

$\varepsilon_e = (h_2 - h_2^*)/h_2$

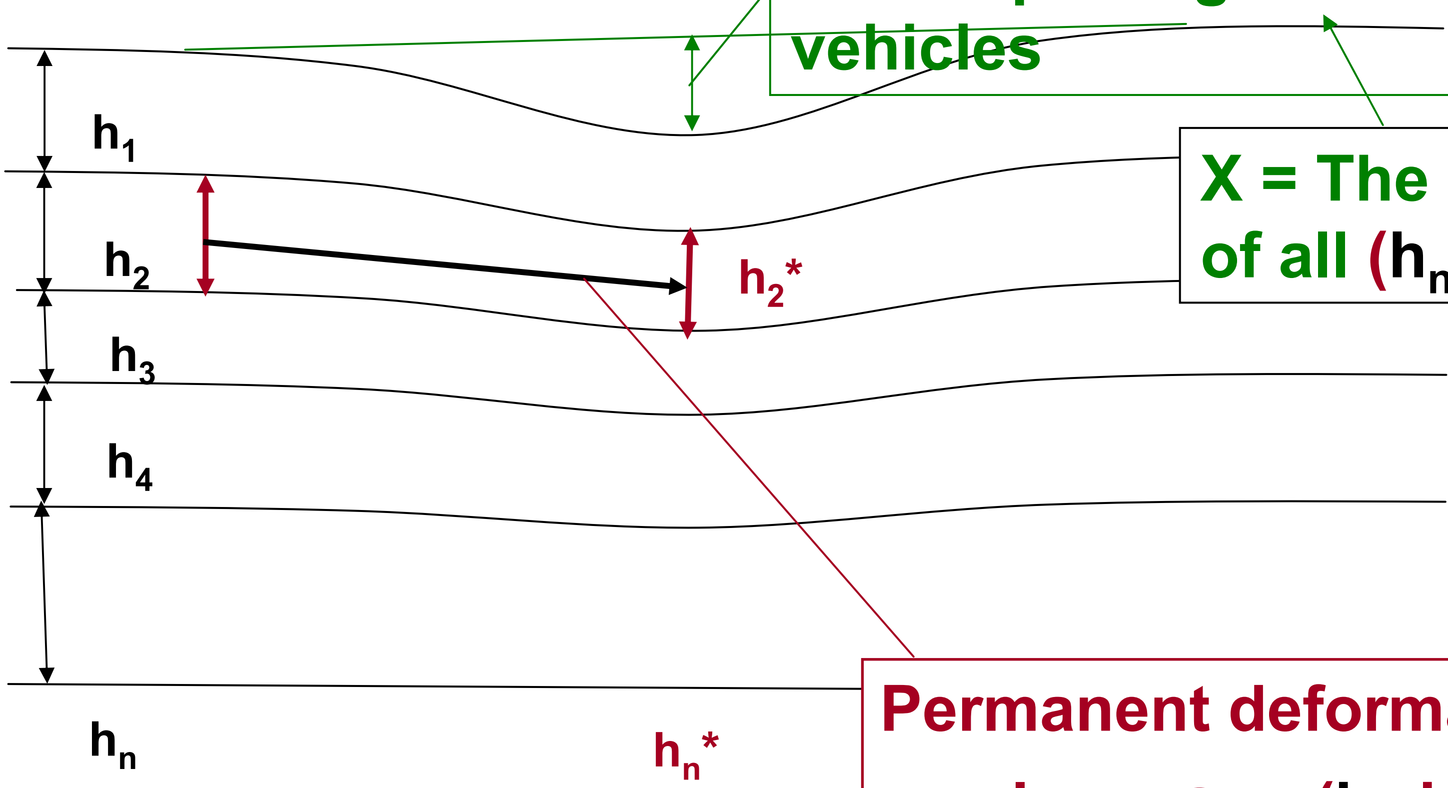
Permanent rutting from heavy vehicle



Permanent rutting from heavy vehicle



Permanent rutting from heavy vehicle



Ruts in the road, X mm, after N passages with heavy vehicles

X = The sum of all $(h_n - h_n^*)$

Permanent deformation in one layer $\varepsilon_p = (h_2 - h_2^*)/h_2$

Triaxial test

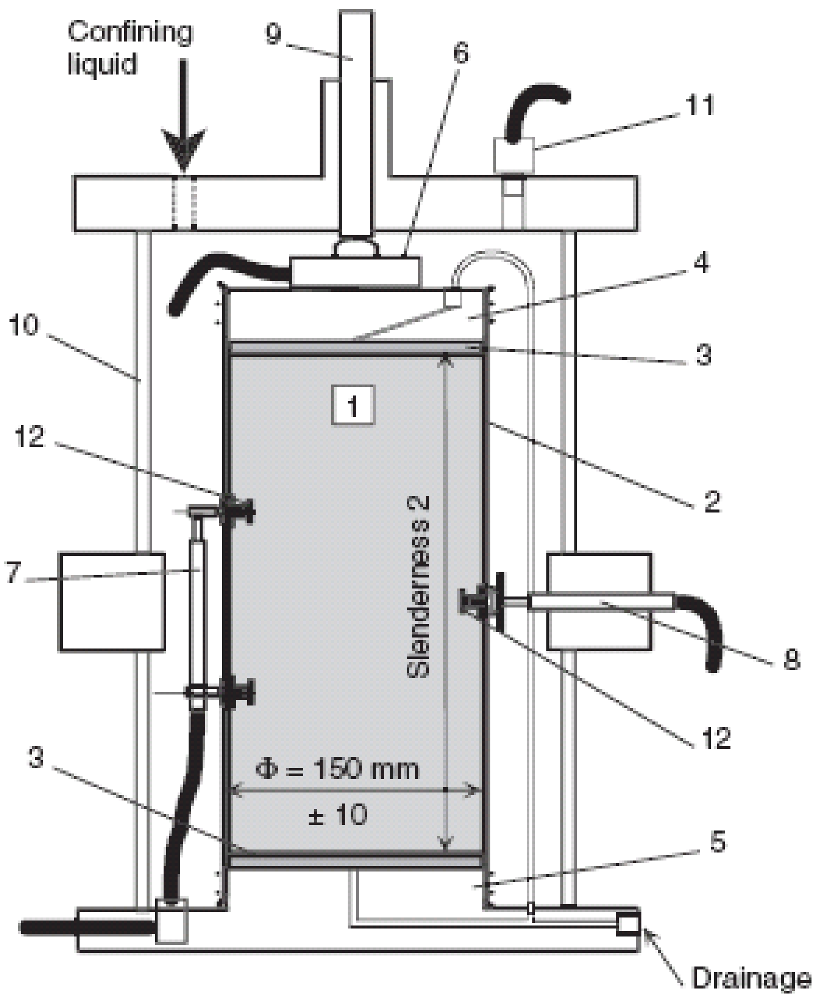


Fig. 1 - The triaxial cell of the repeated load triaxial apparatus.

1. *Specimen.*
2. *Membrane.*
3. *Porous disc.*
4. *Cell top.*
5. *Base.*
6. *Force sensor.*
7. *Axial strain measurement device.*
8. *Radial strain measurement device.*
9. *Loading ram.*
10. *Triaxial cell casing.*
11. *Pressure sensor.*
12. *Displacement transducer fixings.*

Cyclic loadings

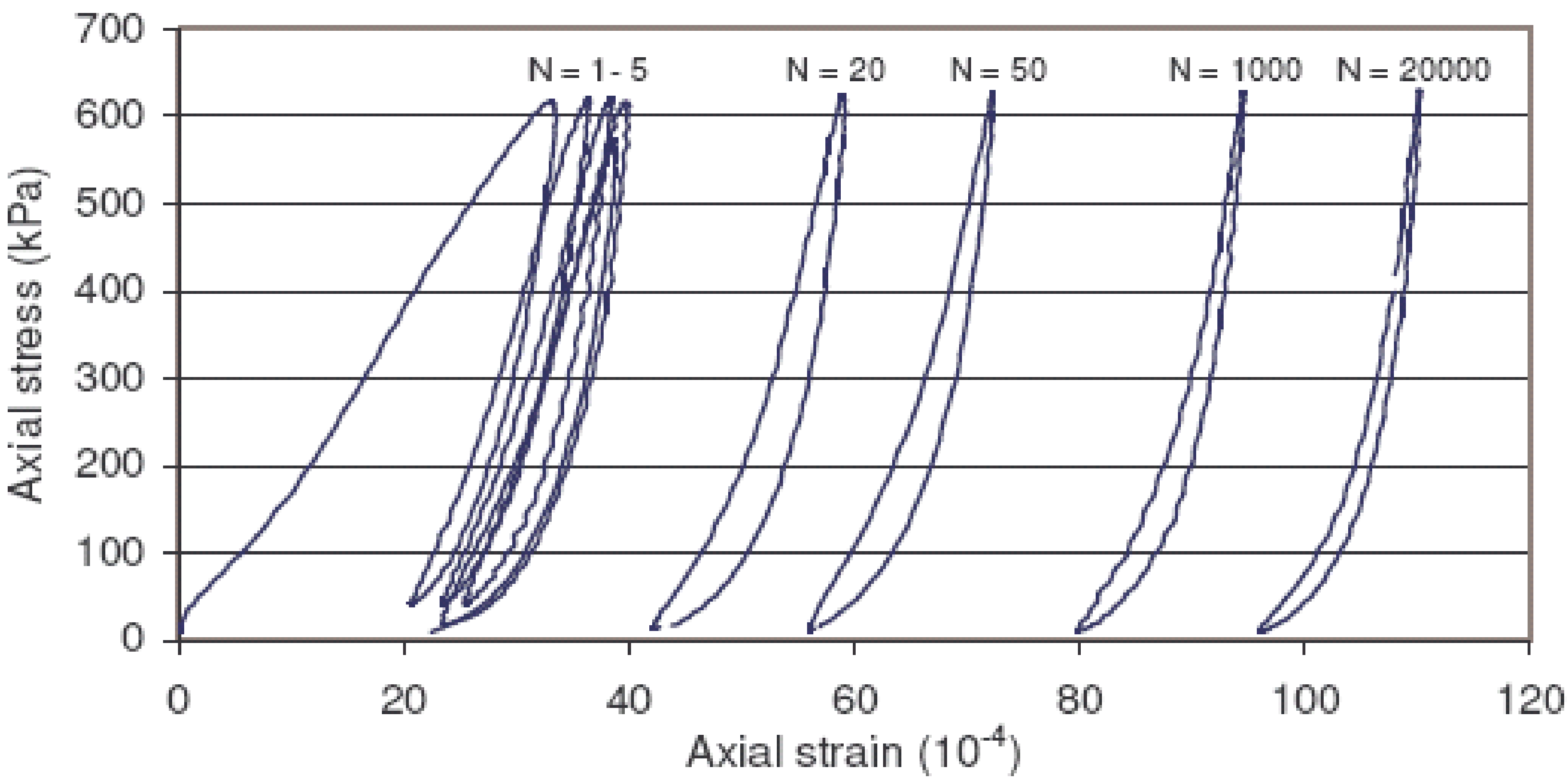
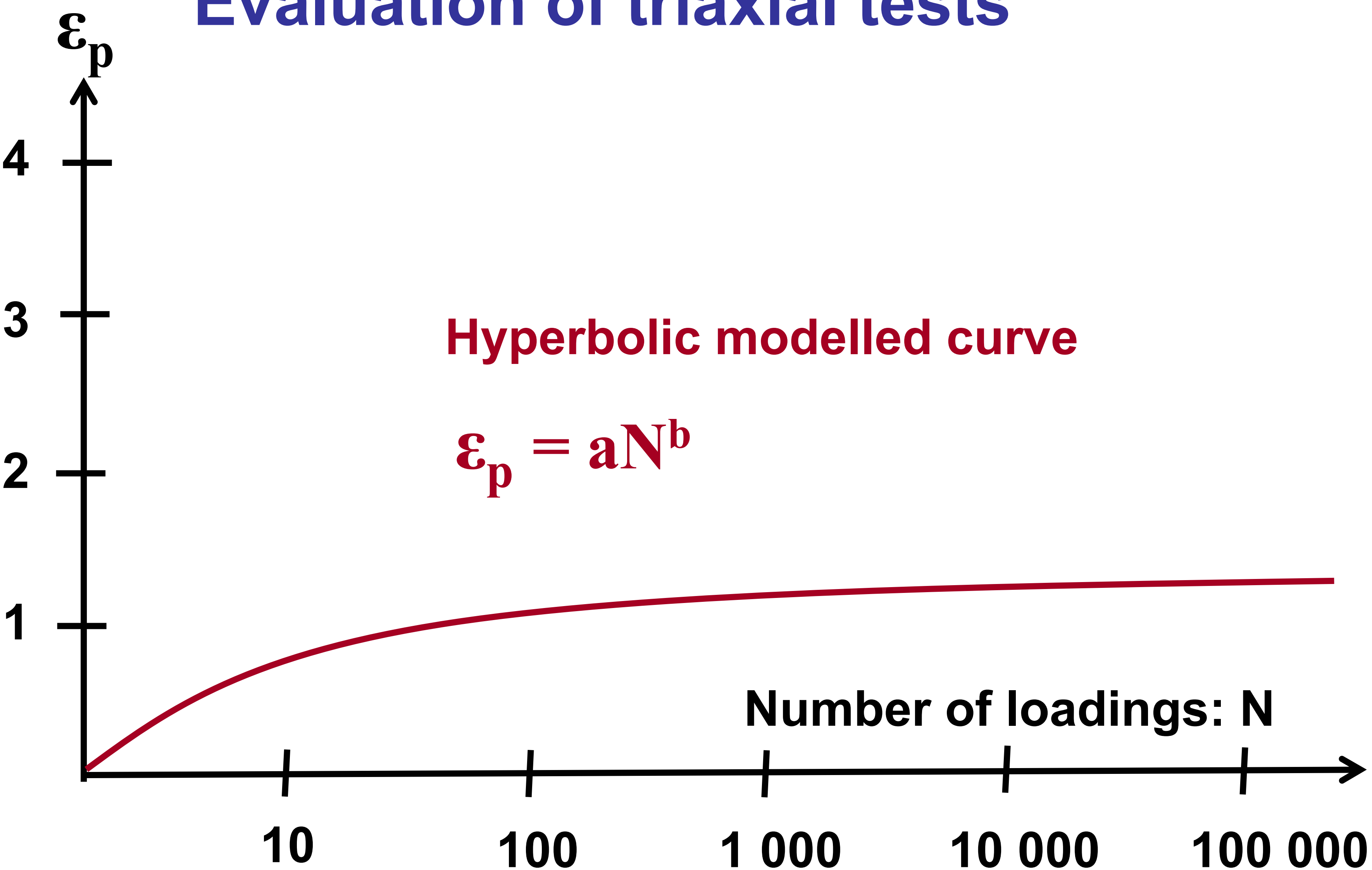
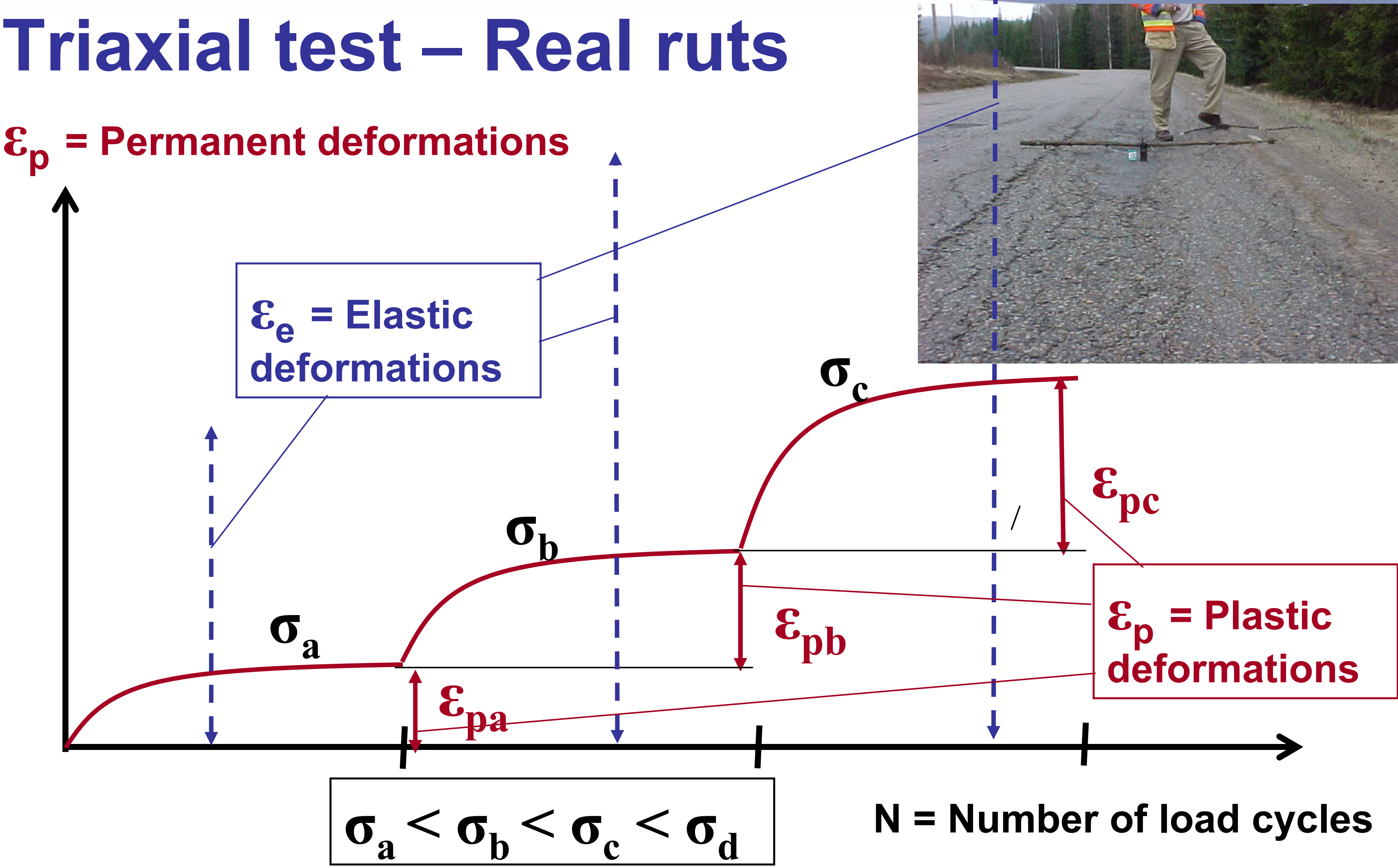


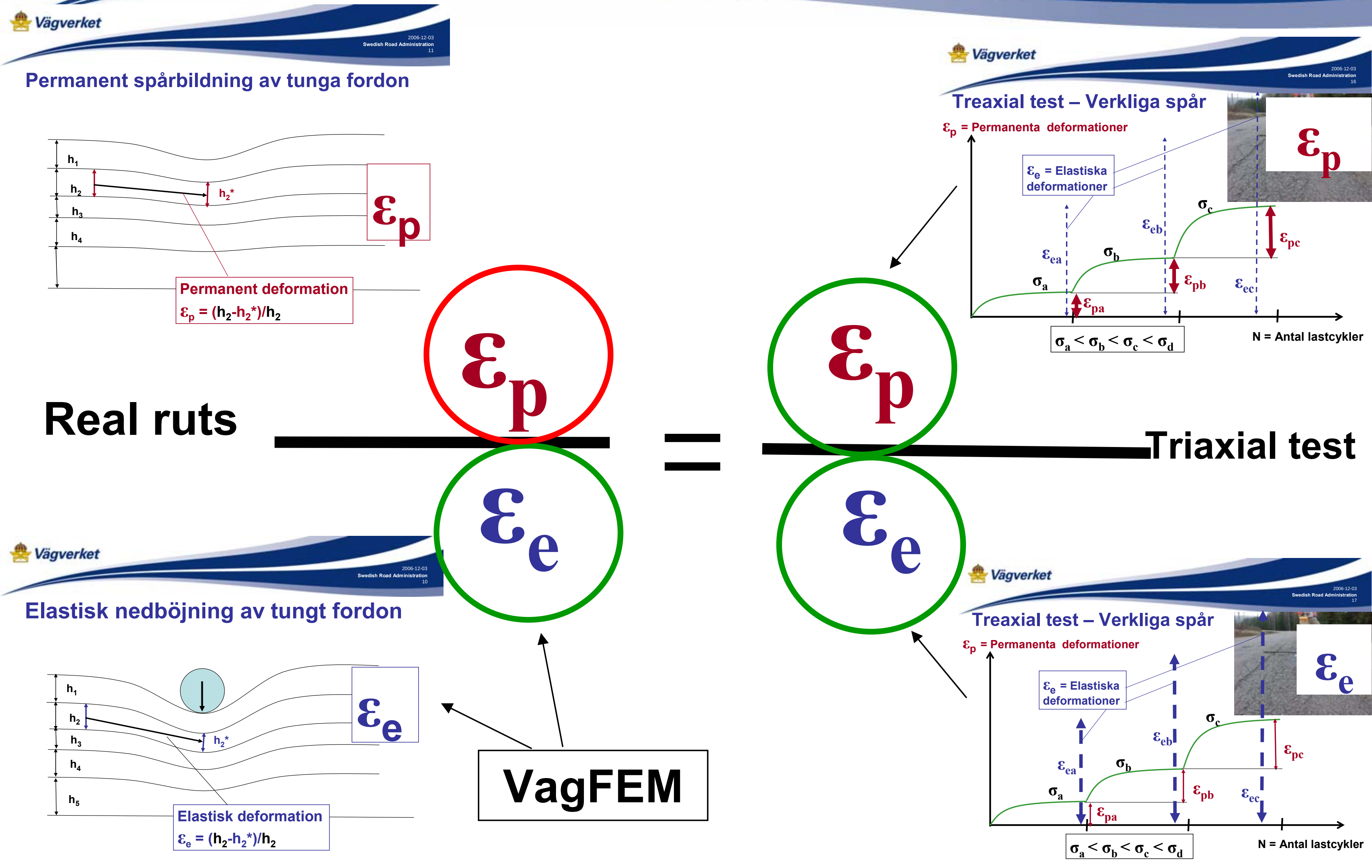
Figure 1. Axial stress – axial strain cycles obtained in a cyclic triaxial test on a UGM.

Evaluation of triaxial tests



Triaxial test – Real ruts




Vägverket
2006-12-03
Swedish Road Administration
11
Permanent spårbildning av tunga fordon
h1
h2
h2*
h3
h4
εp
Permanent deformation
εp = (h2-h2*)/h2
Vägverket
2006-12-03
Swedish Road Administration
16
Treaxial test – Verkliga spår
εp = Permanenta deformationer
εe = Elastiska deformationer
εp
σc
εeb
εpc
εea
σb
σa
εpb
εec
εpa
σa < σb < σc < σd
N = Antal lastcykler
Real ruts
εp
εe
=
εp
εe
Triaxial test
Vägverket
2006-12-03
Swedish Road Administration
10
Elastisk nedböjning av tungt fordon
h1
h2
h2*
h3
h4
h5
εe
Elastisk deformation
εe = (h2-h2*)/h2
VagFEM
Vägverket
2006-12-03
Swedish Road Administration
17
Treaxial test – Verkliga spår
εp = Permanenta deformationer
εe = Elastiska deformationer
εe
σc
εeb
εpc
εea
σb
σa
εpb
εec
εpa
σa < σb < σc < σd
N = Antal lastcykler

MATERIAL MODELS
Rutting in unbound materials

Dresden

Plastic Model

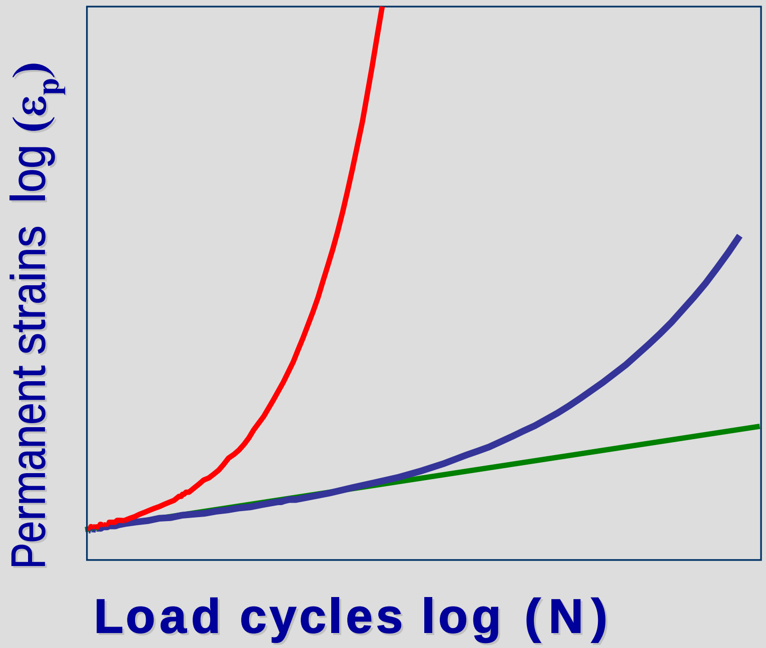
Plastic DRESDEN-Model

$$\varepsilon_p(N) = A \cdot \left(\frac{N}{1000}\right)^B + C\left(e^{D\frac{N}{1000}} - 1\right)$$

Stable behaviour
Range A

Collapse

Range B and C



A, B, C, D = f(σ_1 and σ_3)

(HUURMAN 1997)

Prof Frohmut Wellner
Sabine Werkmeister

MATERIAL MODELS
Rutting in unbound materials

SAMARIS

Calculation of permanent deformations – LCPC

$$\varepsilon_1^p(N) = \varepsilon_{10}^p \cdot \left[1 - \left(\frac{N}{N_0}\right)^{-B}\right] \cdot \left[\frac{L_{max}}{p_a}\right]^n \cdot \frac{1}{\left(m + \frac{s}{p_{max}} - \frac{q_{max}}{p_{max}}\right)}$$

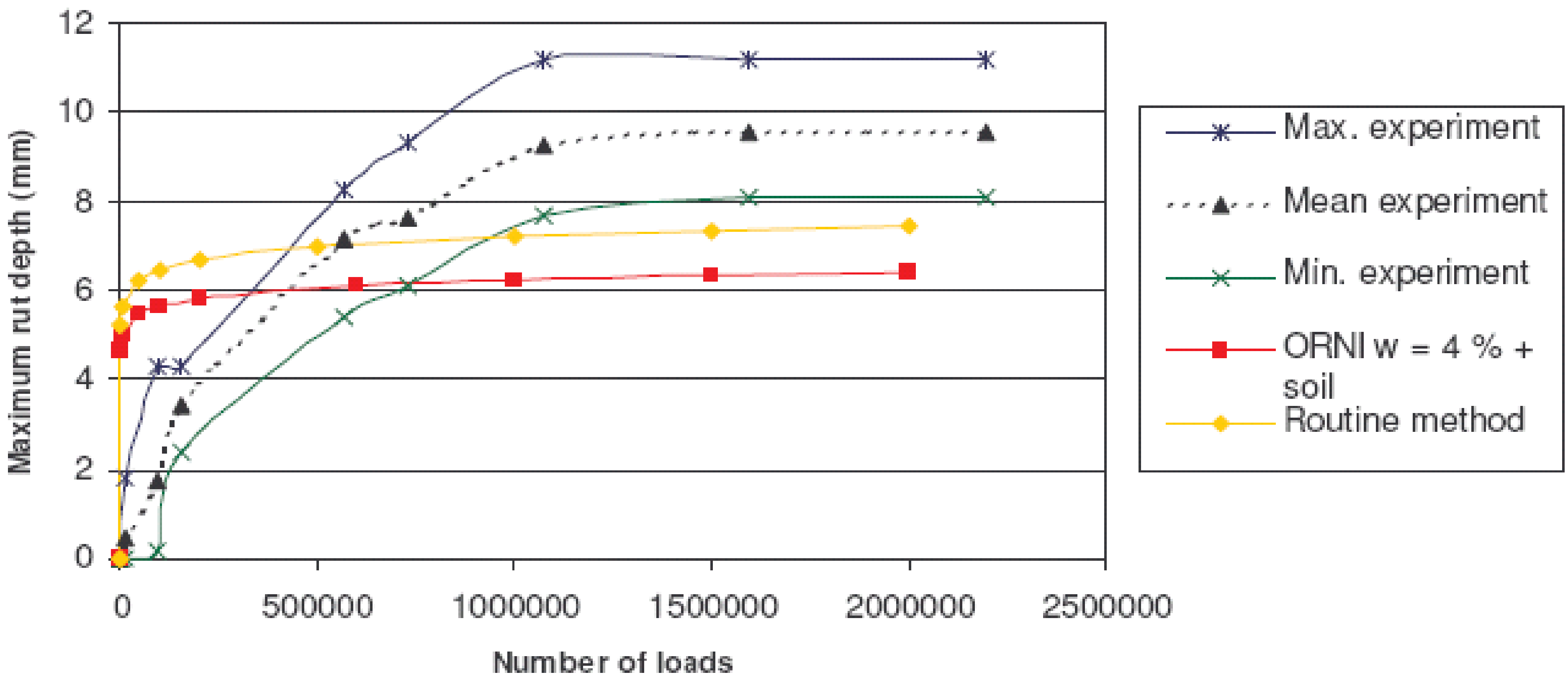
ε_1^p : permanent axial strain; N : number of load cycles;
p_{max}, q_{max} : maximum values of the mean normal stress p and deviatoric stress q;

$$L_{max} = \sqrt{p_{max}^2 + q_{max}^2}$$

Samaris

P_a : reference pressure equal to 100 kPa;
ε_1^{p0}, B, n model parameters;
m,s parameters of the failure line of the material, of equation q = m.p+s;
(from experience, m=2.5 to 2.6 and s=20 kPa)

Result: Prediction of permanent deformation, rutting



MATERIAL MODELS
Rutting in unbound materials

Design Guide

Theoretical background

Original model for calculation of permanent deformations, Tseng and Lytton

$$\delta_a(N) = \beta_{GB}\left(\frac{\varepsilon_0}{\varepsilon_r}\right)e^{-\left(\frac{\rho}{N}\right)^{\beta}}\varepsilon_v h$$

Problems with some strange results made that the choice in Design Guide is a more empirical and statistical model

Modeling permanent deformation – Unbound material

modified models for $\varepsilon_0/\varepsilon_r$, β and ρ developed in NCHRP Project 1-37A for granular and subgrade materials

Granular

$$\log\left(\frac{\varepsilon_0}{\varepsilon_r}\right) = 0.80978 - 0.06626 \cdot W_c - 0.003077 \cdot \sigma_\theta + 0.000003 \cdot E_r$$

$$\log(\beta) = -0.9190 + 0.03105 \cdot W_c + 0.001806 \cdot \sigma_\theta - 0.0000015 \cdot E_r$$

$$\log(\rho) = -1.78667 + 1.45062 \cdot W_c + 0.0003784 \cdot \sigma_\theta^{\,2} - 0.002074 \cdot W_c^{\,2} \sigma_\theta - 0.0000105 \cdot E_r$$

Subgrade

$$\log\left(\frac{\varepsilon_0}{\varepsilon_r}\right) = -1.69867 + 0.09121 \cdot W_c - 0.11921 \cdot \sigma_d + 0.91219 \cdot \log E_r$$

$$\log(\beta) = -0.9730 - 0.0000278 \cdot W_c^{\,2} \sigma_d + 0.017165 \cdot \sigma_d - 0.0000338 \cdot W_c^{\,2} \sigma_\theta$$

$$\log(\rho) = 11.009 + 0.00068 \cdot W_c^{\,2} \sigma_d - 0.40260 \cdot \sigma_d + 0.0000545 \cdot W_c^{\,2} \sigma_\theta$$

MATERIAL MODELS
Rutting in bituminous bound materials

Design Guide

Modeling permanent deformation

Asphalt layer – Design Guide

$$\frac{\varepsilon_p}{\varepsilon_r} = a_1 \cdot N^{a_2} \cdot T^{a_3}$$

Choose a_1, a_2 and a_3 with help of results from triaxial test

ε_p – Accumulated plastic strain at N repetitions of load
ε_r – Resilient strain of the asphalt material
N – Number of load repetitions
T – Temperature (10°C)
a_i – Non-linear regression coefficients (from NCHRP 1-37A)

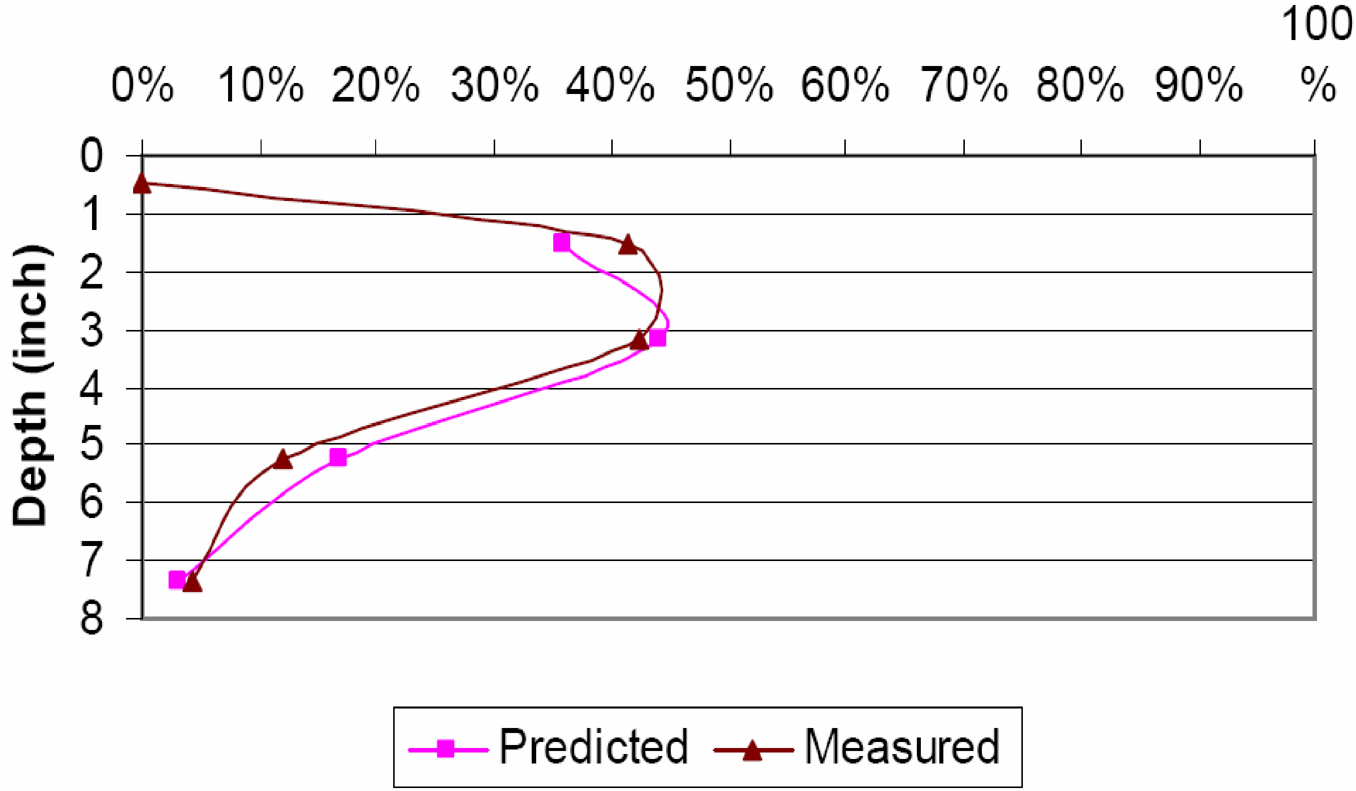
MEPDG – Calibration to Mnroad

$$C_1 = -0.1039 * h_{ac}^2 + 2.4868 * h_{ac} - 17.342$$

$$k_1 = (C_1 + C_2 * depth) * 0.328196^{depth}$$

$$C_2 = 0.0172 * h_{ac}^2 - 1.7331 * h_{ac} + 27.428$$

Average % AC Rutting with Depth



Test metods!

- **It is important that the test methods is syncronized to the design models.**
- **It must be possible to use results from the test methods as input data in the design models.**

We can predict future performance today

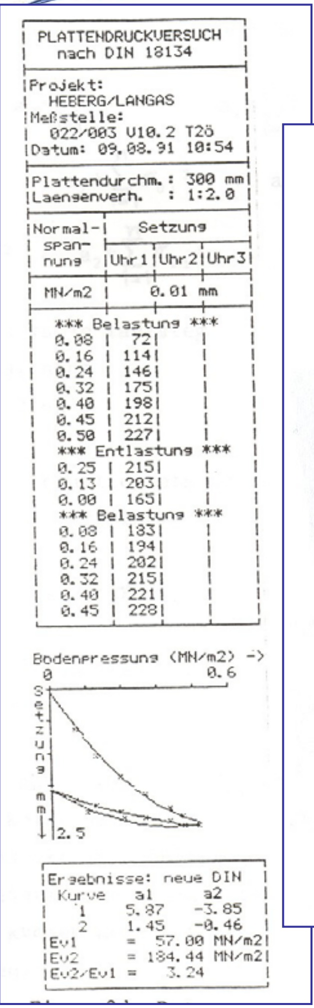
- **Rutting!**
- **Unevenness: MMOPP in Denmark**
- **Cracks? (Tensile strength and fatigue)**

Why don't we do that?

Calculations in practice

- Possible to use actual knowledge and technique: Complete with new Excel programs
- Use the technique of today, and improve it
- Help for understanding – education
- Help for implementation of new technique

Test: Plate loading


PLATTENDRUCKVERSUCH
nach DIN 18134

Projekt:
HEBERG/LANGAS
Meßstelle:
022/003 V10.2 T2ö
Datum: 09.08.91 10:54

Plattendurchm. : 300 mm
Laengenverh. : 1:2.0

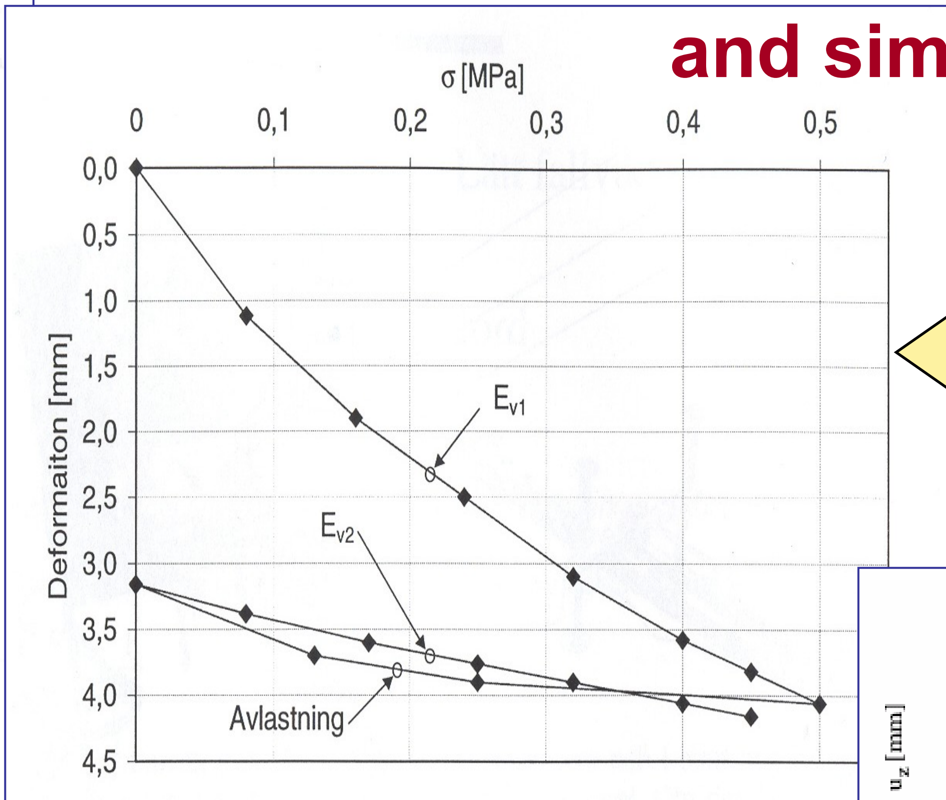
Normal-spannung	Setzung		
	Uhr1	Uhr2	Uhr3
MN/m2	0.01 mm		
*** Belastung ***			
0.08	72		
0.16	114		
0.24	146		
0.32	175		
0.40	198		
0.45	212		
0.50	227		
*** Entlastung ***			
0.25	215		
0.13	203		
0.00	165		
*** Belastung ***			
0.08	183		
0.16	194		
0.24	202		
0.32	215		
0.40	221		
0.45	228		

Ergebnisse: neue DIN

Kurve	a1	a2
1	5.87	-3.85
2	1.45	-0.46

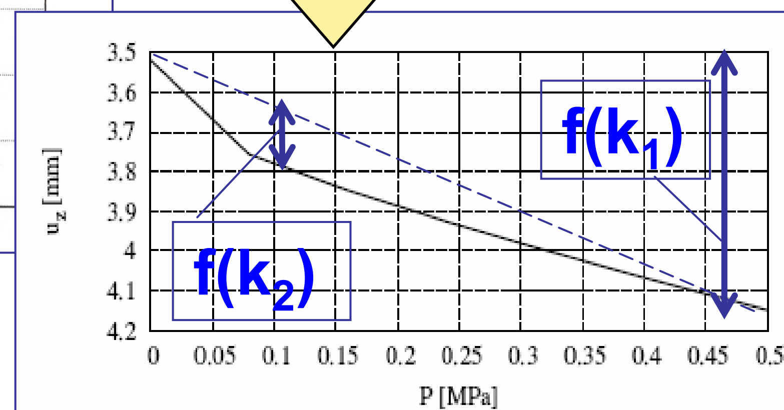
Ev1 = 57.00 MN/m2
Ev2 = 184.44 MN/m2
Ev2/Ev1 = 3.24

Result from Plate loading and simulation in VagFEM



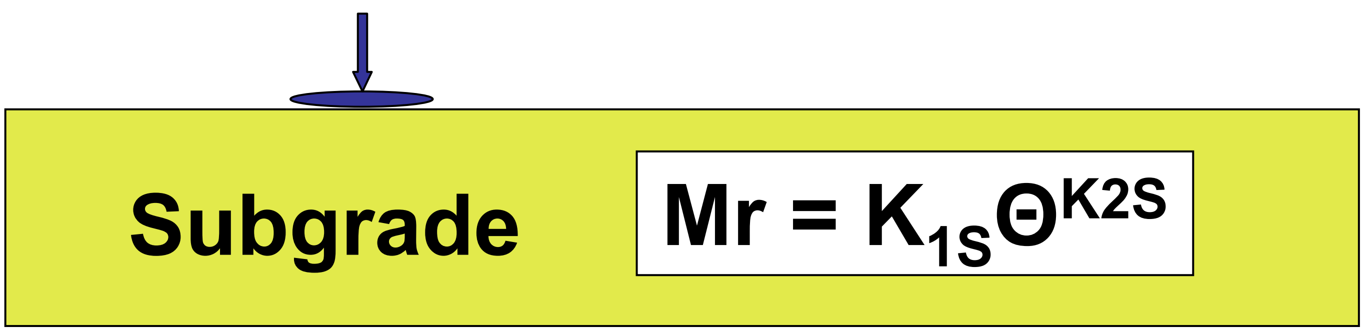
Resilient Module

$$Mr = k_1 \Theta^{k2}$$

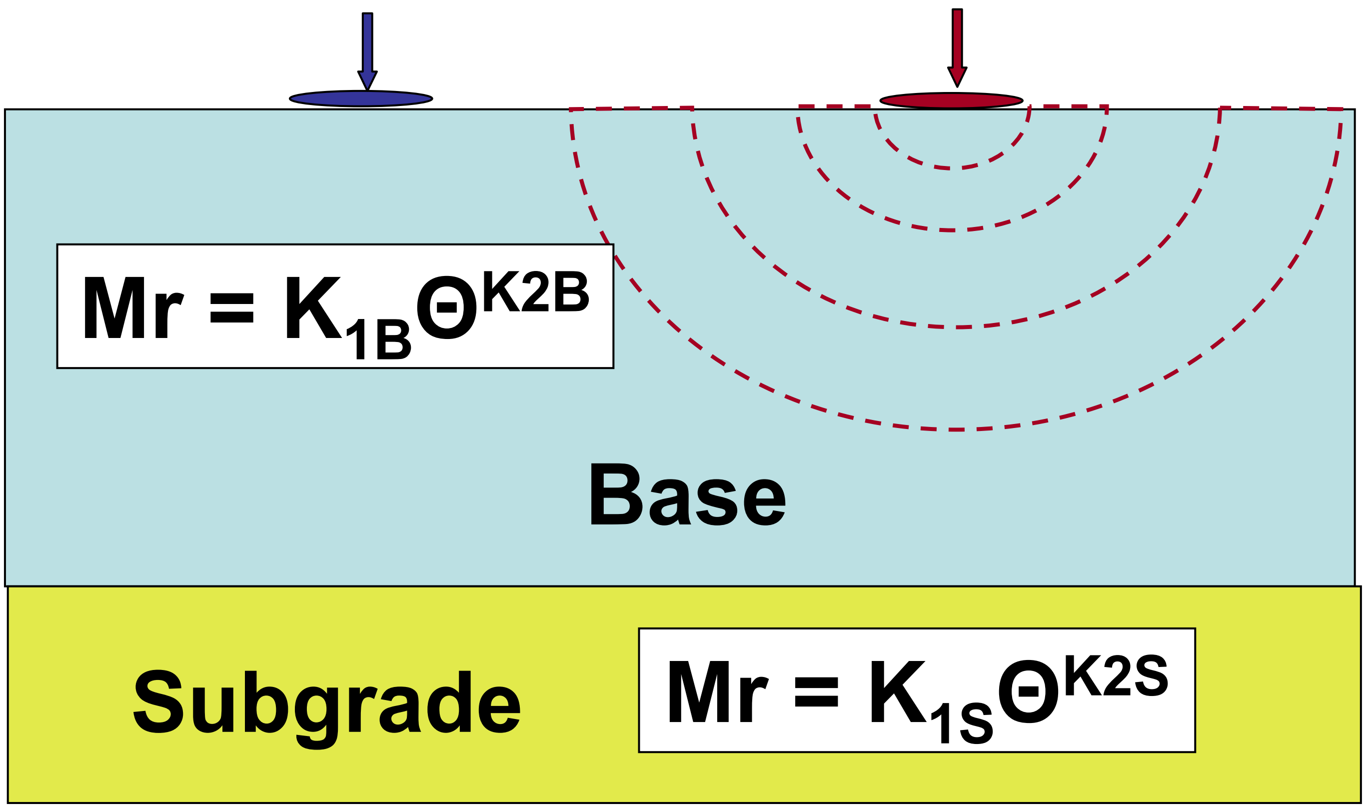


Measured Mr_1 in subgrade is used as input data in calculation of Mr_2 in base material

Calculate the resilient modulus in the subgrade material?



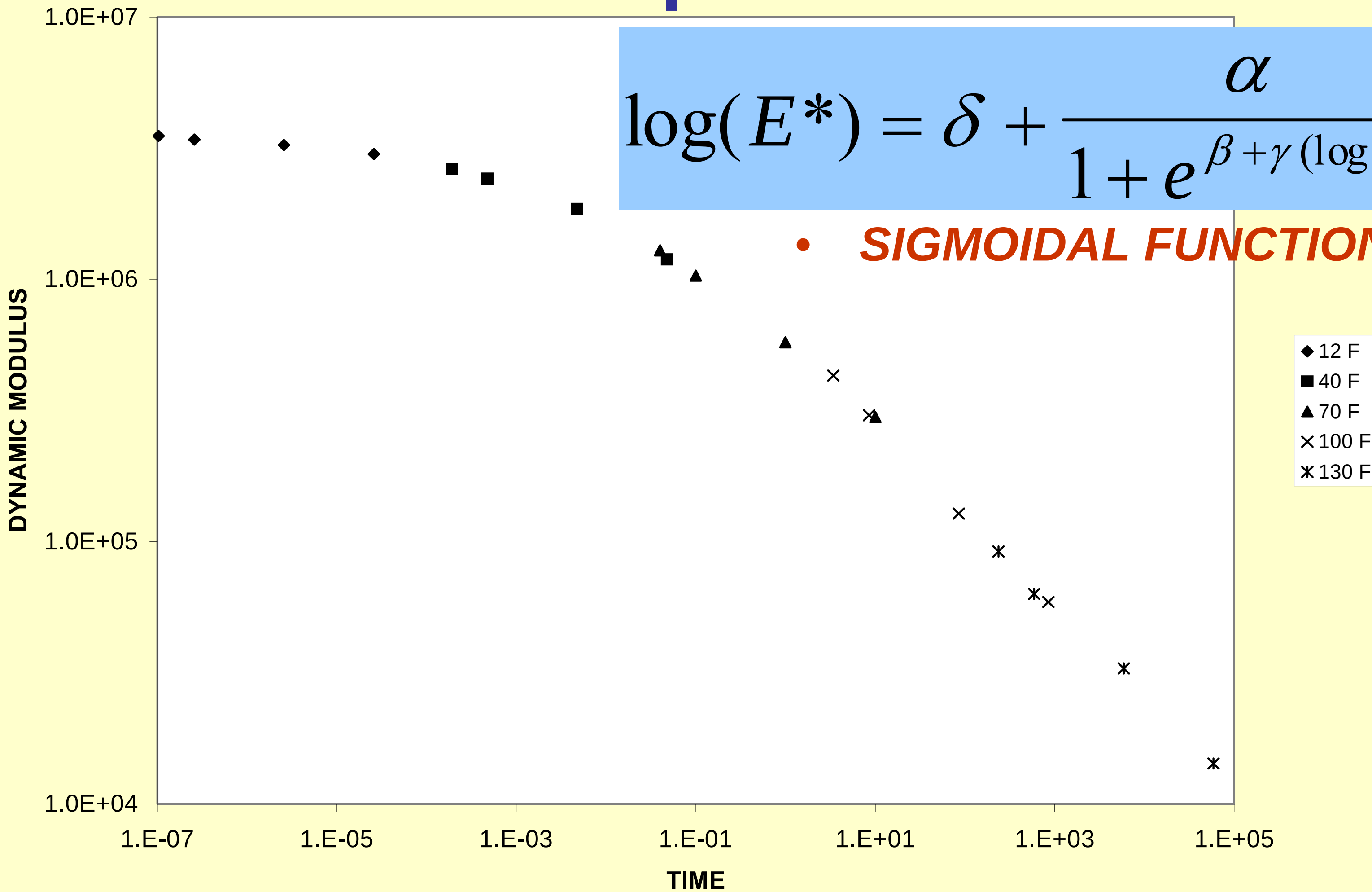
Calculate the resilient modulus in the base material?



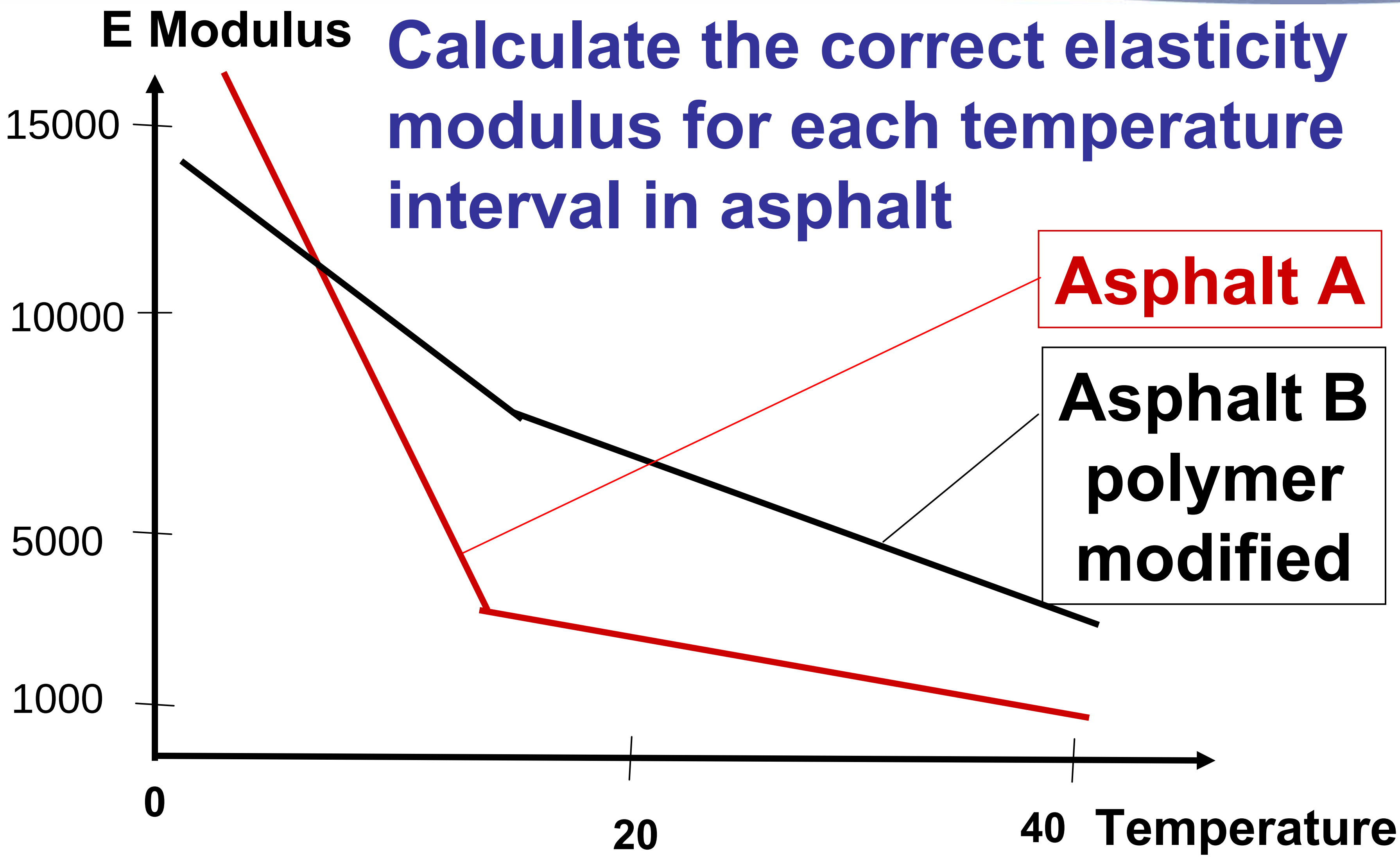
Calculate the Dynamic Modulus Master Curve in Asphalt

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log t_r)}}$$

- *SIGMOIDAL FUNCTION*

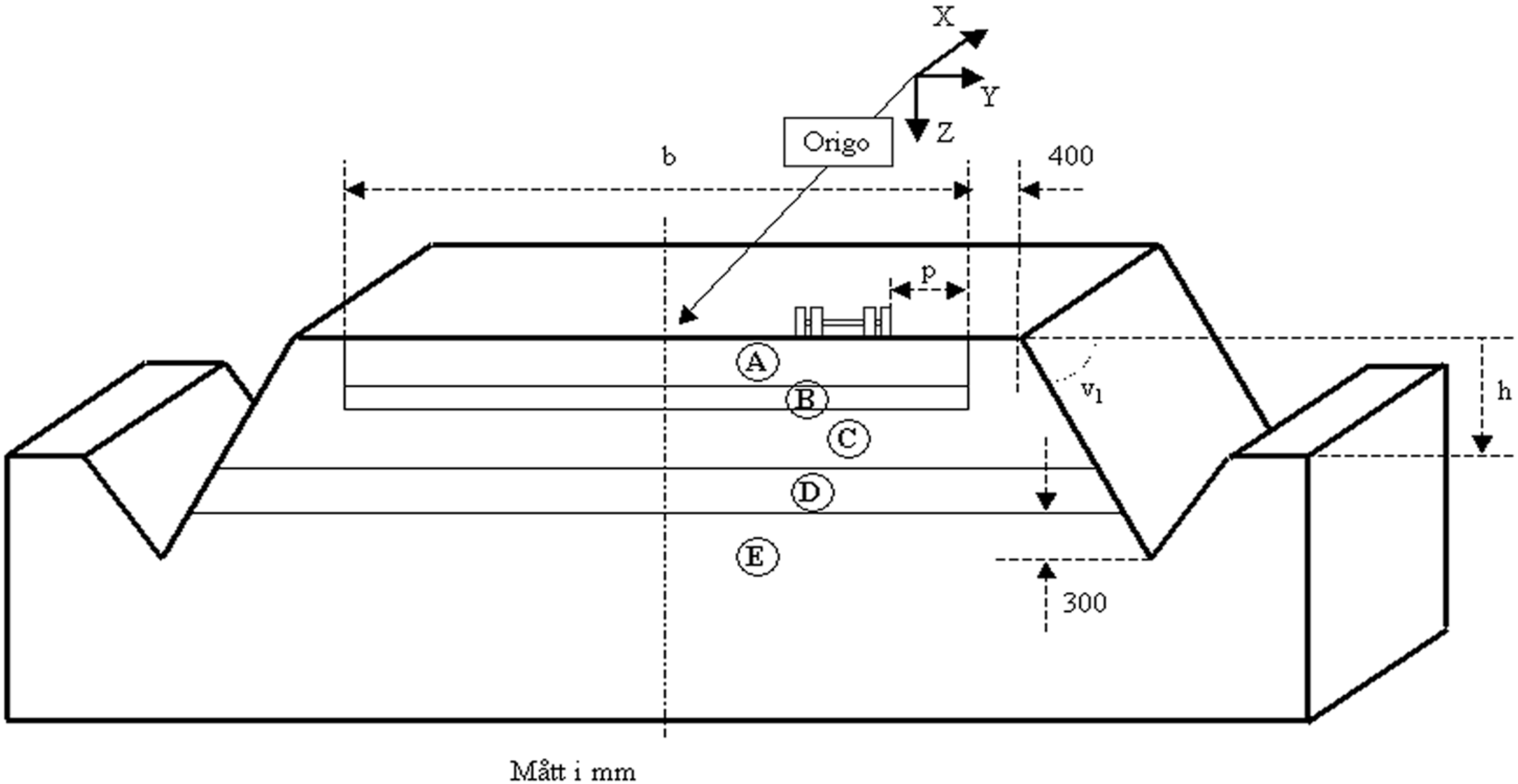


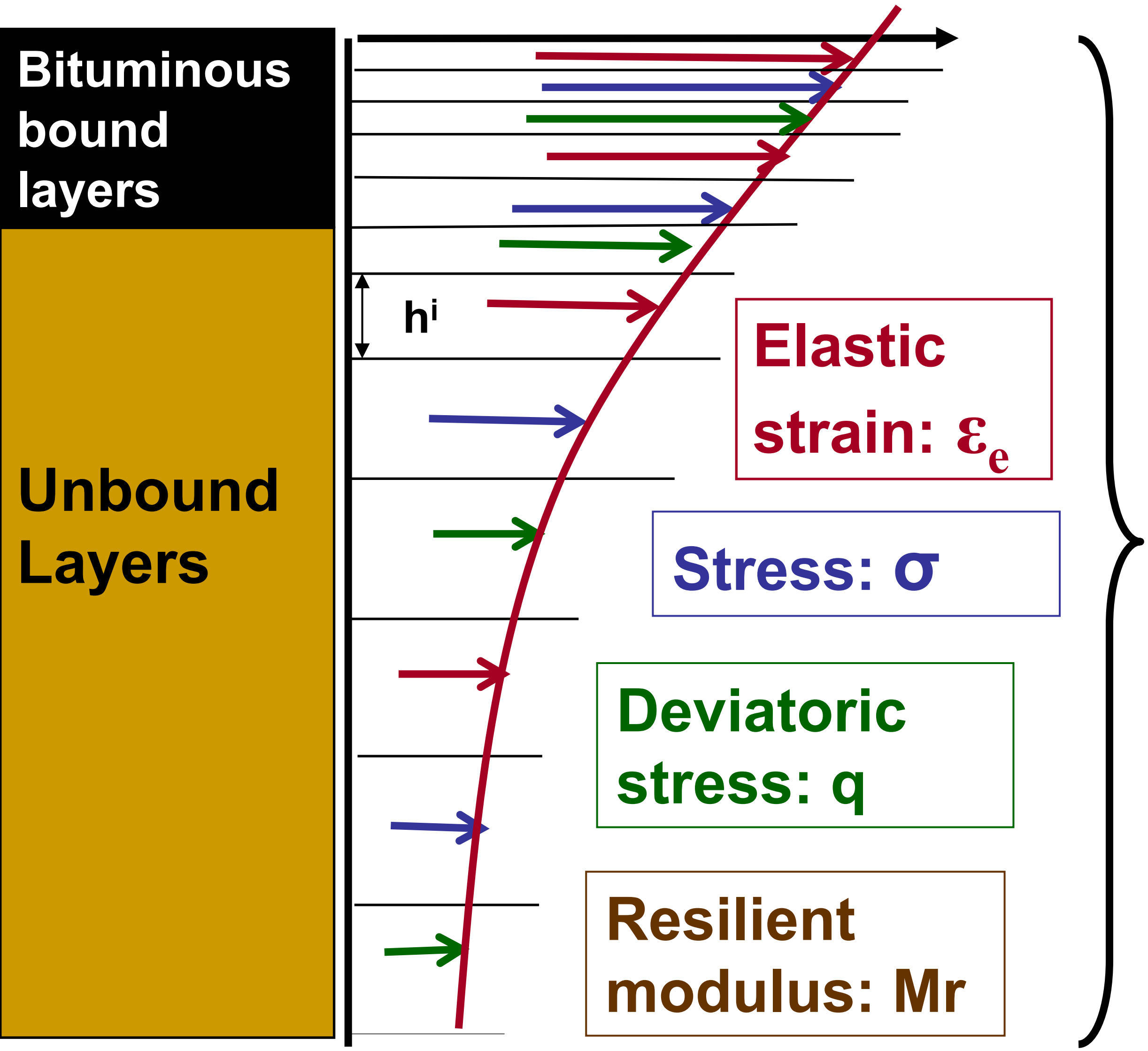
Calculate the correct elasticity modulus for each temperature interval in asphalt



VagFEM

Calculate stress, strain and resilient modulus with VagFEM

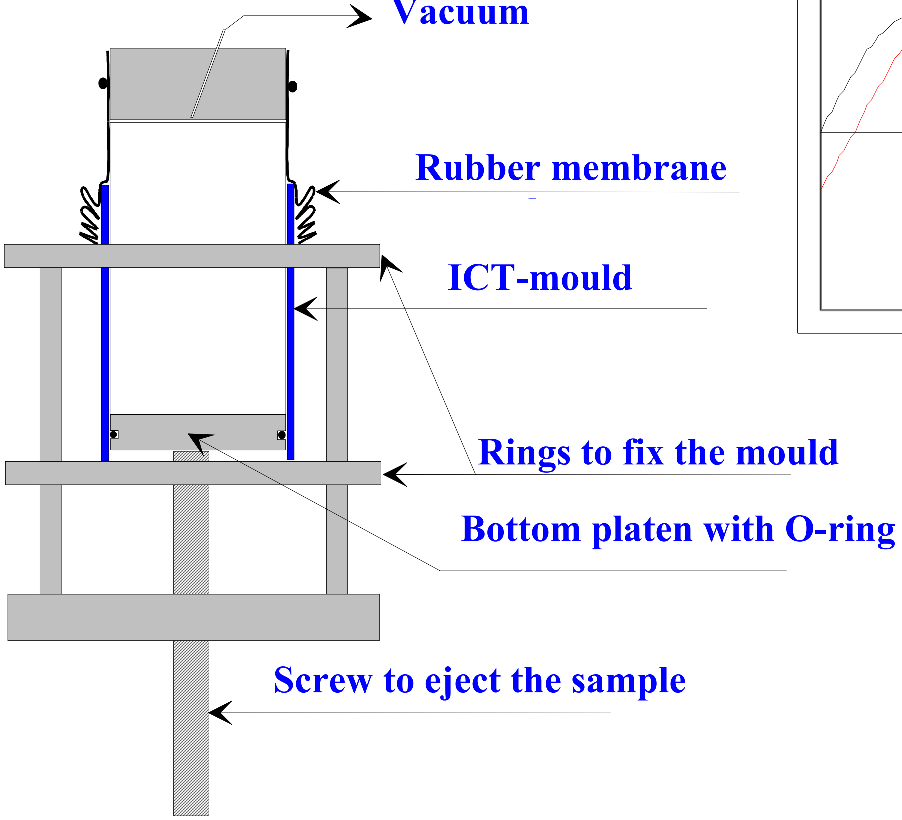


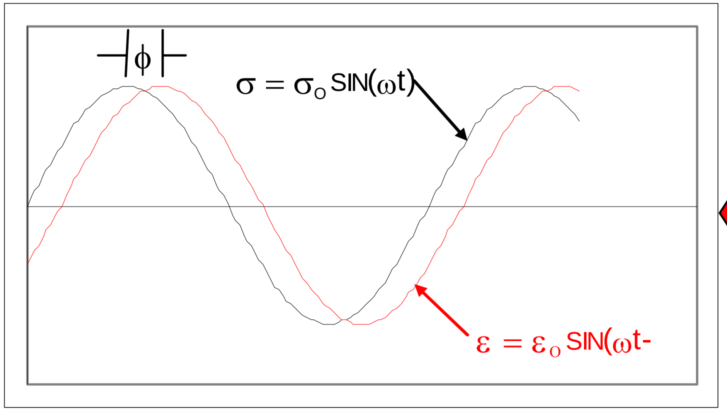


Input data for calculation of permanent deformations

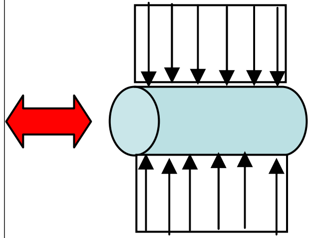
Elastic response, resilient modulus, as digital output data from VagFEM

Calculation of parameters from triaxial tests



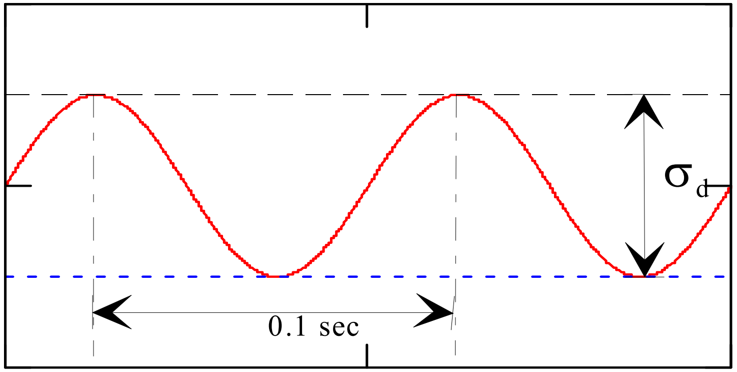


Site tests



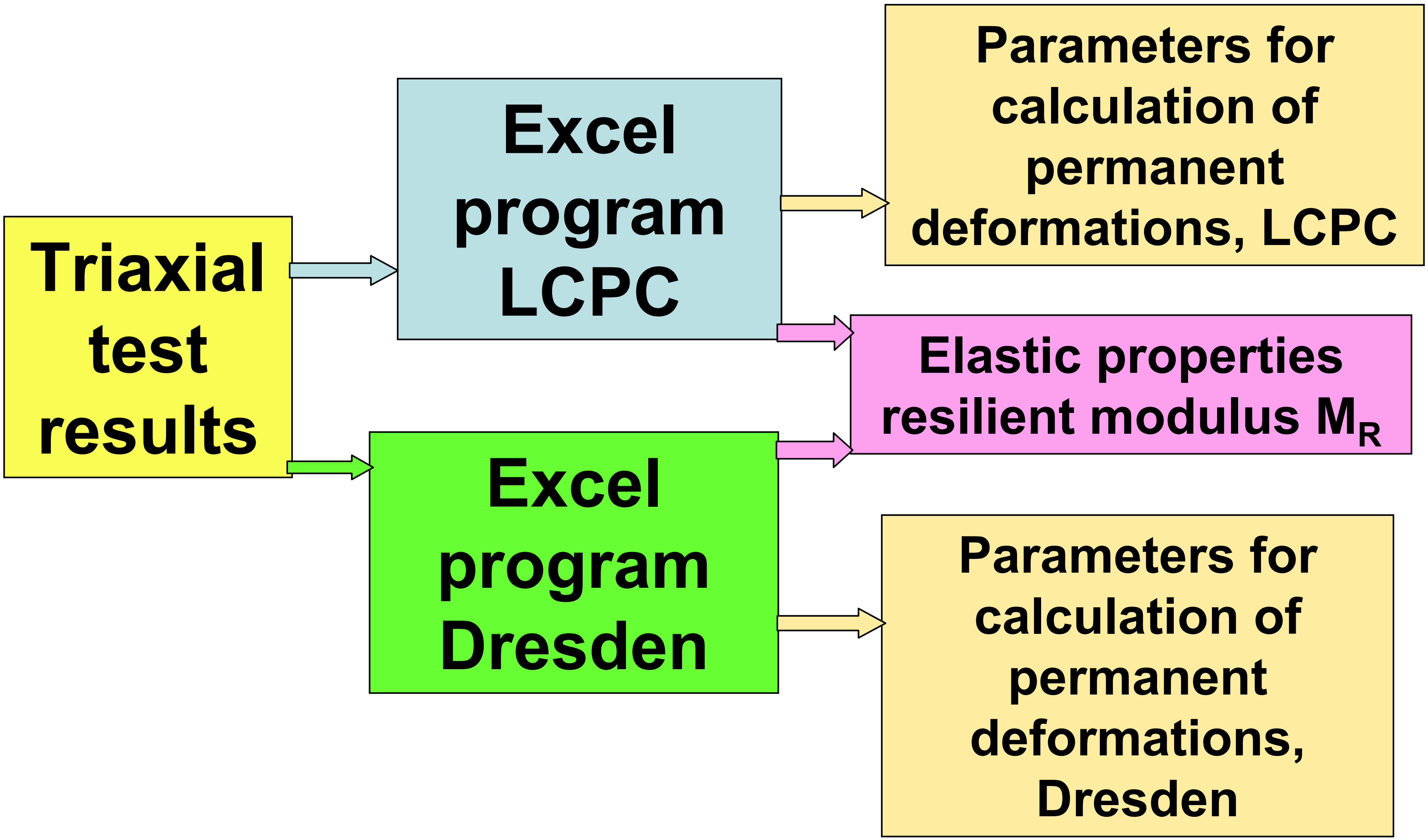
on drilled out cores

Asphalt material



Unbound material

Evaluation of triaxial tests



Calculate future rutting with VagFEM

Parameters for calculation of permanent deformations, LCPC

Parameters for calculation of permanent deformations, Dresden

Parameters for calculation of permanent deformations, Design guide, unbound mtrl

Parameters for calculation of permanent deformations, Design guide, asphalt mtrl

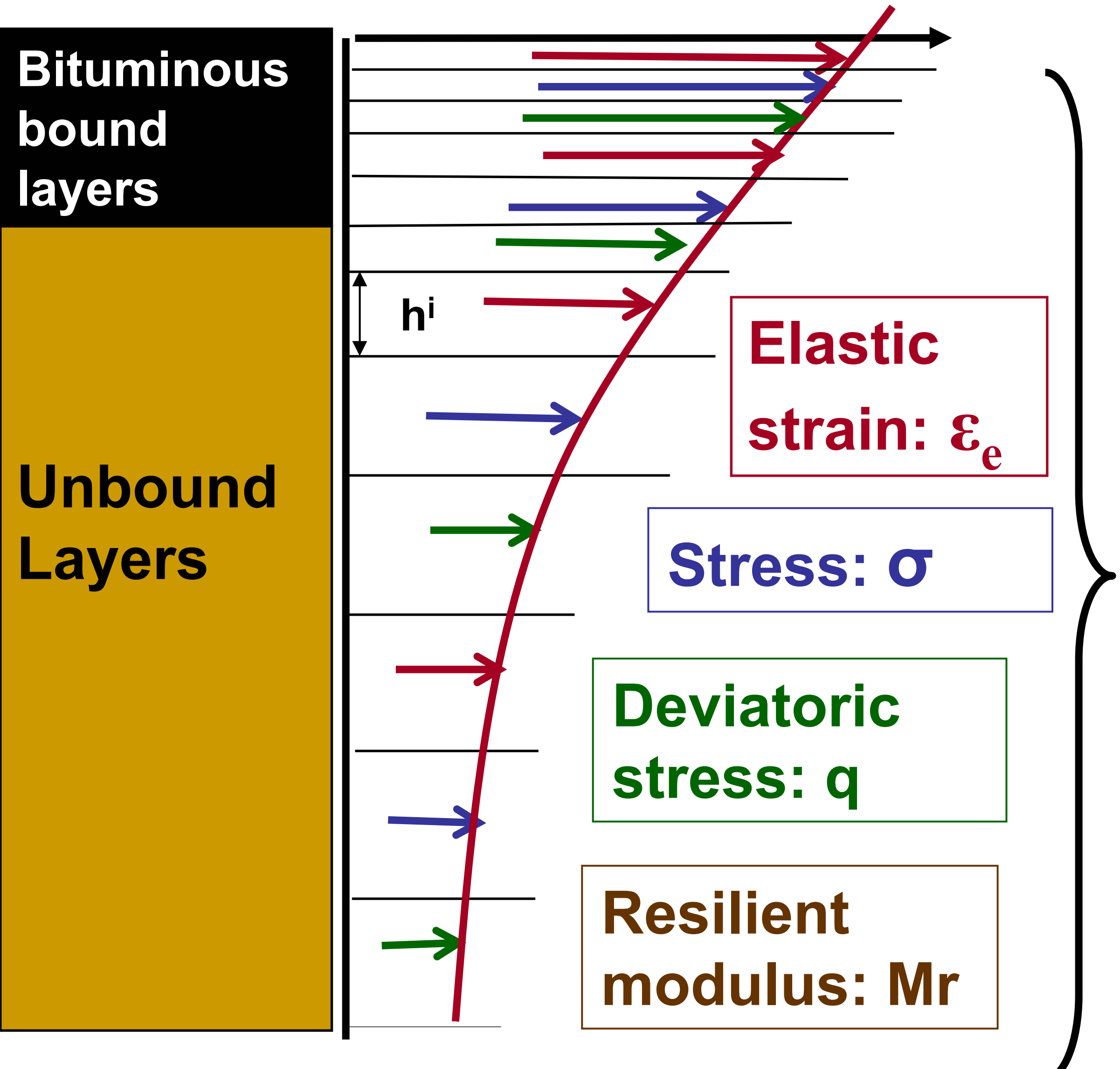
Elastic response, resilient modulus, as digital output data from VagFEM

Excel programs for calculation of future rutting

$$\varepsilon_1^p(N) = \varepsilon_{10}^p \cdot \left[1 - \left(\frac{N}{N_0}\right)^{-B}\right] \cdot \left[\frac{L_{max}}{p_a}\right]^n \cdot \frac{1}{(m + \frac{s}{p_{max}} - \frac{q_{max}}{p_{max}})}$$

$$\frac{\varepsilon_p}{\varepsilon_r} = a_1 \cdot N^{a_2} \cdot T^{a_3}$$

$$\varepsilon_p(N) = A \cdot \left(\frac{N}{1000}\right)^B + C\left(e^{D\frac{N}{1000}} - 1\right)$$



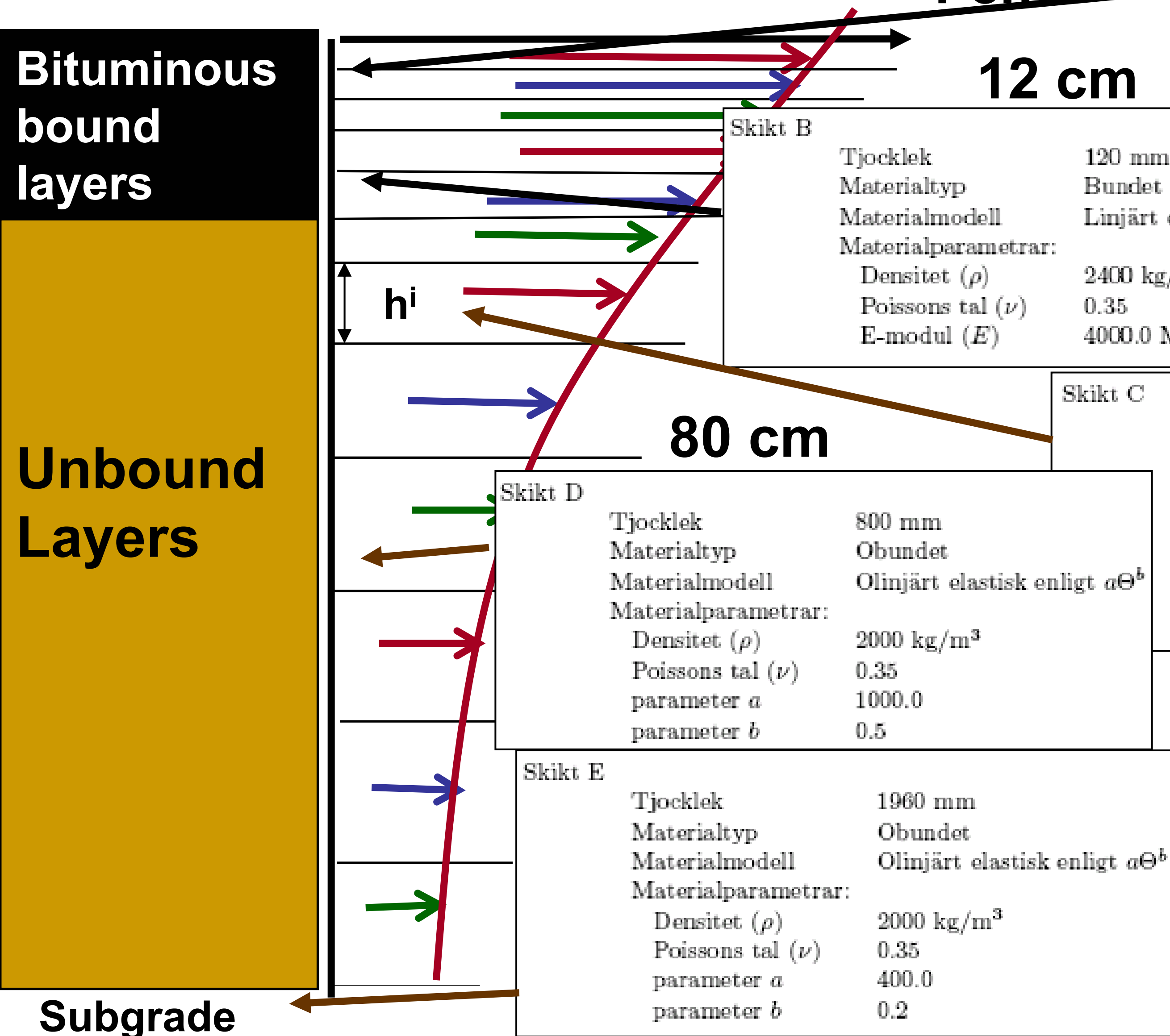
$$PD = \sum_{i=1}^{nsublayers} \varepsilon_p^i \cdot h^i$$

PD – Permanent Deformation

Nsublayers – Number of sublayers

ε_p^i – Total plastic strain in sublayer i

h^i – Thickness of sublayer i



Skikt A

Tjocklek	40 mm
Materialtyp	Bundet
Materialmodell	Linjärt elastisk
Materialparametrar:	
Densitet (ρ)	2400 kg/m^3
Poissons tal (ν)	0.35
E-modul (E)	3000.0 MPa

Skikt B

Tjocklek	120 mm
Materialtyp	Bundet
Materialmodell	Linjärt elastisk
Materialparametrar:	
Densitet (ρ)	2400 kg/m^3
Poissons tal (ν)	0.35
E-modul (E)	4000.0 MPa

Skikt C

Tjocklek	80 mm
Materialtyp	Obundet
Materialmodell	Olinjärt elastisk enligt $a\Theta^b$
Materialparametrar:	
Densitet (ρ)	2000 kg/m^3
Poissons tal (ν)	0.35
parameter a	1200.0
parameter b	0.4

Skikt D

Tjocklek	800 mm
Materialtyp	Obundet
Materialmodell	Olinjärt elastisk enligt $a\Theta^b$
Materialparametrar:	
Densitet (ρ)	2000 kg/m^3
Poissons tal (ν)	0.35
parameter a	1000.0
parameter b	0.5

Skikt E

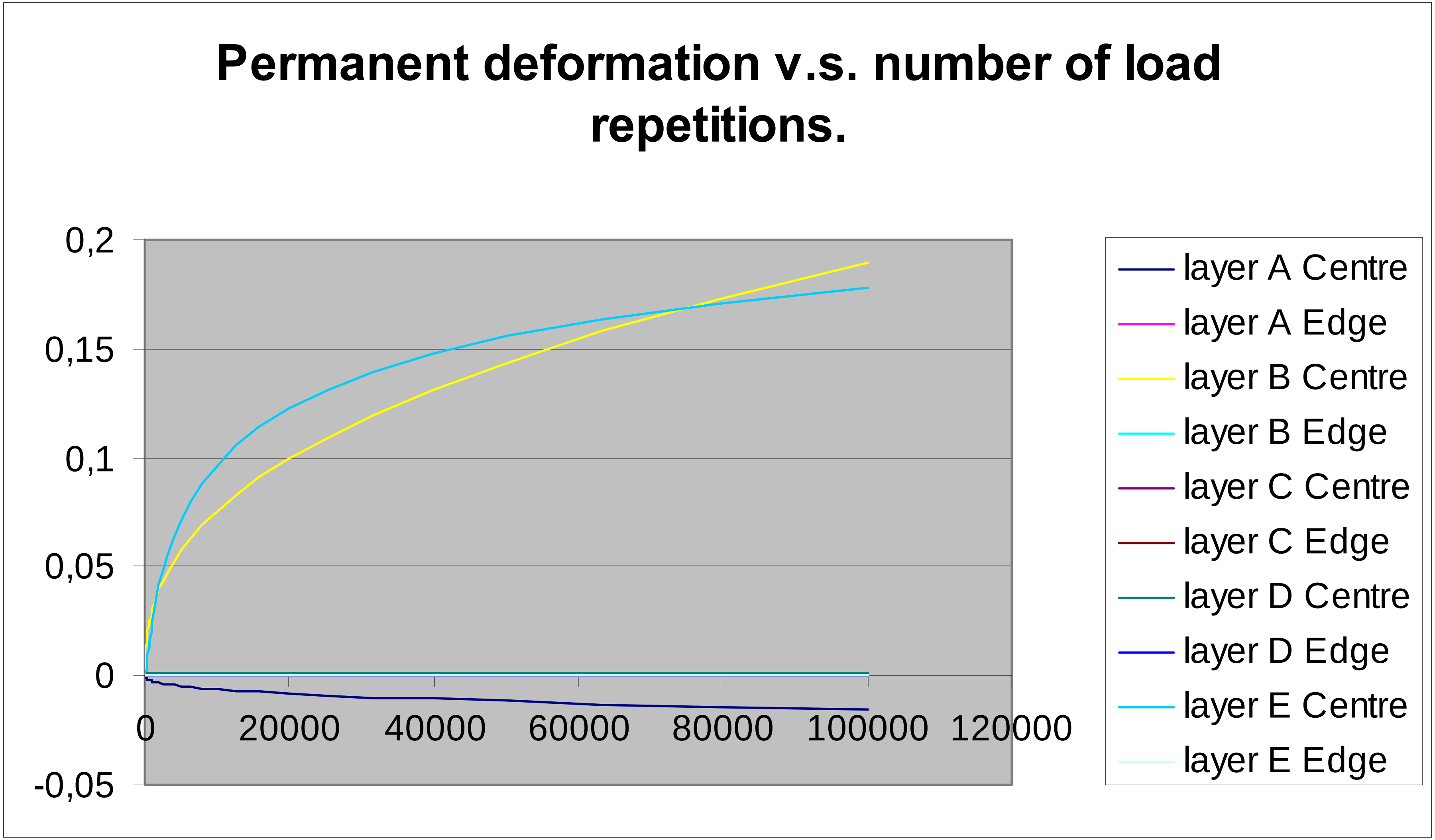
Tjocklek	1960 mm
Materialtyp	Obundet
Materialmodell	Olinjärt elastisk enligt $a\Theta^b$
Materialparametrar:	
Densitet (ρ)	2000 kg/m^3
Poissons tal (ν)	0.35
parameter a	400.0
parameter b	0.2

12 ton

Lastförutsättningar:

Axeltyp	Supersingle
Axelbredd (yttermått)	2500 mm
Axellast	12 ton
Däckstryck	1000 kPa
Placering (p)	3000 mm

Results from VagFEM



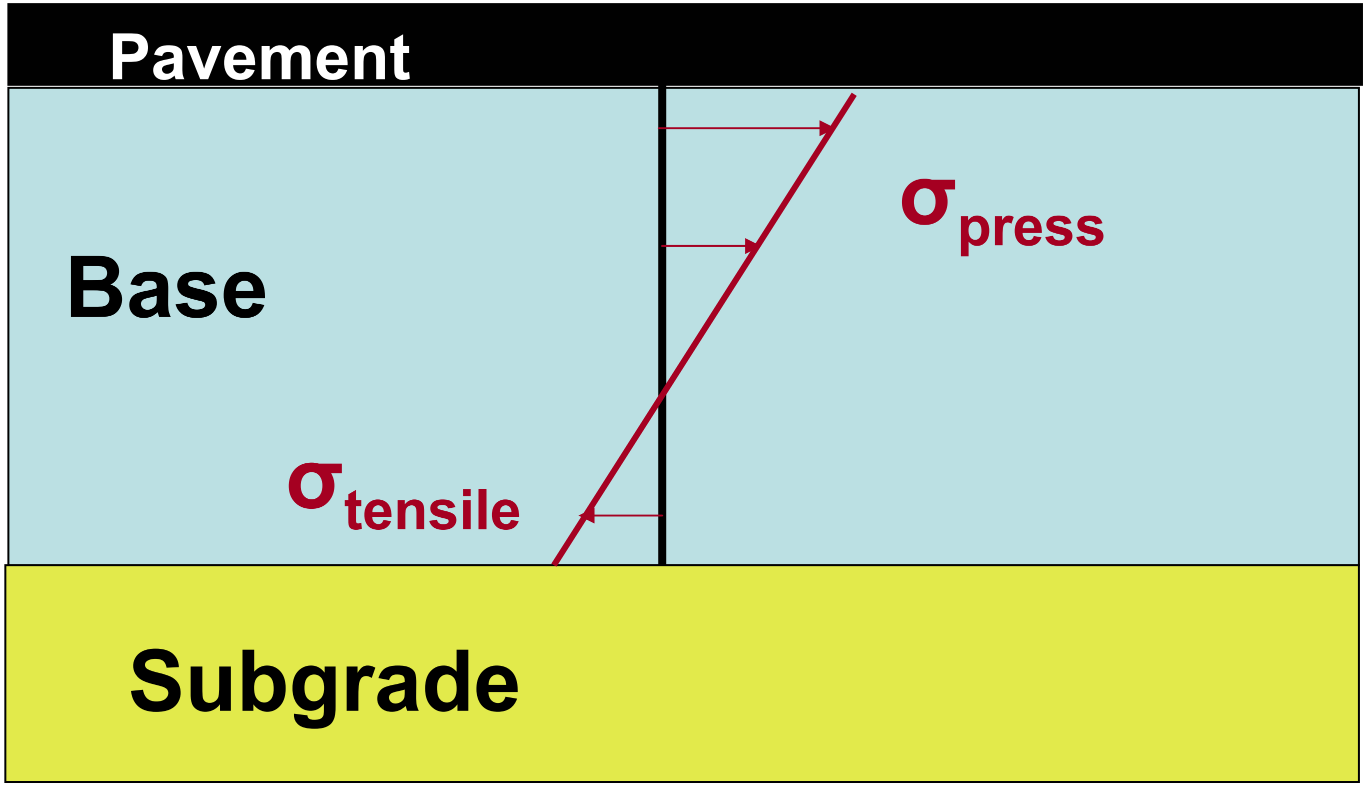
So, why do we not use this knowledge, test methods and models?

Future development

NordFoU

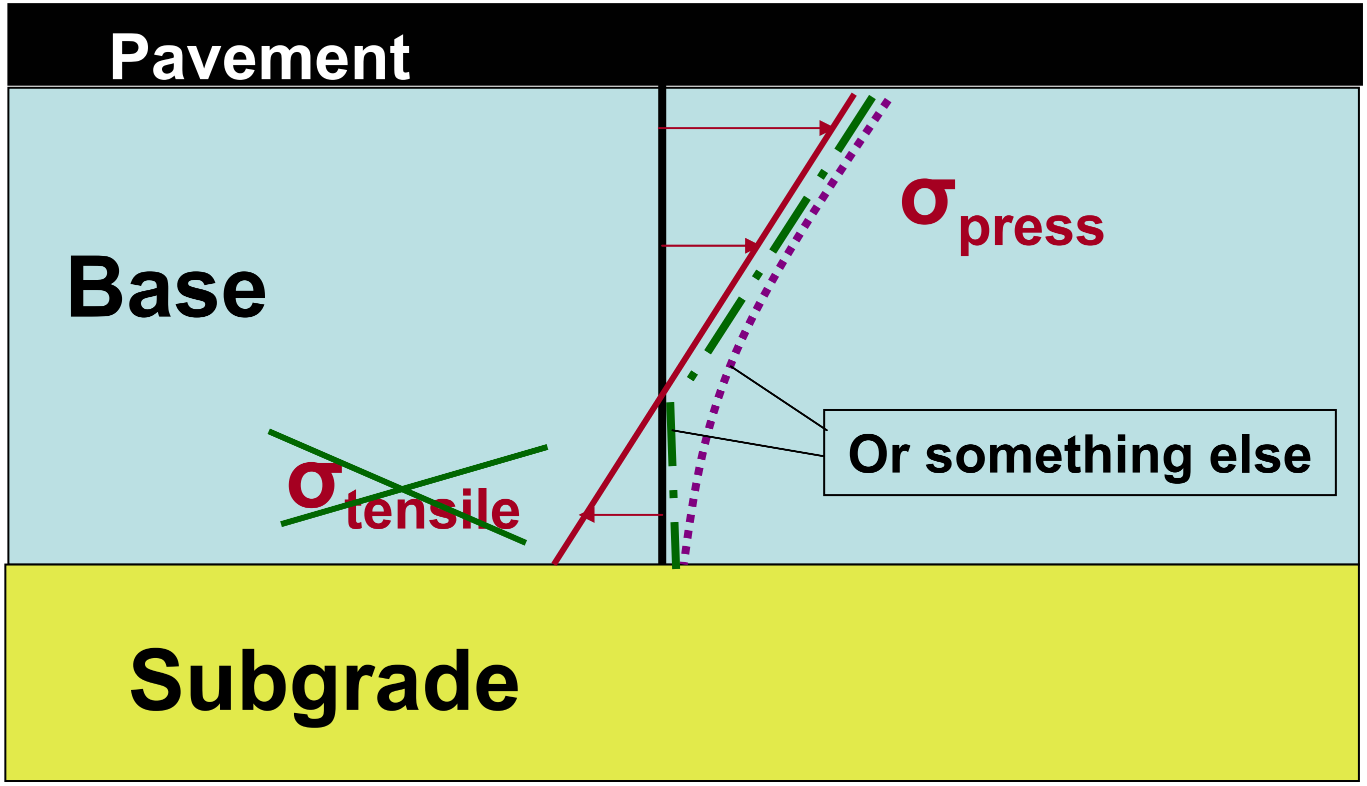
Sweden, Norway, Denmark and Island

Tensile stress in the bottom of unbound layers?

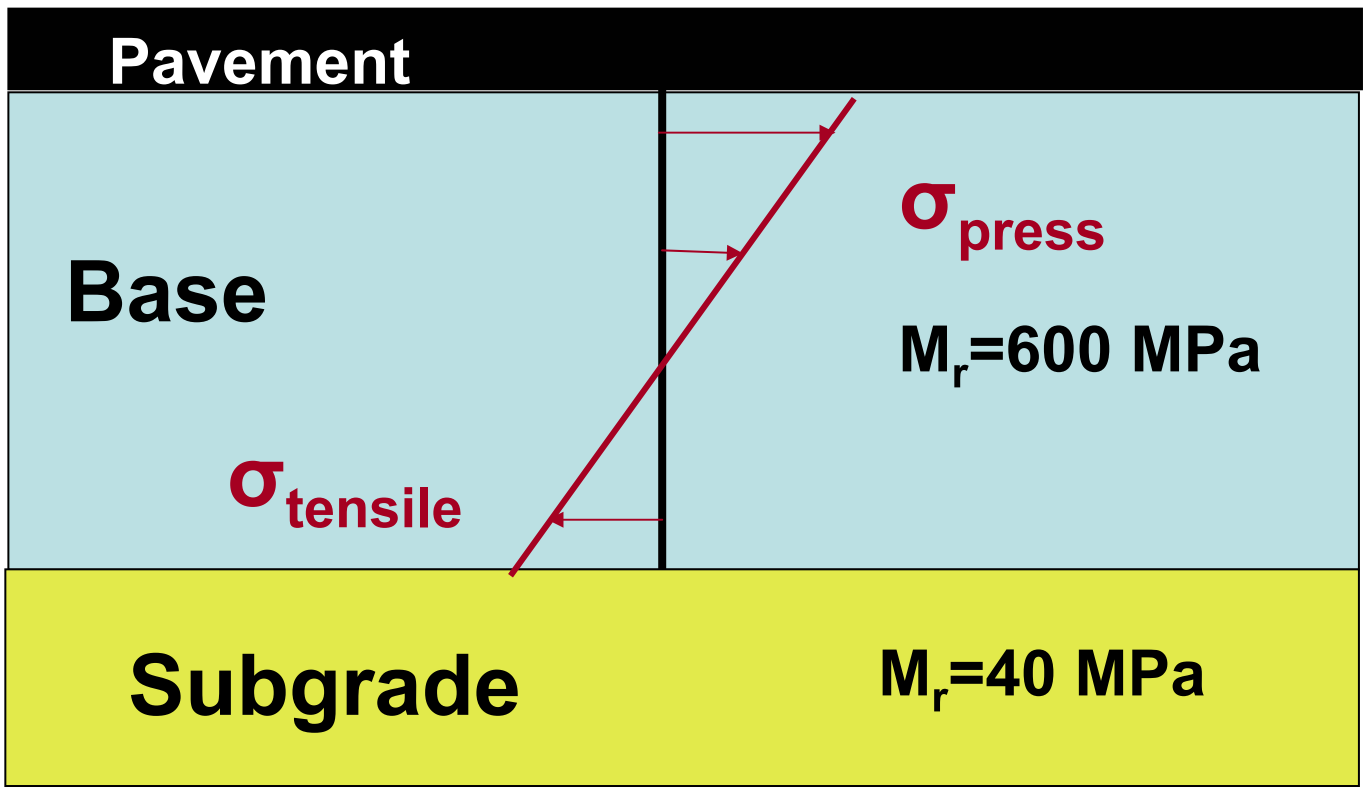


Tensile stress in the bottom of unbound layers?

Which is the real stress distibution?

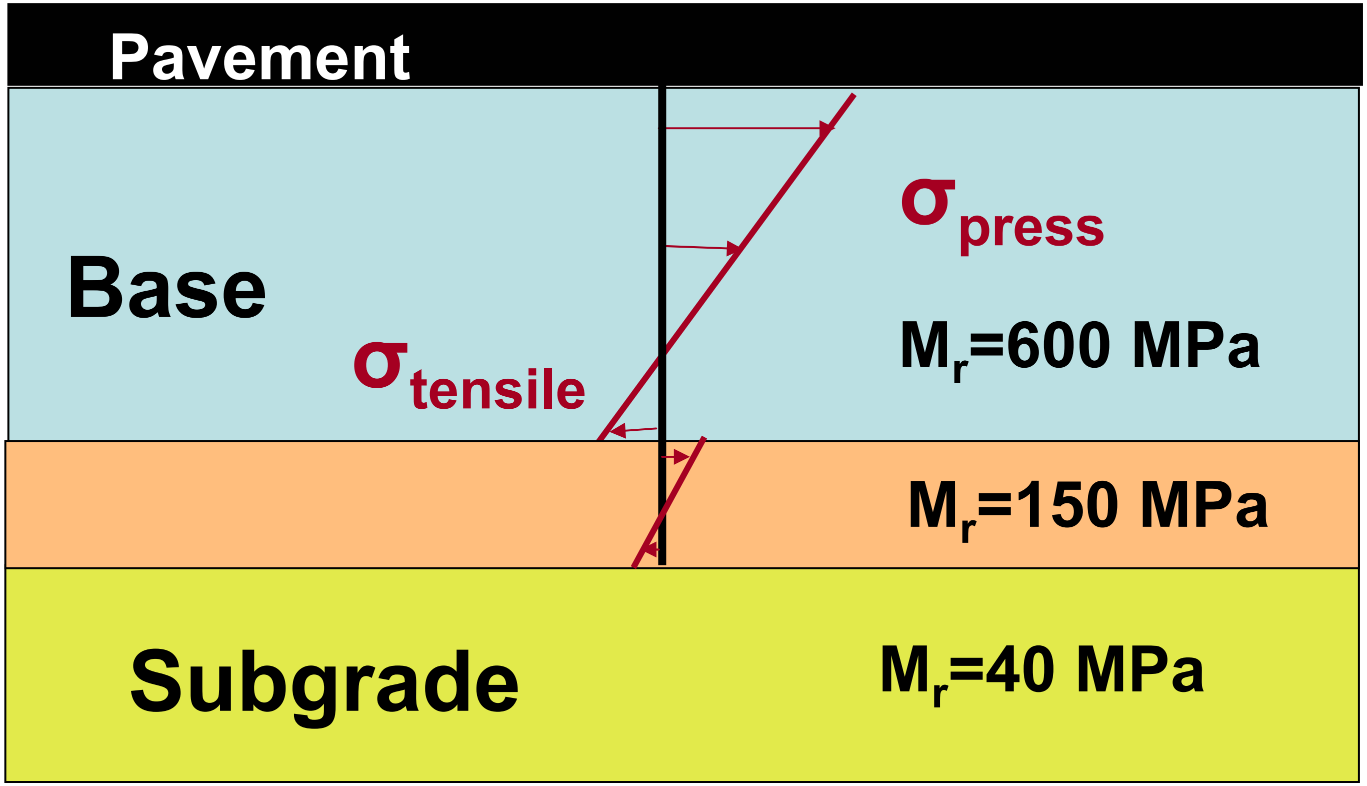


Unbound layers with large difference in resilient modulus?

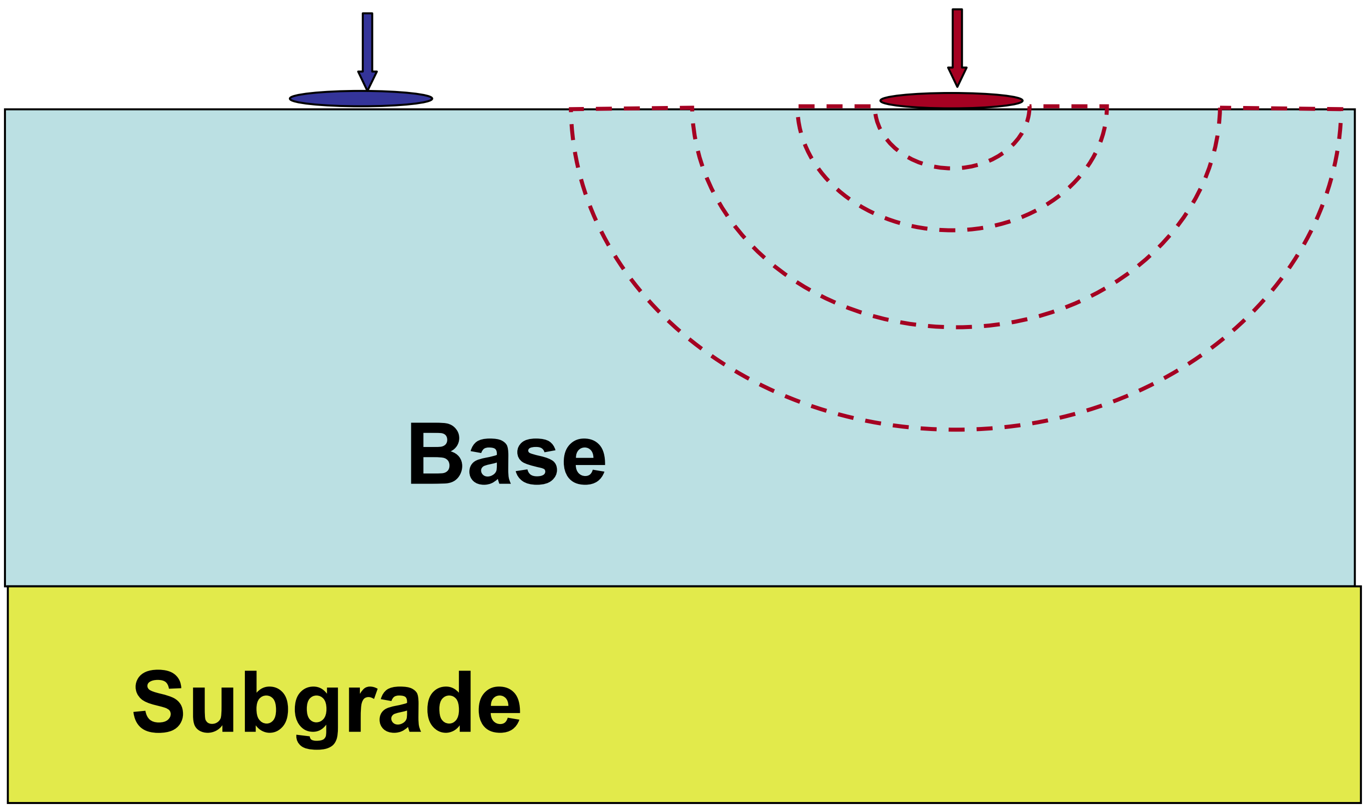


Unbound layers with large difference in resilient modulus?

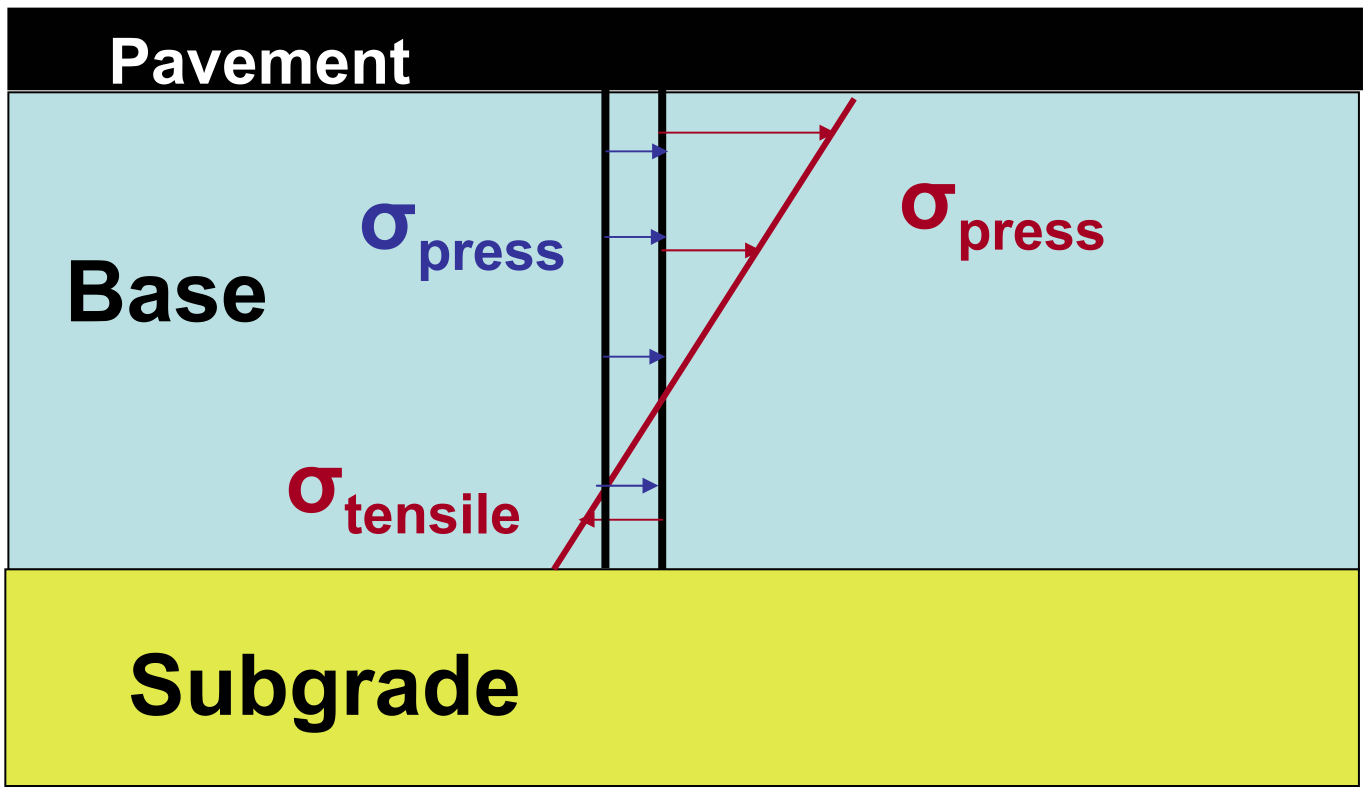
Old experience: Insert a layer with medium resilient modulus!



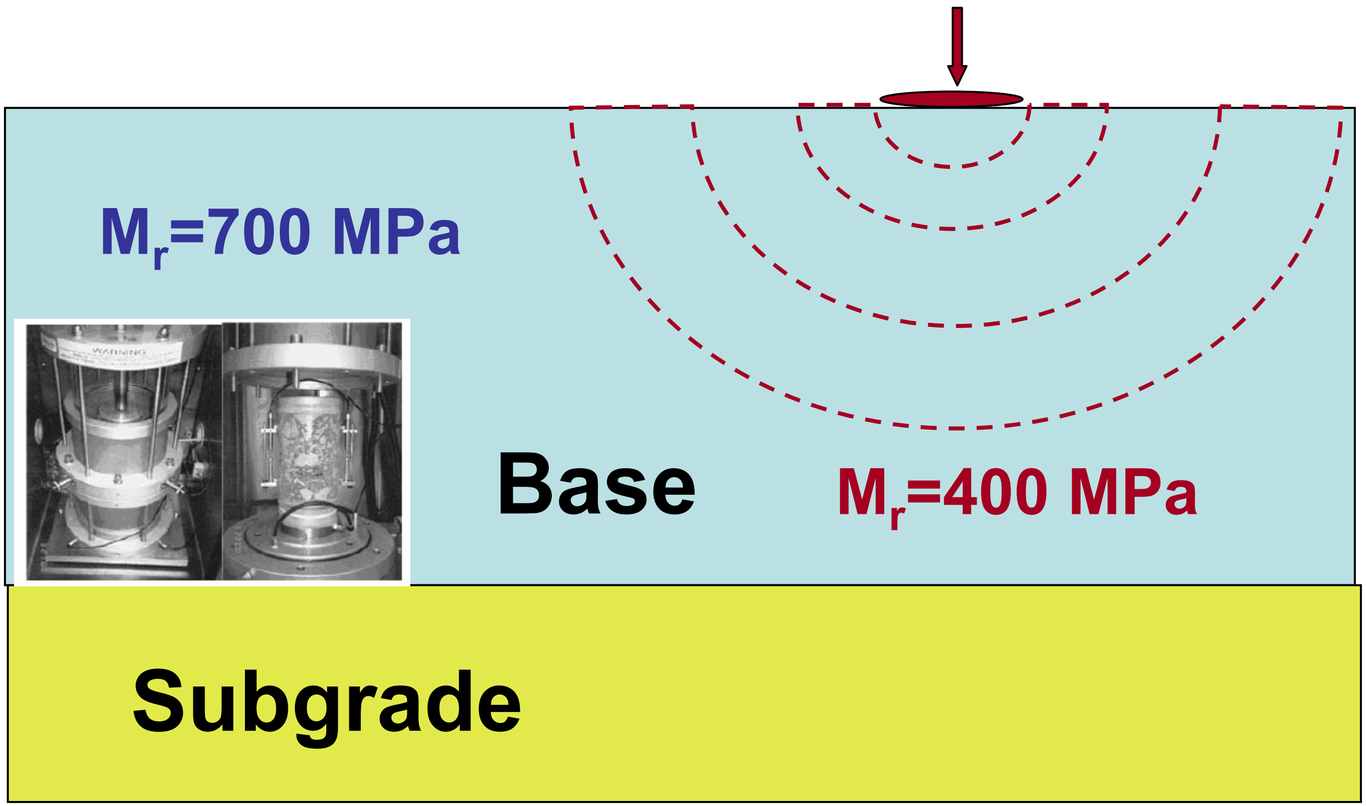
Difference/connection between static and dynamic resilient modulus?



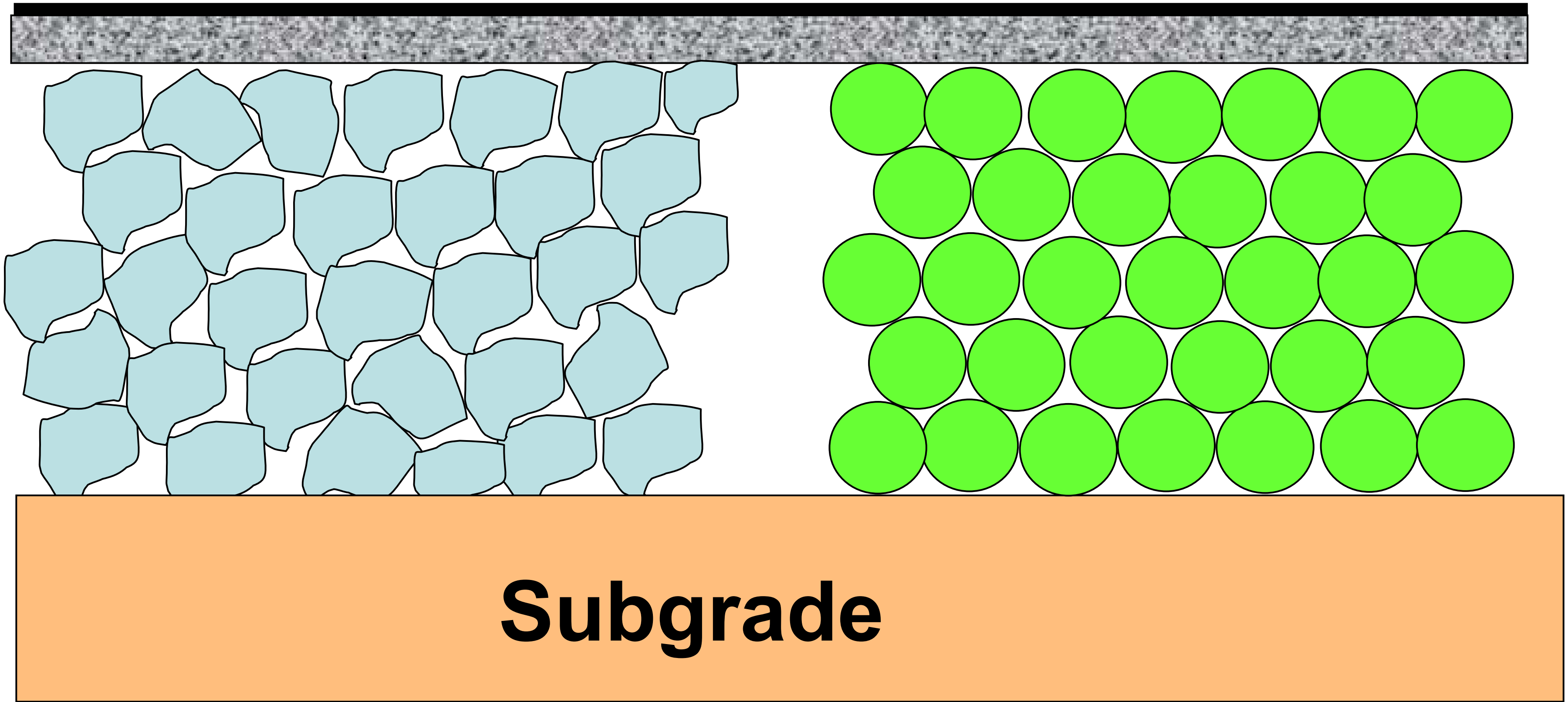
Horisontal stress depending on compaction and traffic ?



Difference/connection between resilient modulus measured with triaxial test and on site with plate loading etc.?



Material models different for crushed and uncrushed material?



Why does high plate loading values give small rutting?

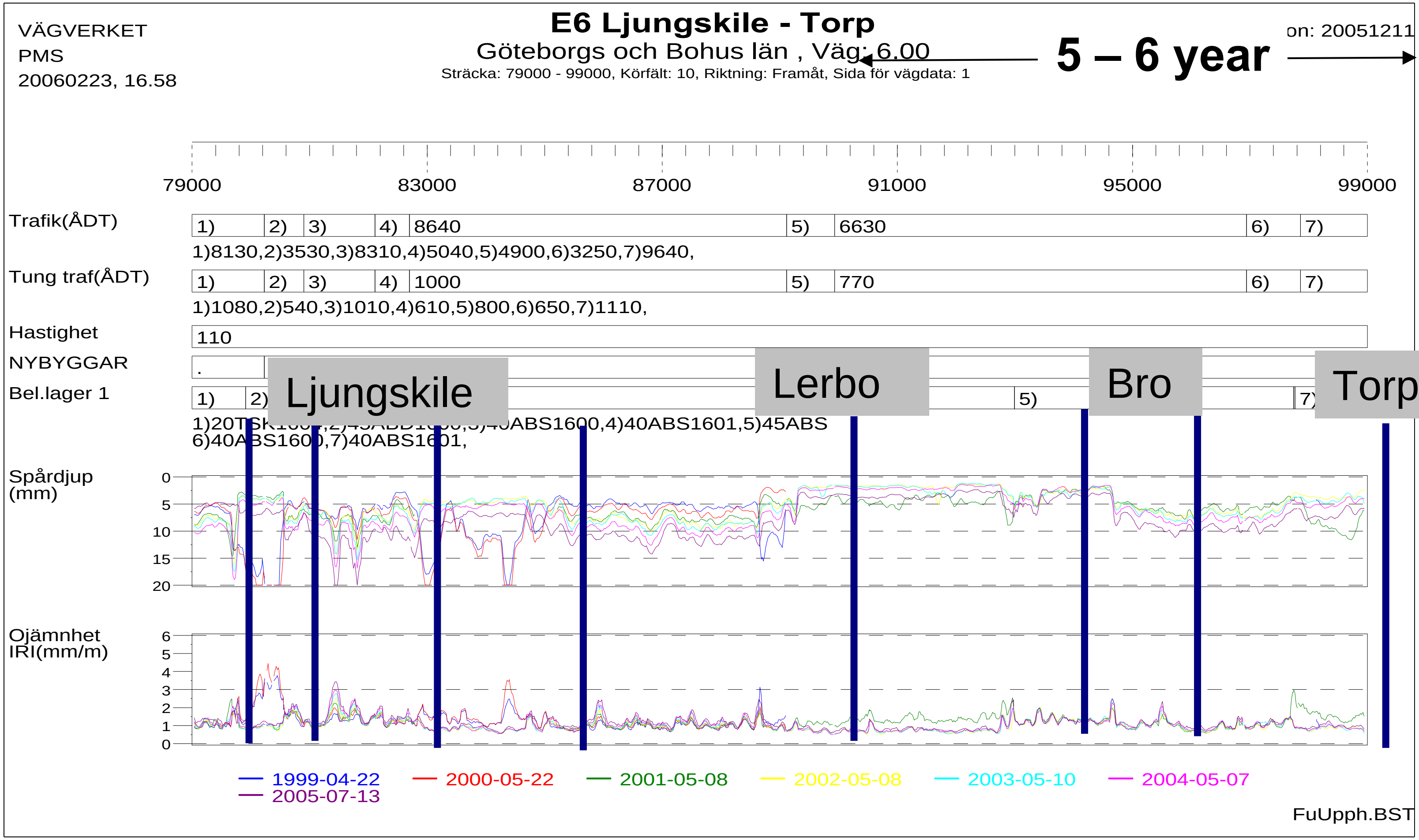
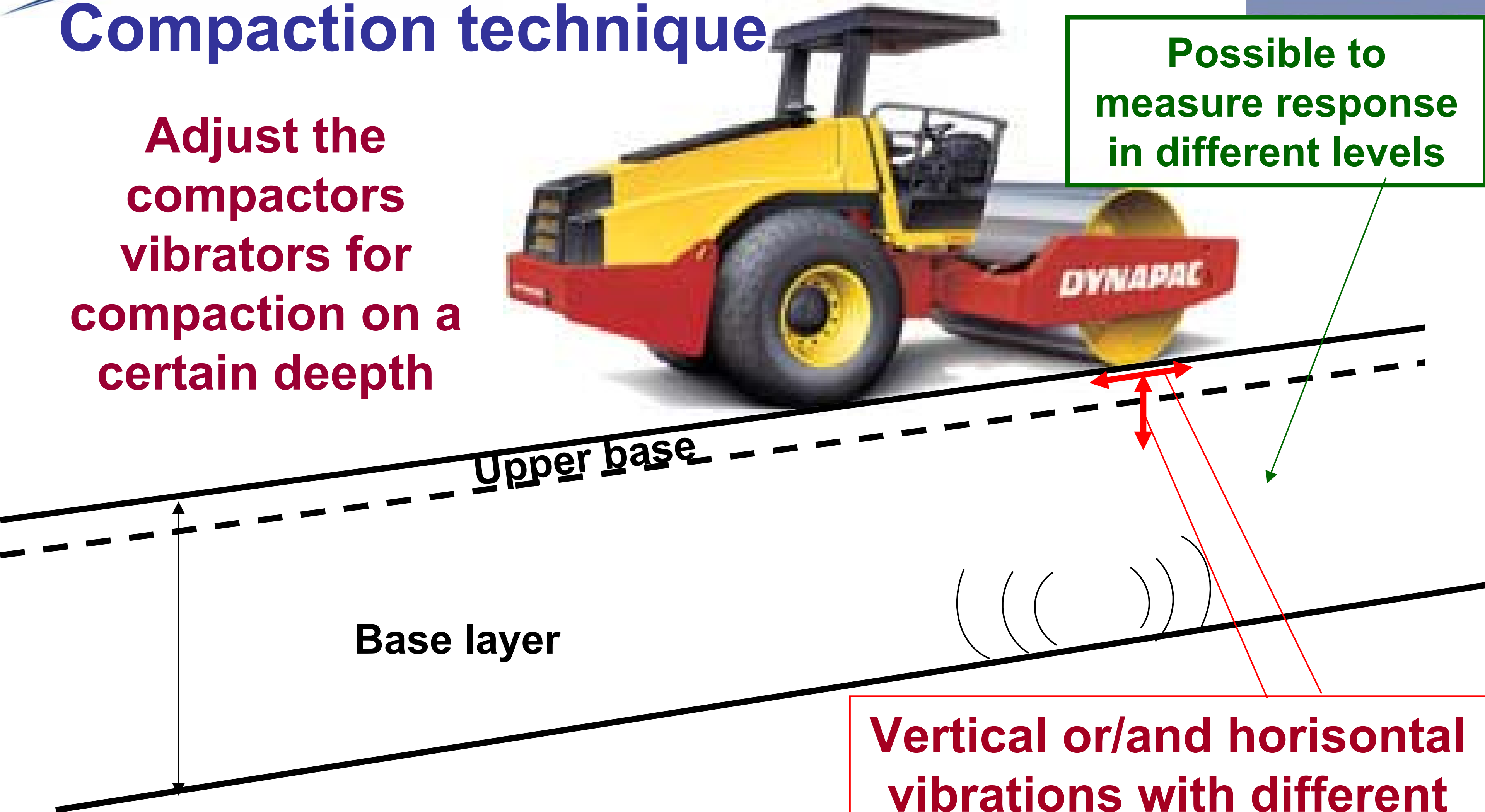


Plate loading: ca 90 MPa 250 – 500 MPa ca 150 MPa

Compaction technique

Adjust the compactors vibrators for compaction on a certain deepth

Possible to measure response in different levels



Vertical or/and horisontal vibrations with different amplitude and frequency

Connection between aggregate characteristics etc. and permanent rutting?

- Grain maximum size
- Aggregate gradation
- Rock material, Geology
- Moisture content

M_R Model Including Moisture and Density

Moisture? **Pore volume?**

$$M_R = F_{moisture} \cdot F_{density} \cdot k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

$$F_{moisture} = a + \frac{b-a}{1 + EXP\left(\ln_e\left(\frac{-b}{a}\right) + k_S \cdot \left(S - S_{opt}\right)\right)}$$

$$F_{density} = \left(\frac{\gamma_d}{\gamma_{d\max}}\right)^{k_\gamma}$$

Is it possible to simplify: k_3 = - 0.2

Where: S = degree of saturation

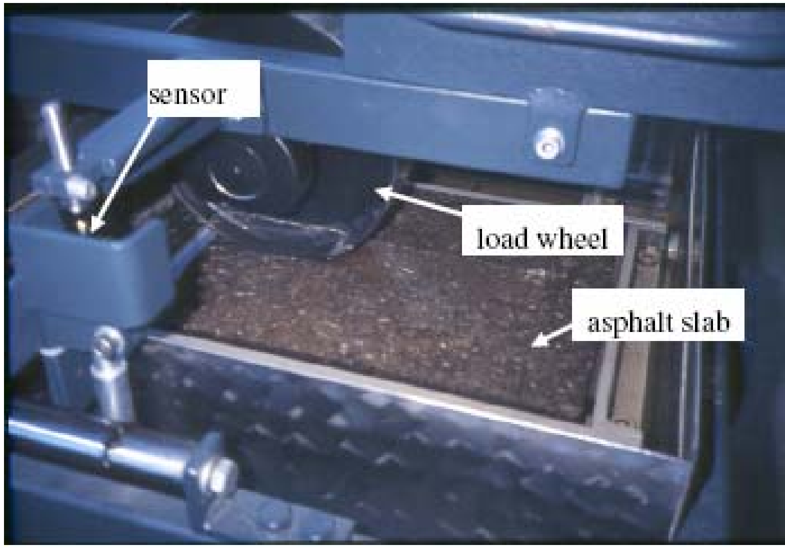
γ_d = dry unit weight

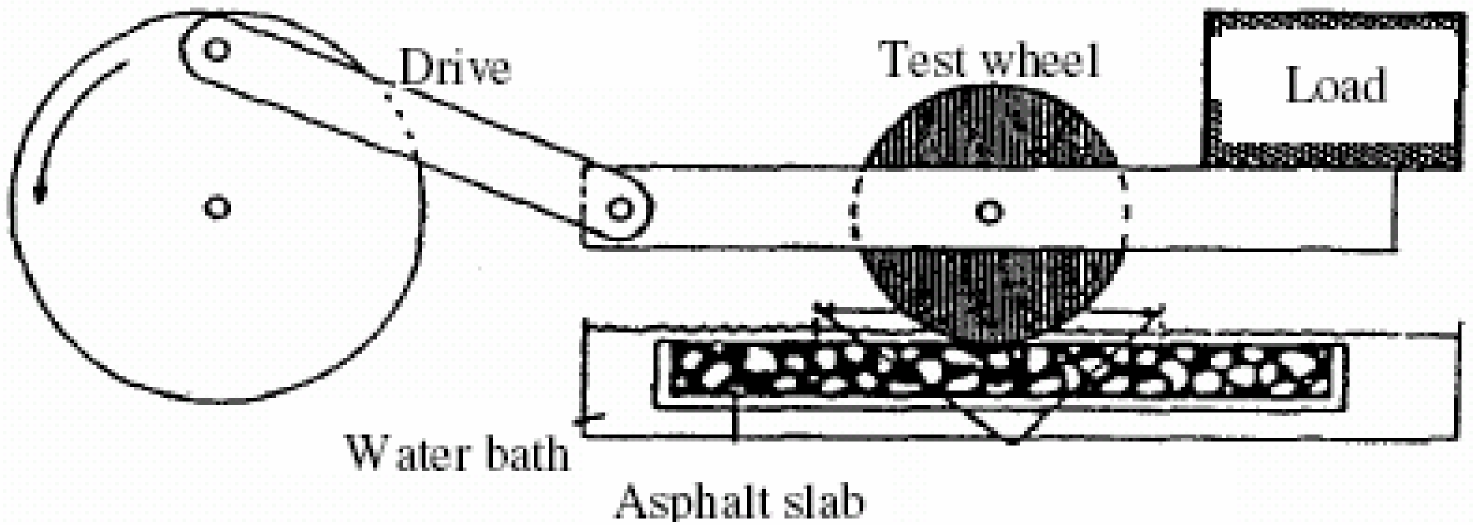
k_S, k_γ = regression constants

a,b = constants (function of soil type)

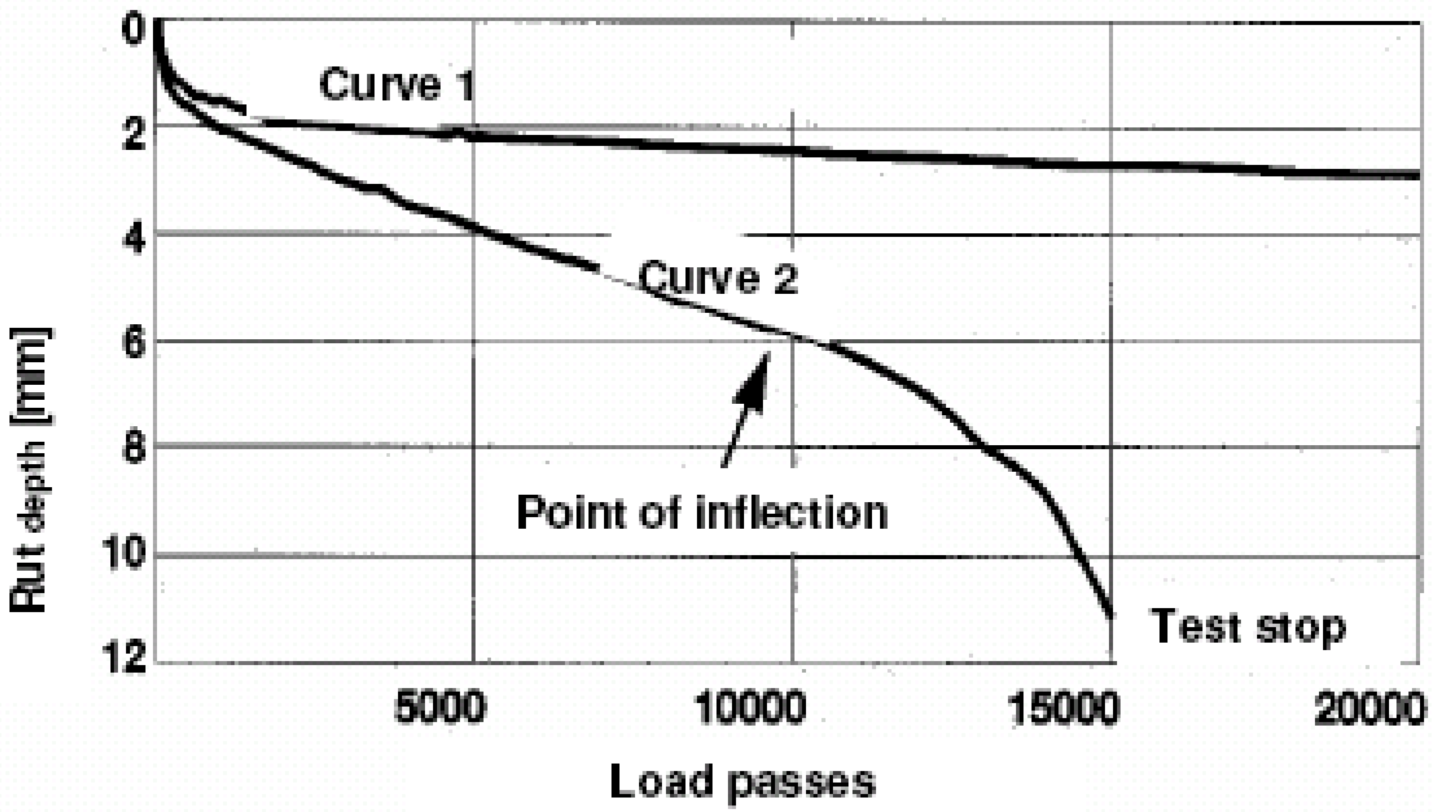
Design Guide USA

Wheel Tracking Test





Wheel tracking; Result



Is it possible to backcalculate parameters from Wheel track tests in order to get parameters for calculation of permanent deformations in asphalt?

Effect of stabilisation

MATERIAL MODELS
Rutting in bituminous bound materials

SAMARIS

THANK YOU FOR YOUR ATTENTION

Anders Huvstig

Swedish Road Administration (SRA)