COST Action TU1208

Civil Engineering Applications of Ground Penetrating Radar

This presentation is part of the TU1208 Education Pack

Structural evaluation of existing pavements

based on deflection and GPR measurements

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Summary of the lecture (1/2)

Introduction to approaches for the evaluation of the structural properties of pavement

- Old-fashioned way: the equivalent single layer model
- Modern way: the back-calculation approach
- Multi-layer model of a road
- Application of loads and measurement of deflections

Evolution of mathematical models of pavement

- Pavement models based on the theory of elasticity
- Pavement models based on the strength of materials
- Model proposed by Burmister (1943)

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Summary of the lecture (2/2)

Evaluation of the bearing capacity of a multilayered road structure

- The equivalent semi-infinite body
- Deflections and interpretation of the surface modulus
- Example: Back-calculation for a three-layer model of a road
- Sensitivity of the procedure

Application: Back-calculation and redesign of a road

- Measured deflections and present road structure
- Back-calculation and redesign with Qualidim
- Study of the influence of layer thicknesses on the road lifetime

Biography and contact details of the Author

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Introduction to approaches for the evaluation of the structural properties of pavement

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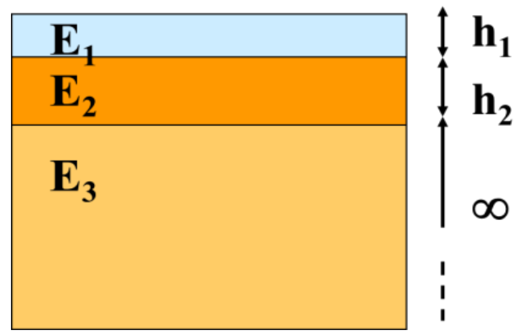
The old-fashioned way: equivalent single layer model

- Replace each layer of the multi-layer model of the road by one layer with "equivalent" thickness h_e (thicker than the sum of thicknesses h_i)



  - Multi-layer model: thicknesses h_1, h_2, …
  - The so-called 'equivalent factors' a1, a2, … can be calculated by using the following formula:

$$a_i = \sqrt[3]{E_i / 500}$$

Here, E_i is the layer elasticity modulus, measured or taken from a table (this is a parameter depending on the layer material)

  - Thickness of the equivalent layer:

$$h_e = \sum a_i + h_i$$

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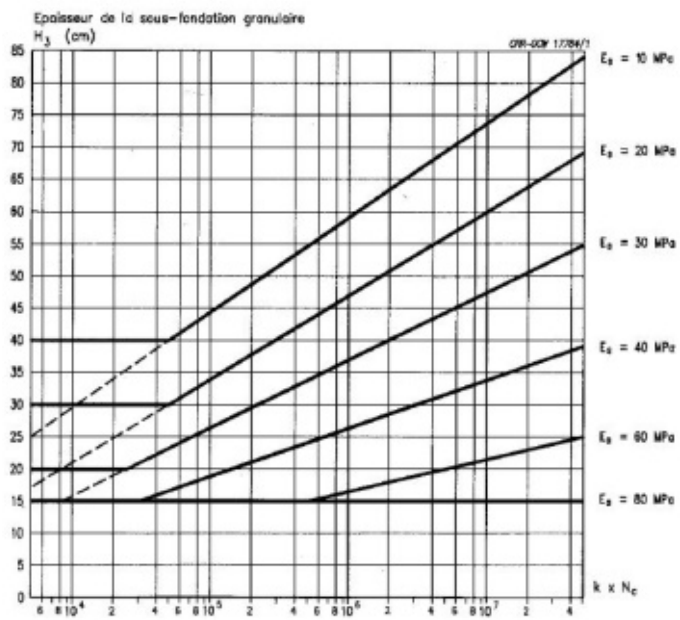
Equivalent single layer model: thickness of overlay…

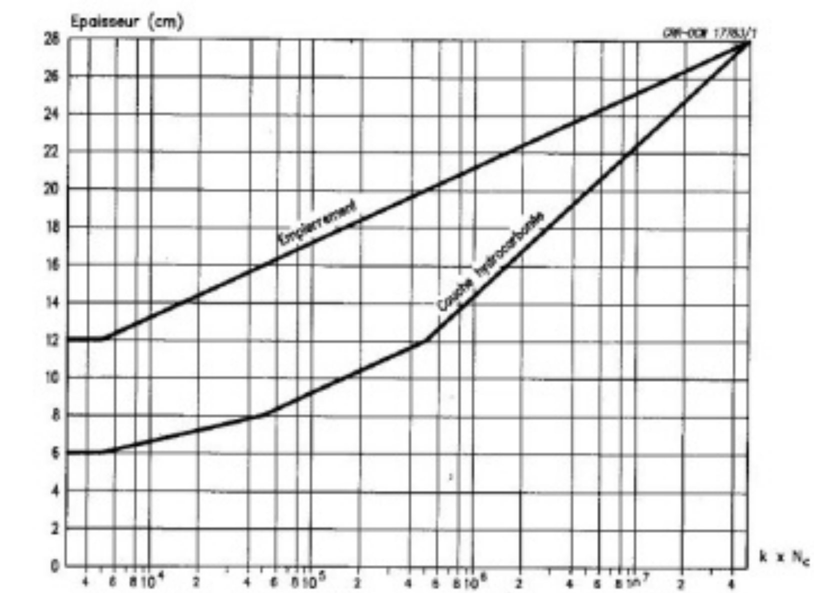
- Determine traffic (kN_c): Past, present and future traffic
- Graphs established in 1991 (BRRC report R56/85)

Thickness of granular subbase (for different soils)



Traffic (kNc)

Thicknesses of crushed stone base course and asphalt layer



Traffic (kNc)

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Equivalent single layer model: thickness of overlay…

- Traffic maps are used to determine the thicknesses H_1,H_2,H_3 of the ideal multi-layer road.
- The ideal equivalent thickness is: $H_e = \Sigma\, a_i \cdot H_i$ (for the equivalent 1-layer model).
- Then, do overlay: $W = (H_e - h_e) / 2.7$ (with a_i =2.7 for a bituminous layer) is the needed thickness of the bituminous overlay, in order to achieve equivalence with the ideal multi-layer road structure.

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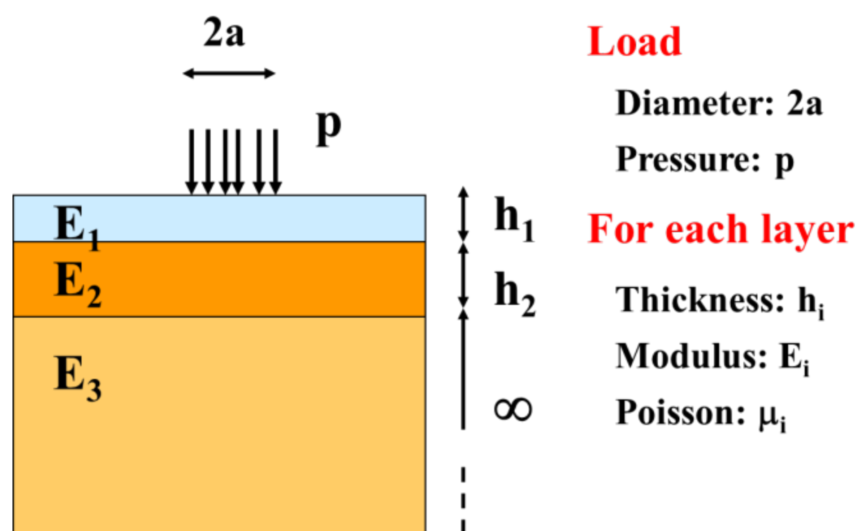
The modern way: back-calculation approach

- Objective: Determine E-modules of all layers
  - Compute deflection bowl from a multi-layer model
  - Compare the computed deflection bowl with the measured deflection bowl
  - If deflection bowls are not "identical" then modify E-modules and iterate…



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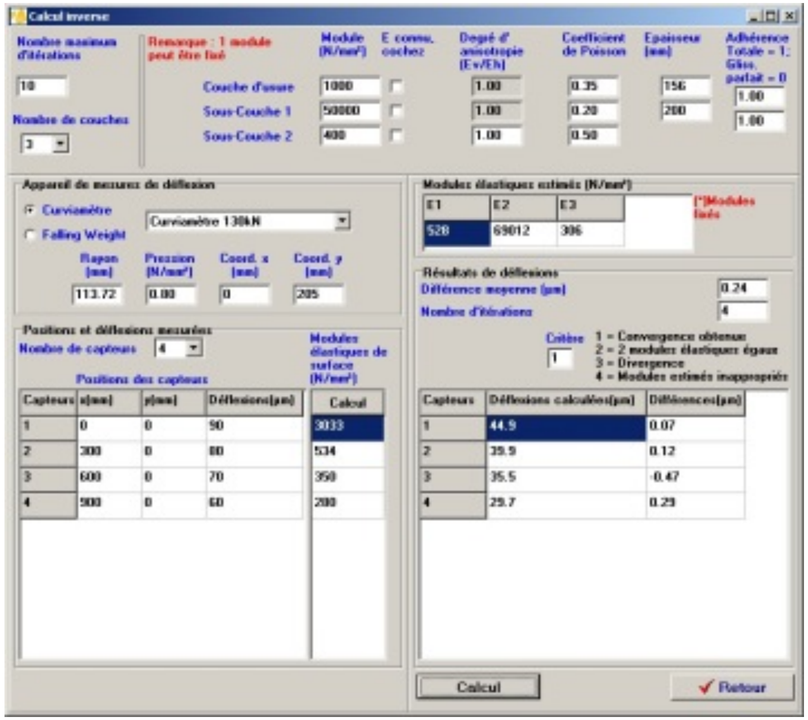
The modern way: back-calculation approach



- Then redesign the "current structure + overlay" (as if you are designing a new road) with a suitable software and estimate the expected lifetime.
- If results are poor, then do changes in deeper part of the road structure.

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Back-calculation software tools

- Free software:
  - "Qualidim": Intended for Belgium, to be used by non-specialists

- Commercial software:
  - Alizé-LCPC (itech-soft)
  - PAVERS (VIA Aperta)
  - Rosy (SWECO – carlBro)
  - ELMOD (Dynatest)
  - …

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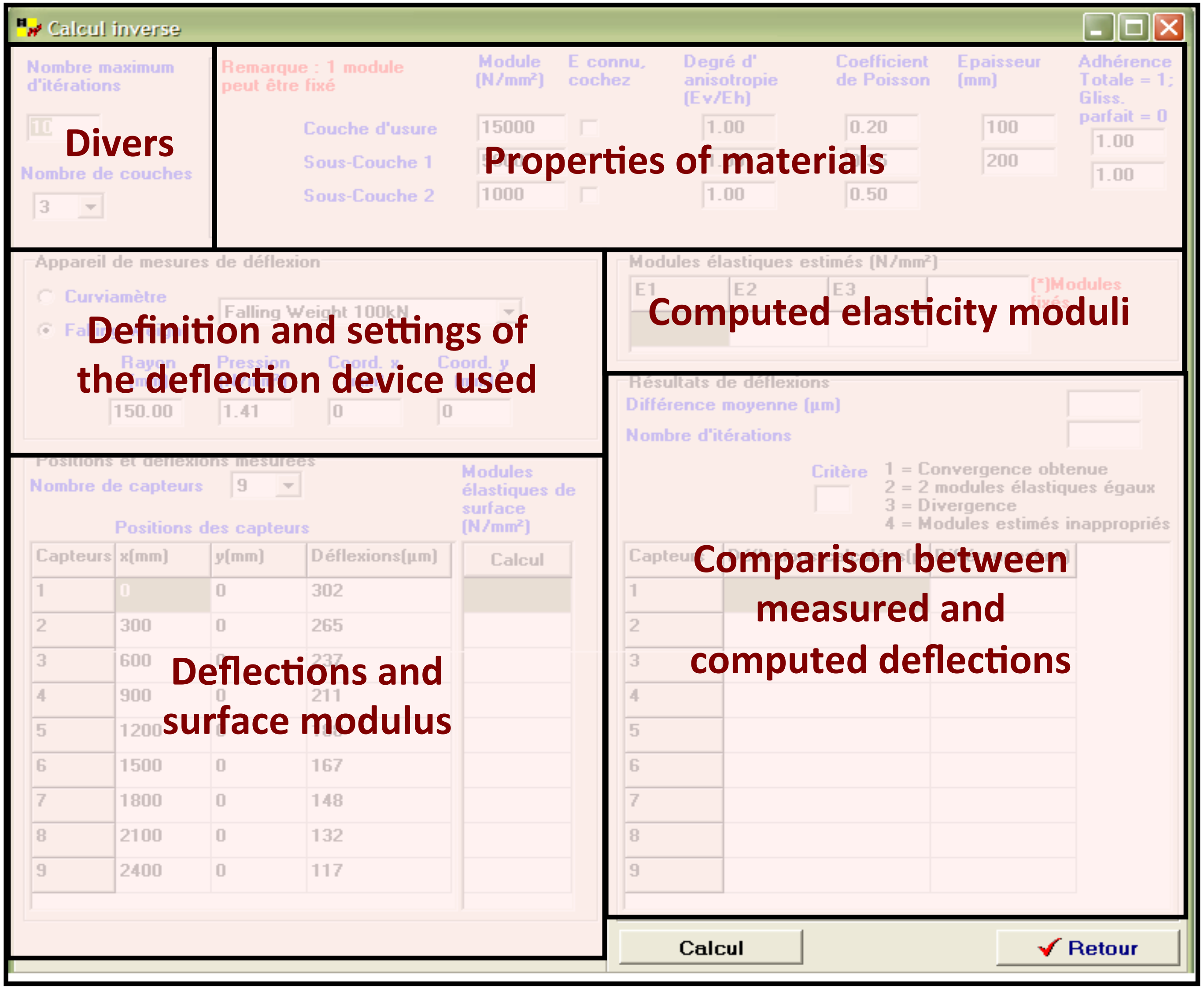
Back-calculation: Qualidim



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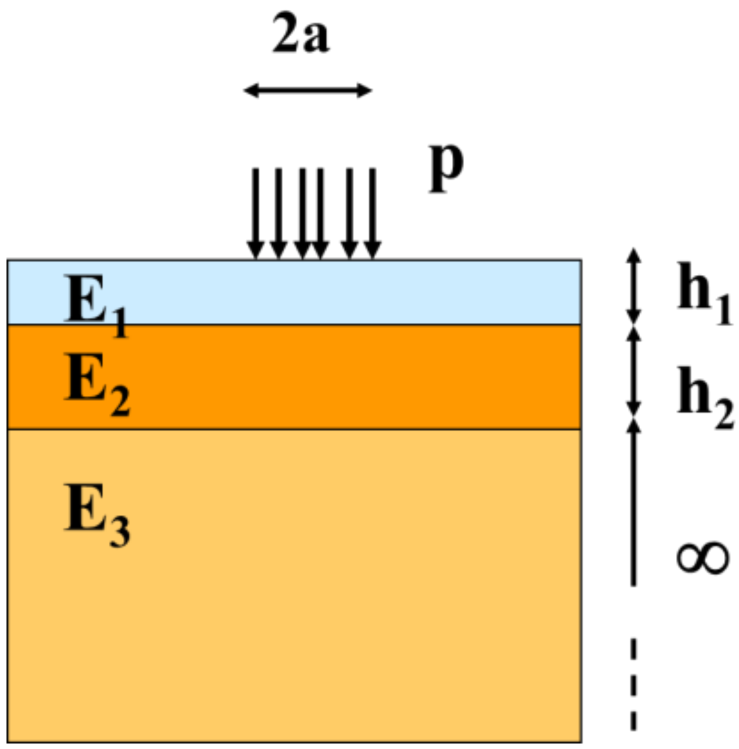
Model of the road: a multi-layer



Load

- Diameter: 2a
- Pressure: p

For each layer i

- Thickness: h_i
- Modulus: E_i
- Poisson: μ_i

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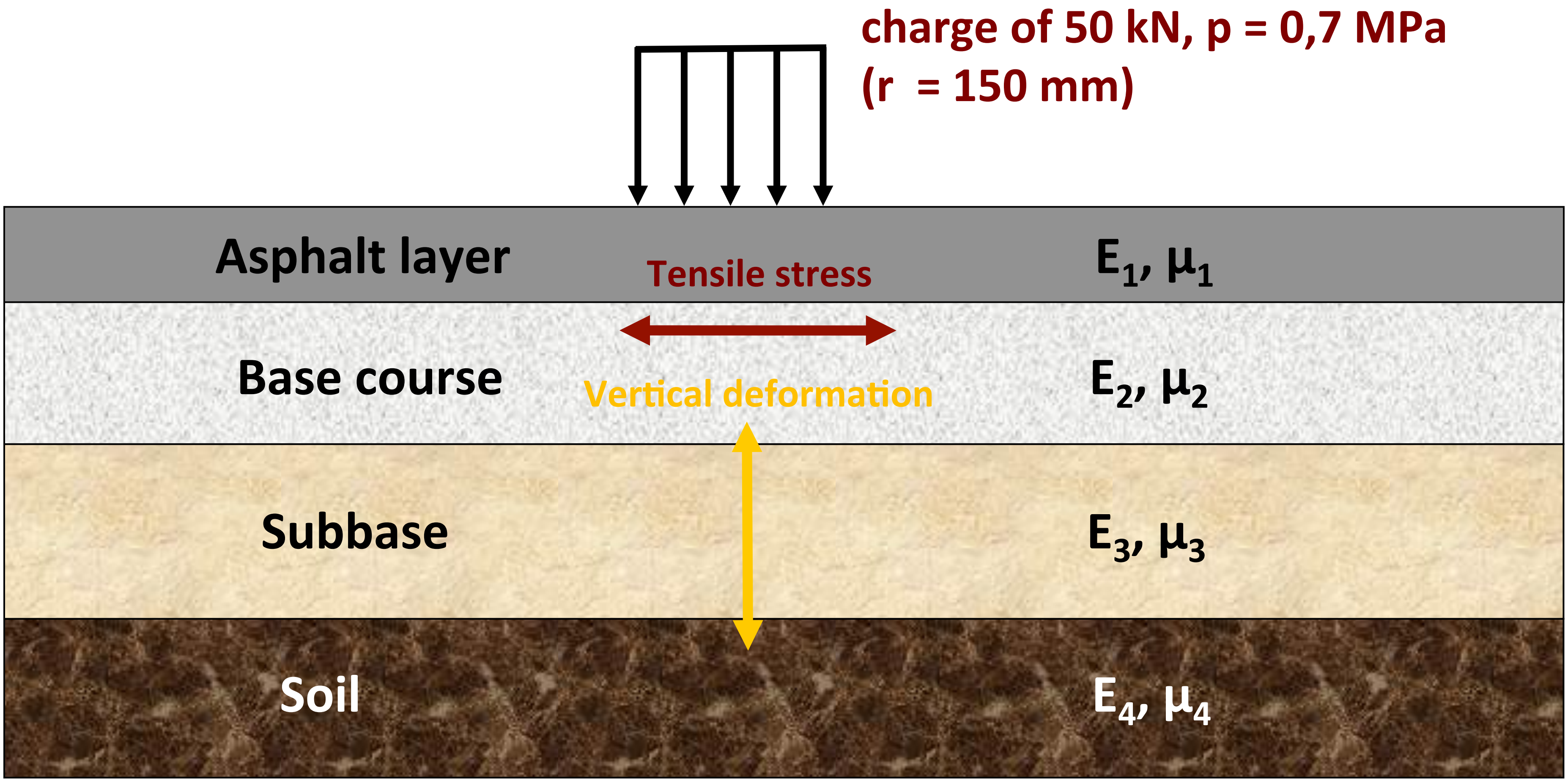
Application of loads and their effects

- A load is applied to the multi-layer system…



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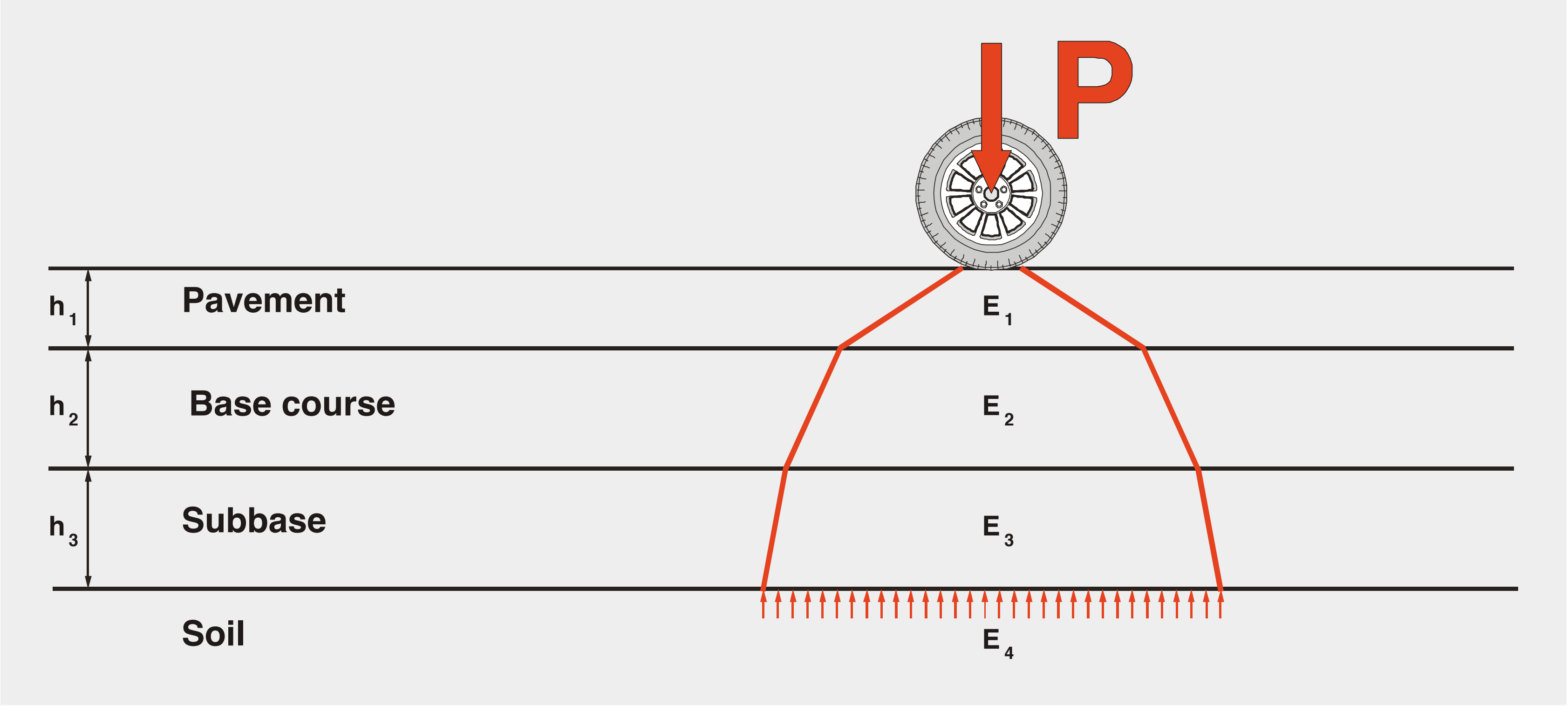
Distribution of the load and measurement of deflections

- Only the part of the pavement that is subjected to stresses, will deform… (i.e. only the area inside the red cone, in the sketch)



➢ The farther the deflection is measured from the centre of impact, the less the deflection is caused by the upper part of the road structure…

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Evolution of mathematical models in pavement design

See also the book:

Frans Van Cauwelaert, « Pavement design and evaluation: The required mathematics and applications,» ISBN 978-2-960043-00-6

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Pavement models based on the theory of elasticity

- Semi-infinite body subjected to a vertical load P
  - The subgrade is an isotropic body (Boussinesq, 1883)

$$\sigma_z = -\frac{3P}{2\pi z^2}$$

  - Definition of a stress concentration factor (Fröhlich, 1934)

$$\sigma_z = -\frac{\nu P}{2\pi z^2}$$

Concentration: $\nu > 3$

Dispersion: $\nu < 3$

  - The subgrade is an orthotropic body (Lekhnitskii, 1963)

$$\sigma_z = -\frac{1+s+s^2}{s^2}\frac{P}{2\pi z^2} \qquad s^2 = \frac{n-\mu^2}{n^2-\mu^2} \qquad n = \frac{E_{vert}}{E_{hor}}$$

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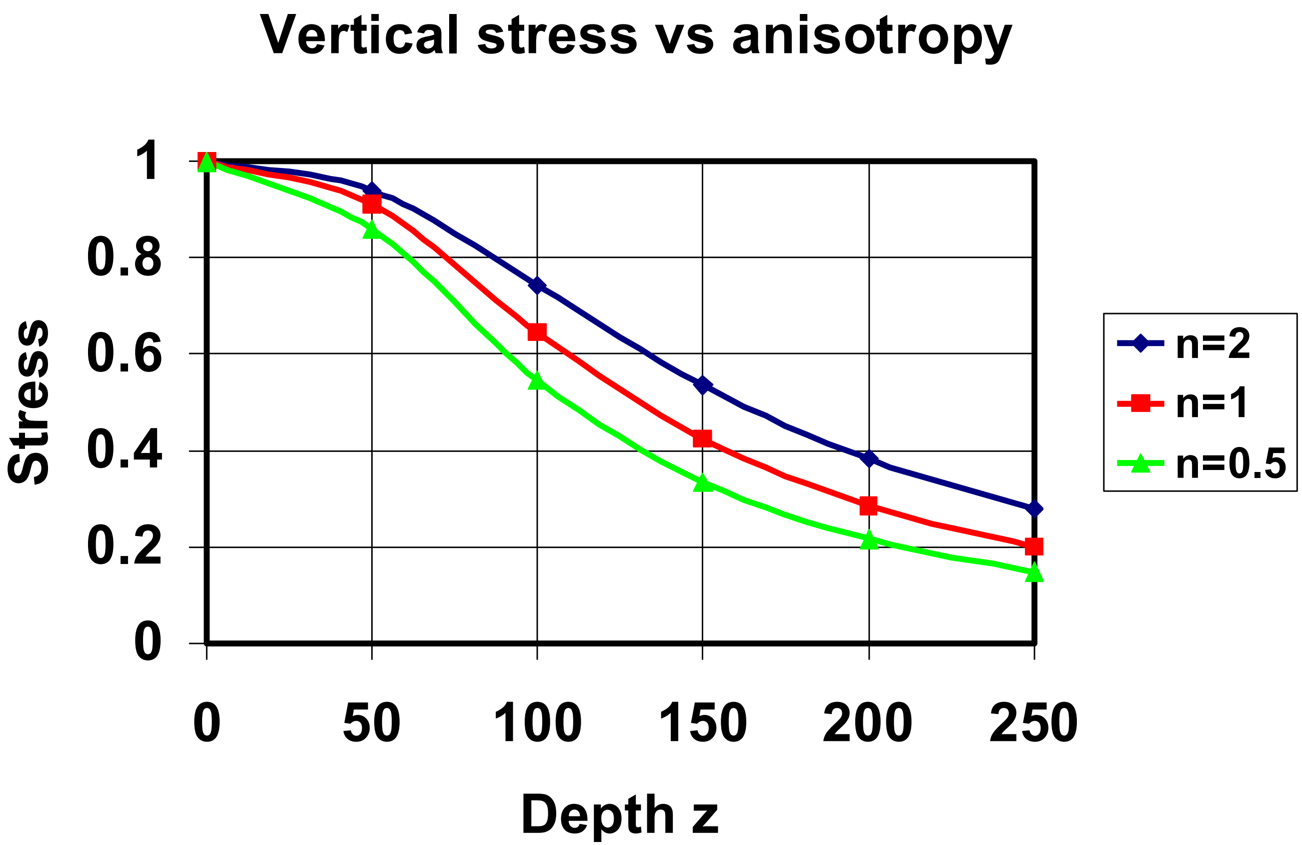
Pavement models based on the theory of elasticity



(Lekhnitskii, 1963)

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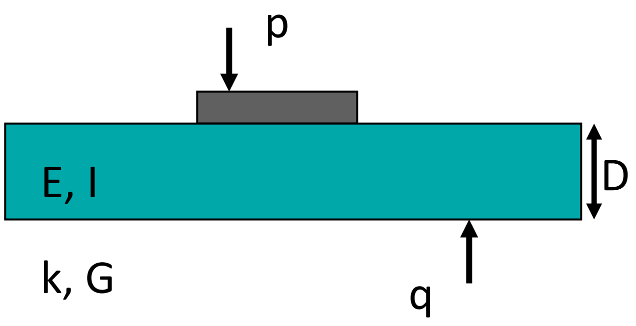
Pavement models based on the strength of materials

- Slab subjected to a vertical pressure *p*

  - Equilibrium equation

$$\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}\right)\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}\right)=\frac{p-q}{D}$$



  - Westergaard (1924): The subgrade is a series of vertical springs (k)

$$q = kw$$

  - Pasternak (1954): The subgrade is a series of vertical (k) and horizontal springs (G)

$$q = -G\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}\right)+kw$$

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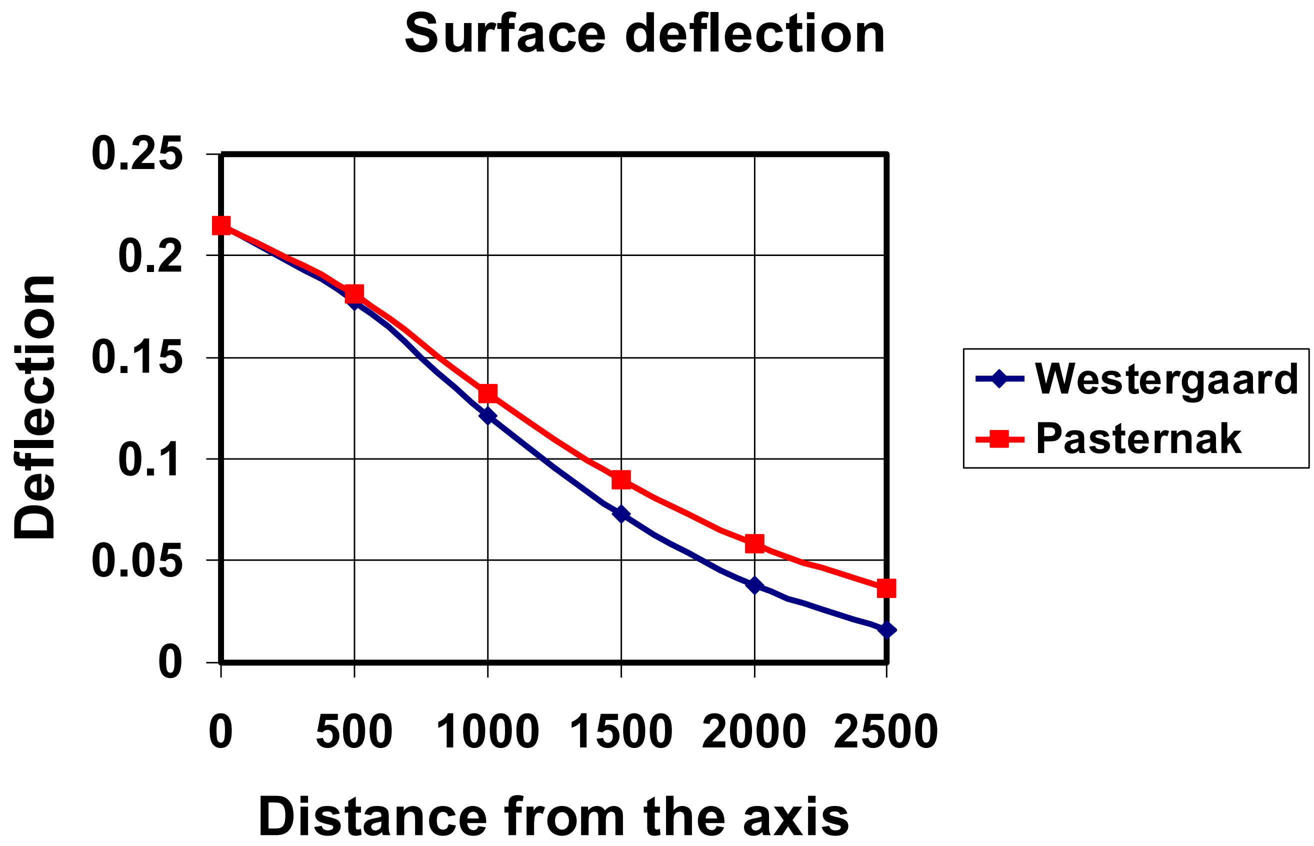
Pavement models based on the strength of materials



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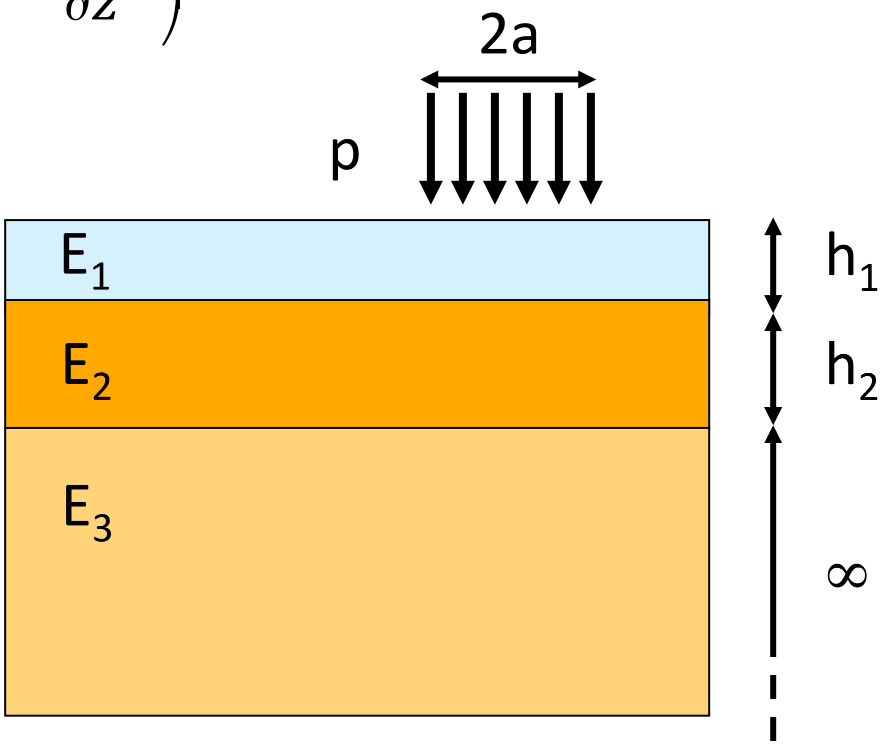
Model proposed by Burmister (1943)

- Multilayered structure
  - Hypotheses of the theory of elasticity: equilibrium, continuity and elasticity for each layer

$$\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}\right)\left(\frac{\partial^2\varphi_i}{\partial r^2}+\frac{1}{r}\frac{\partial\varphi_i}{\partial r}+\frac{\partial^2\varphi_i}{\partial z^2}\right)=0$$



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Model proposed by Burmister (1943)

- Mathematical solution (here, we skip the mathematical steps, but you are encouraged to calculate them!)

$$\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}\right)\left(\frac{\partial^2\varphi_i}{\partial r^2}+\frac{1}{r}\frac{\partial\varphi_i}{\partial r}+\frac{\partial^2\varphi_i}{\partial z^2}\right)=0$$

By introducing in the equation the expression $\phi(r,z) = J_0(mr)f(z)$, we obtain:

$$\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}\right)J_0(mr)=-m^2J_0(mr)$$

$$J_0(mr)\left(m^4-2m^2\frac{\partial^2}{\partial z^2}+\frac{\partial^4}{\partial z^4}\right)f(z)=0$$

$$\varphi_i(r,z)=J_0(mr)\left(A_ie^{mz}-B_ie^{-mz}+zC_ie^{mz}-zD_ie^{-mz}\right)$$

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Model proposed by Burmister (1943)

- Stresses and displacements (again, we ignore the mathematical steps leading to these formulas):

$$\sigma_z = f(r)\left\{Am^2e^{mz} + Bm^2e^{-mz} - (1-2\mu+mz)Cme^{mz} + (1-2\mu-mz)Dme^{-mz}\right\}$$

$$\tau_{rz} = f(r)\left\{Am^2e^{mz} - Bm^2e^{-mz} + (2\mu+mz)Cme^{mz} + (2\mu-mz)Dme^{-mz}\right\}$$

$$u = \frac{f(r)}{E}\left\{Am^2e^{mz} + Bm^2e^{-mz} + (1+mz)Cme^{mz} - (1-mz)Dme^{-mz}\right\}$$

$$w = \frac{f(r)}{E}\left\{Am^2e^{my} - Bm^2e^{-my} - (2-4\mu-mz)Cme^{mz} - (2-4\mu+mz)Dme^{-mz}\right\}$$

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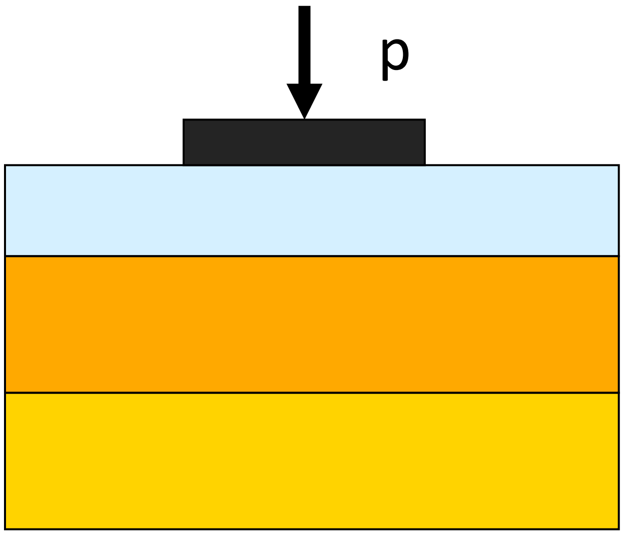
Boundary conditions (Burmister)



- Surface (load)
  - Vertical stress = - p
  - Shear stress = 0
- Interfaces (layers in contact)
  - Vertical stresses are all equal
  - Shear stresses are all equal
  - Deflections are all equal
- Interfaces: horizontal condition, there are three alternatives:
  - Displacements are equal: Friction
  - Shear forces are null: Slip
  - Intermediate scenario: Partial friction

bonding

- Subgrade, there are two alternatives
  - Semi-infinite body
  - Fixed bottom

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Evaluation of the bearing capacity of a multilayered road structure

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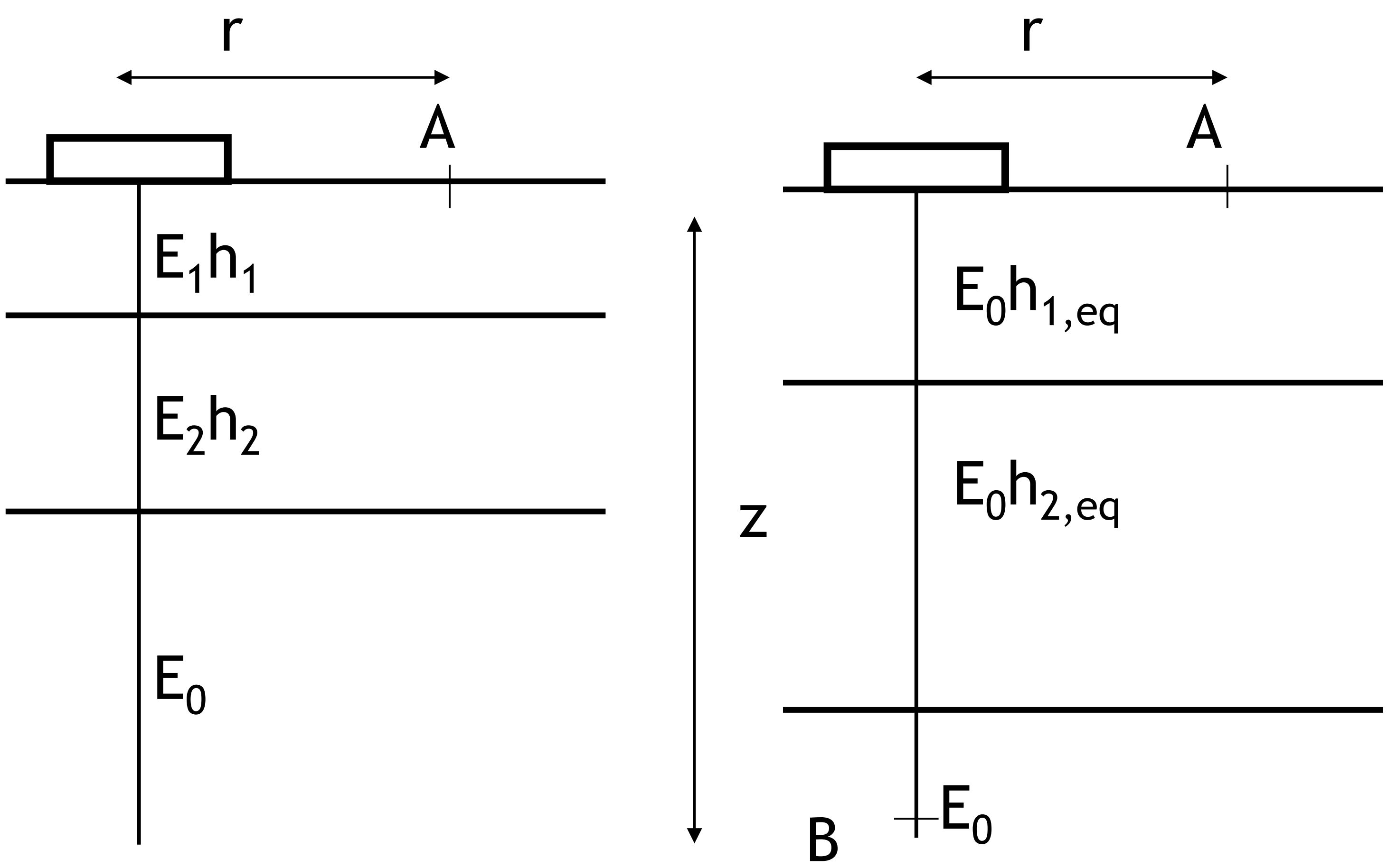
The equivalent semi-infinite body



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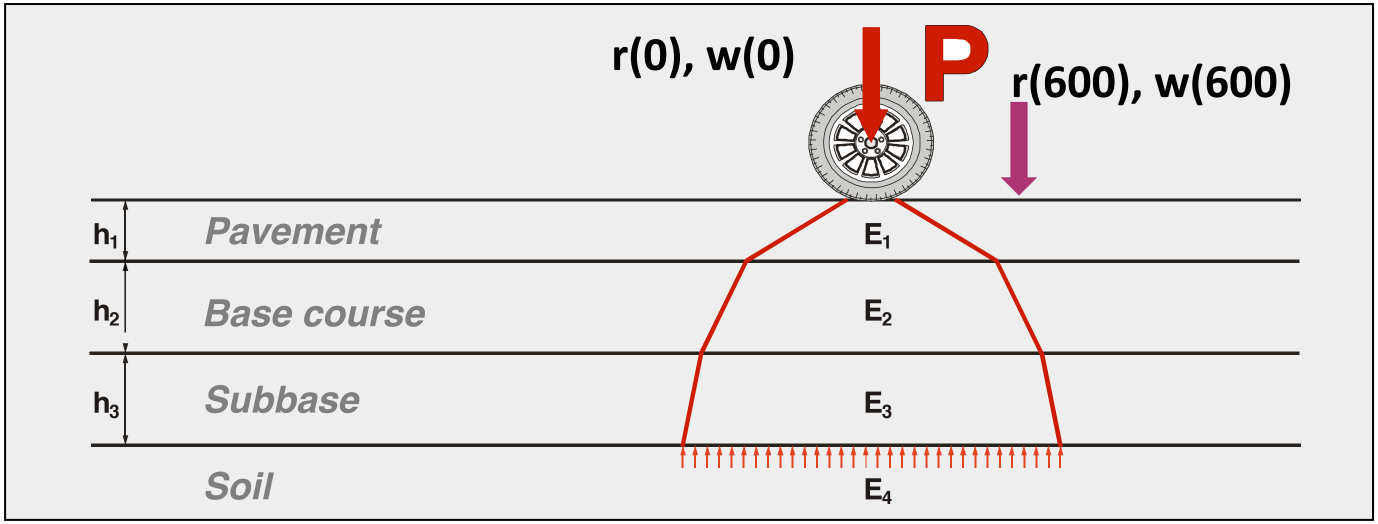
The further away from the centre of pressure...



$$E_0(i) = pa^2 \frac{(1-\mu^2)}{r(i)w(i)}$$

- Deflection "at the centre of impact": is influenced by the whole road structure

  → hence, the derived surface modulus characterizes the whole road structure

- Deflection "far away" from the centre of impact: it is influenced by the lower part of the road structure, only

  → hence, the derived surface modulus characterizes the lower part of the road structure

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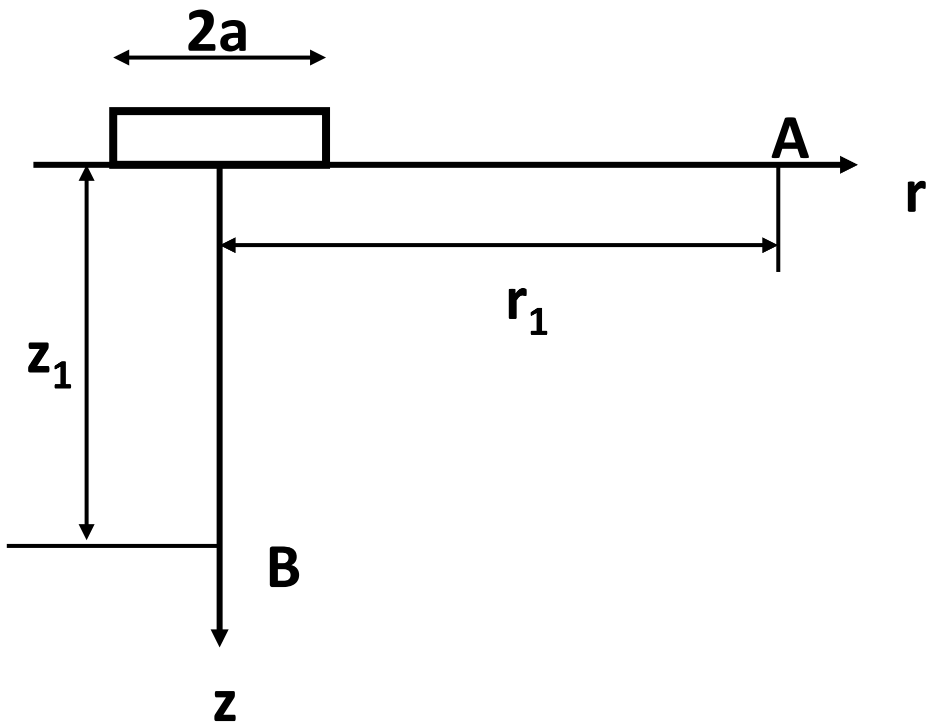
Identical deflections



$$w(r) = \frac{2(1-\mu^2)}{E}\frac{P}{2\pi . r}$$

Simple transformation:

$$w(r) = w(z/2 \rightarrow 2z/3)$$

$$w(z) = \frac{1+\mu}{E}\frac{P}{2\pi . z}(3-2\mu)$$

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Interpreting the surface modulus

- The surface modulus $E_0(i)$ corresponds to the deflection $w(i)$ measured at a distance $r(i)$

$$E_0(i) = \frac{2(1-\mu^2)}{r(i)w(i)}\frac{P}{2\pi} = pa^2\frac{(1-\mu^2)}{r(i)w(i)}$$

  - Pressure p, radius a, Poisson coefficient (Poisson's ratio) μ
  - Model used: Boussinesq's theory, computation of the elastic modulus of a homogeneous half-space

- So, from the measured deflection $w(i)$ at a distance $r(i)$, we can compute the surface modulus $E_0(i)$

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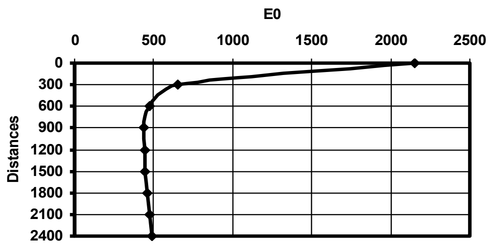
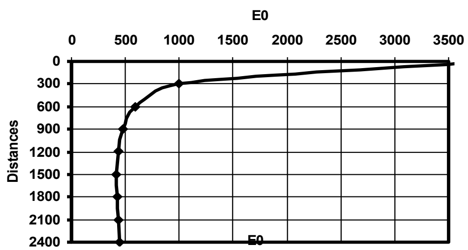
Example: Compute E_0, then draw conclusions on the E-moduli of the different layers of the 3-layer model

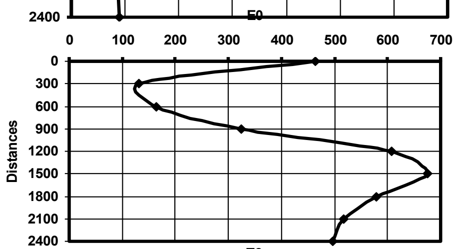
- Input: Measured deflections at different distances from load centre



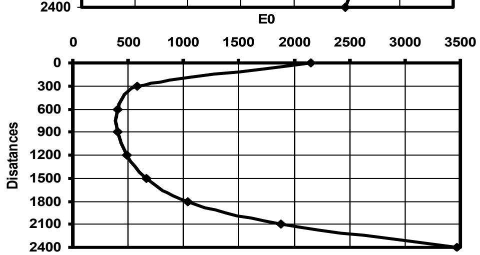
A three-layer road model with decreasing moduli



A three-layer road model with a stiff interlayer



A three-layer road model with a weak interlayer



A three-layer road model with an increasing modulus of the subgrade or a stiff bottom

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Back-calculation of a three-layer (1/2)

- Let w_1, w_2, … w_n be the deflections at the distances r_1, r_2, … , r_n
- Let us assume the seed values E_{10}, E_{20}, E_{30}
- We compute the theoretical deflections $z_0(1)$, $z_0(2)$,…, $z_0(n)$
- We choose $E_{11} = E_{10} \cdot z_0(1)/w_0$, $E_{21} = E_{20} \cdot z_0(2)/w_1$, $E_{31} = E_{30} \cdot z_0(n)/w_n$
- With E_{11}, E_{20}, E_{30}, we compute $z_1(1)$, $z_1(2)$,… $z_1(n)$
- With E_{10}, E_{21}, E_{30}, we compute $z_2(1)$, $z_2(2)$,… $z_2(n)$
- With E_{10}, E_{20}, E_{31}, we compute $z_3(1)$, $z_3(2)$,… $z_3(n)$

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Back-calculation of a three-layer (2/2)

- We apply the "Al Bush III" algorithm:
  - For k = 0 to 3, we define:

    $z_k(i) = a(i)\log E_{1.} + b(i)\log E_{2.} + c(i)\log E_{3.} + d(i)$

- From this, we compute the solution for a(i), b(i), c(i), d(i)
  - We introduce these in the n equations (i=1,..,n):

    $z_0(i) = a(i)\log E_1 + b(i)\log E_2 + c(i)\log E_3 + d(i)$

  - We minimise $\sum_{1}^{n}\left[w(i) - z_0(i)\right]^2$ and obtain the expected values E_1 , E_2 , E_3

- If this sum of squares is "small enough" then we stop
  - Else we iterate with E_1 , E_2 , E_3 as new seed values…

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Sensitivity of the procedure

- Given $E_1 = 10000$, $E_2 = 3000$, $E_3 = 500$
  - We compute w(0)=69.6, w(1)=38.1, w(2)=26.2, w(3)= 19.1, w(4)=14.3, w(5)=11.2, w(6)=9.0, w(7)=7.5, w(8)=6.5

Backcalculation

w(0)	E_1	E_2	E_3	Fit	Loops
69.6	10036	2993	500	0.02	7
75.0	6469	3351	503	0.06	6
58.0	33840	2371	497	0.10	7

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Application:
Back-calculation and redesign of a road

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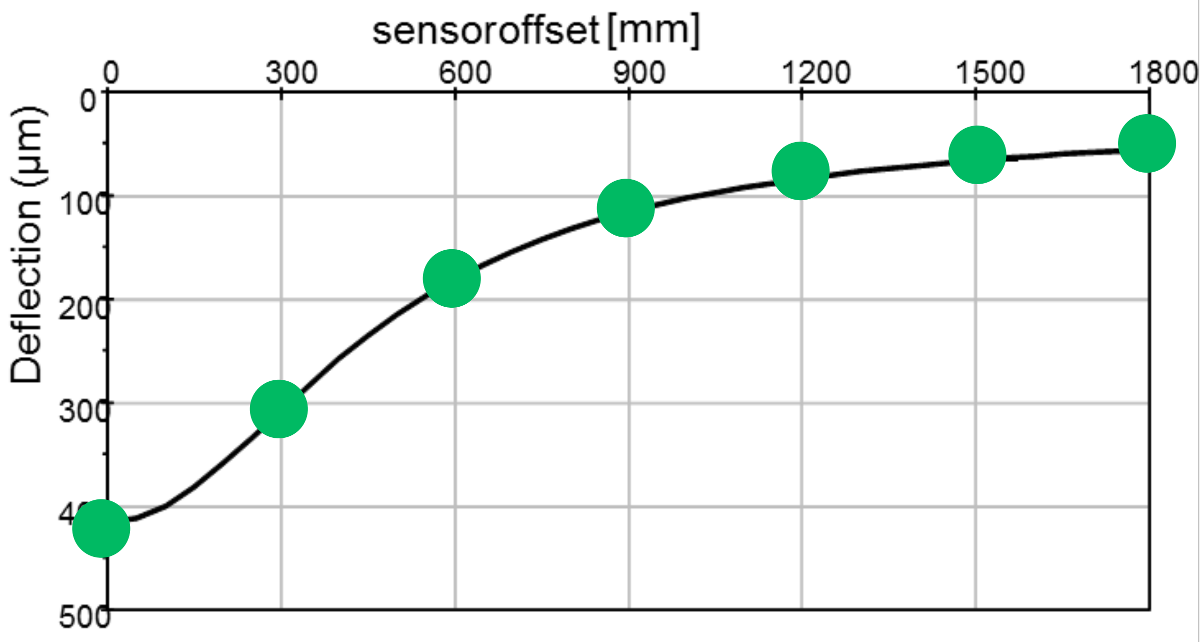
Deflections & present road structure

- Deflections measured with a FWD in the middle of a concrete slab:



Distances r_i (mm)	0	300	600	900	1200	1500	1800
Deflections w_i (µm)	91	76	59	46	36	30	26

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Deflections & present road structure

- Present road structure, hypothetical E-moduli (seed values):

Layer/Type of material	Thickness (mm)	Modulus (N/mm^2)	Poisson Ratio
Concrete slabs (no dowels)	180	37000	0.20
Base course	500	2000	0.35
Stabilized subbase		350	0.50

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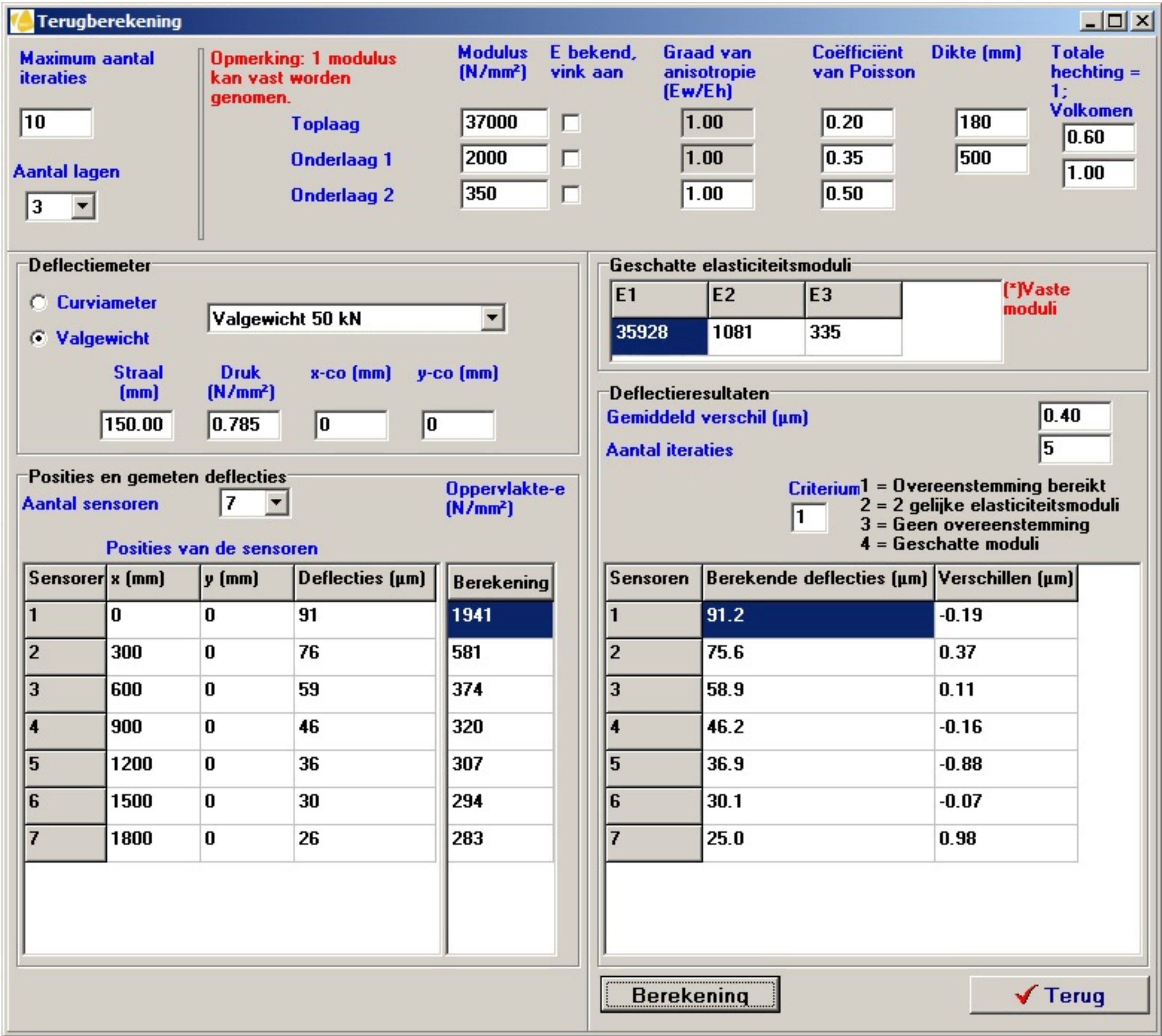
Back-calculation



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Back-calculation

- Results (with software Qualidim©):

Layer/Type of material	Thickness (mm)	Modulus (N/mm^2)	Poisson Ratio
Concrete slabs (no dowels)	180	35928	0.20
Base course	500	1081	0.35
Stabilized subbase		335	0.50

- Present structure, hypothetical E-moduli (seed values):

Layer/Type of material	Thickness (mm)	Modulus (N/mm2)	Poisson Ratio
Concrete slabs (no dowels)	180	37000	0.20
Base course	500	2000	0.35
Stabilized subbase		350	0.50

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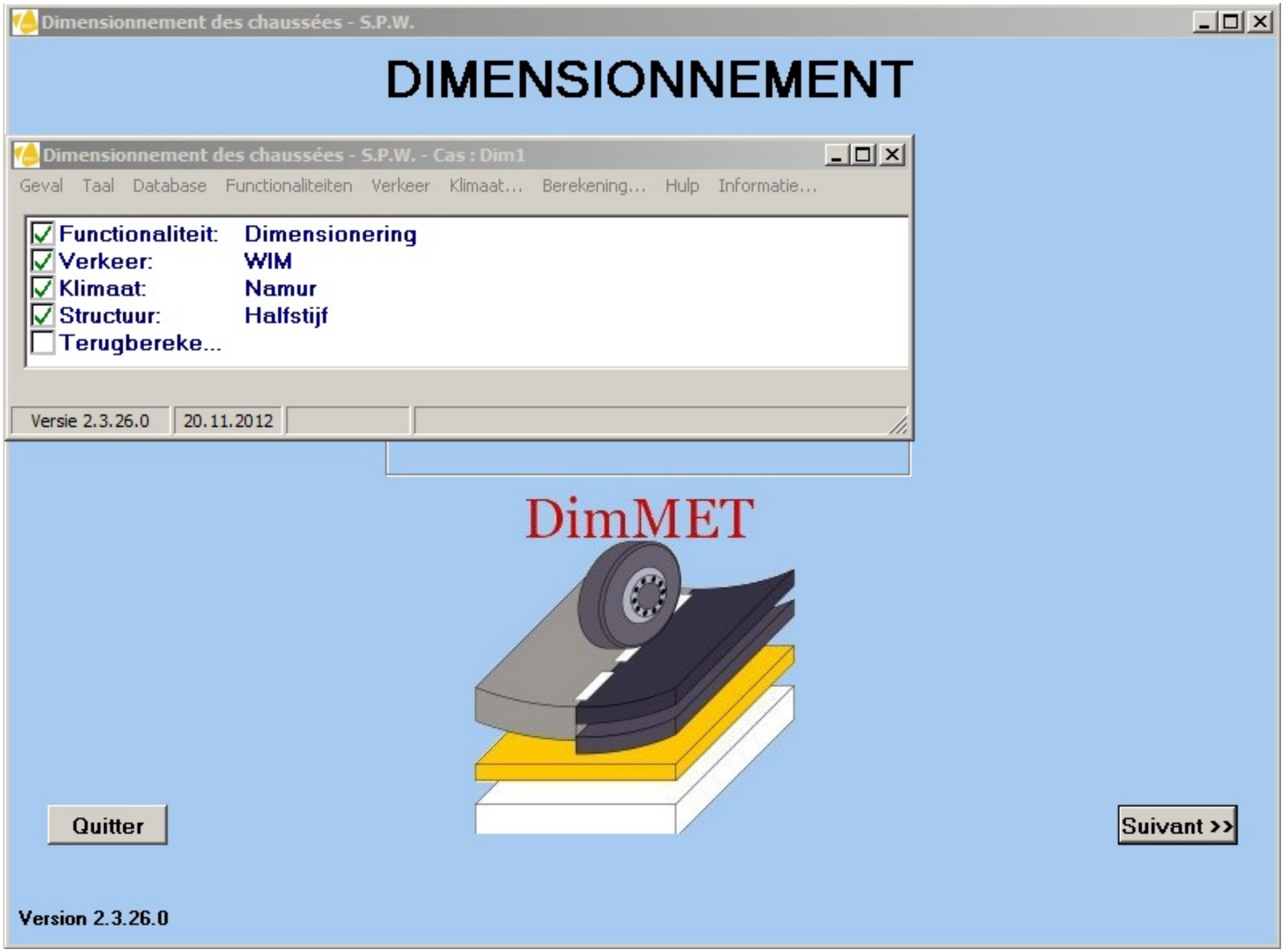
Qualidim

- Designing new roads…



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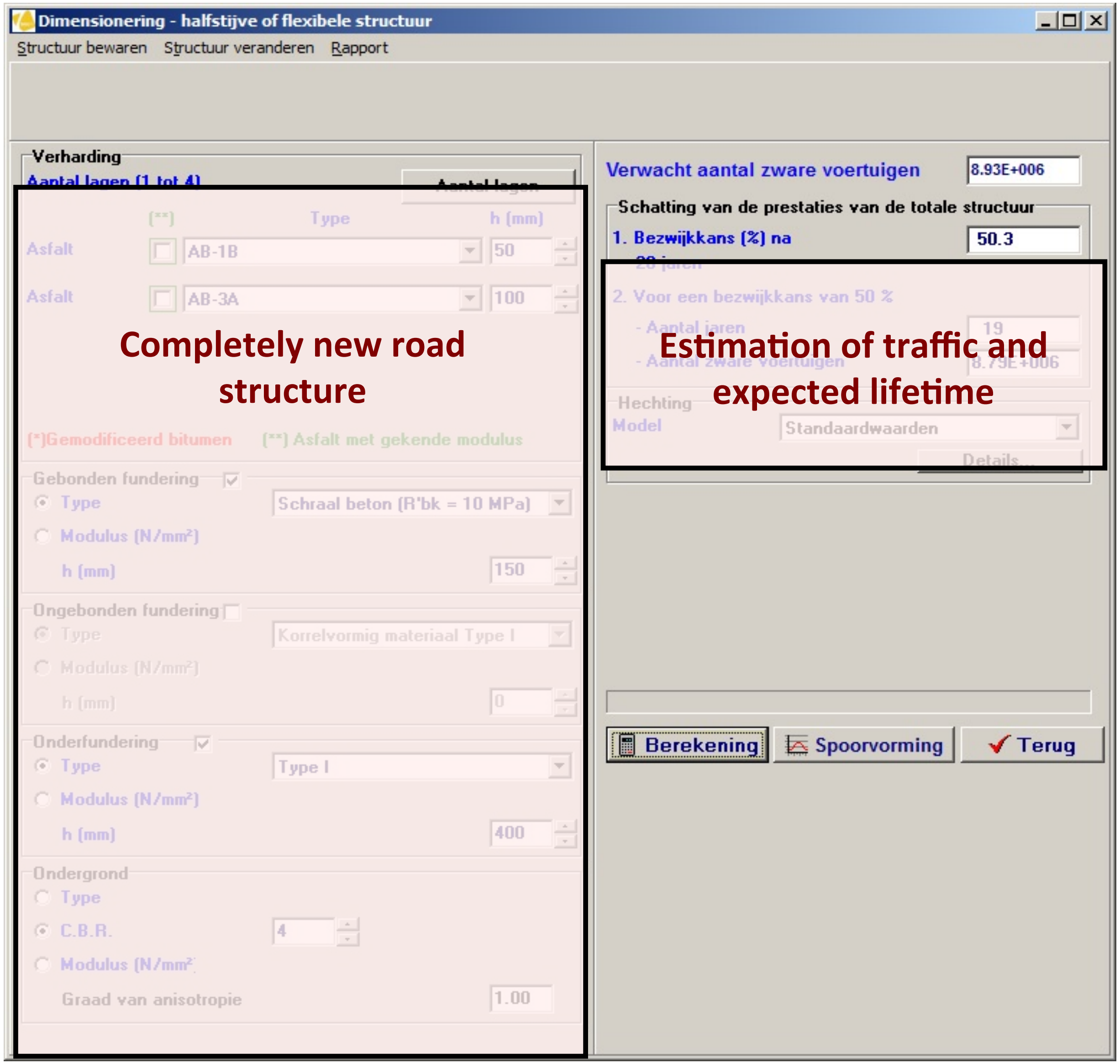
Qualidim



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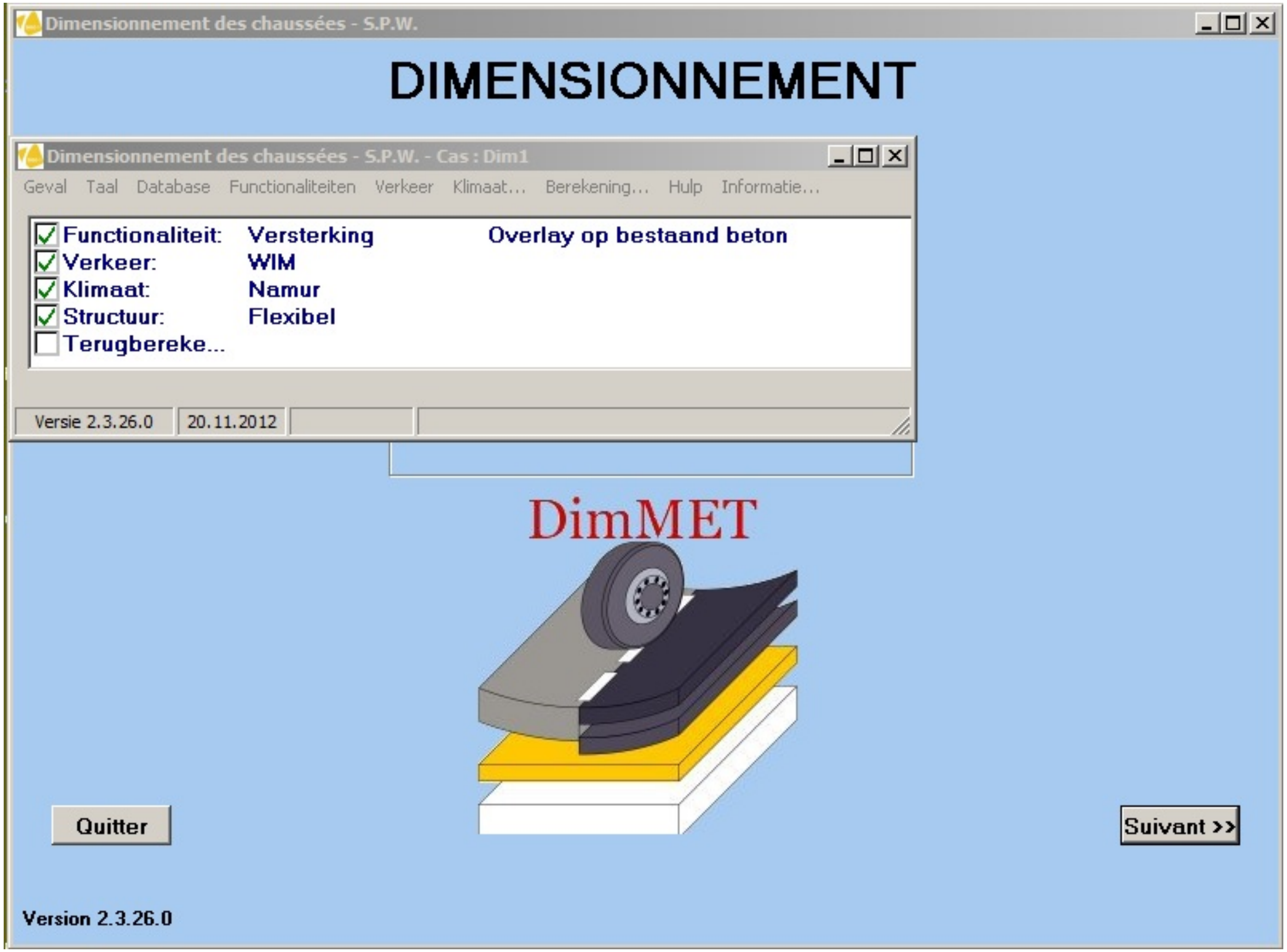
Qualidim

- Overlay on existing road…



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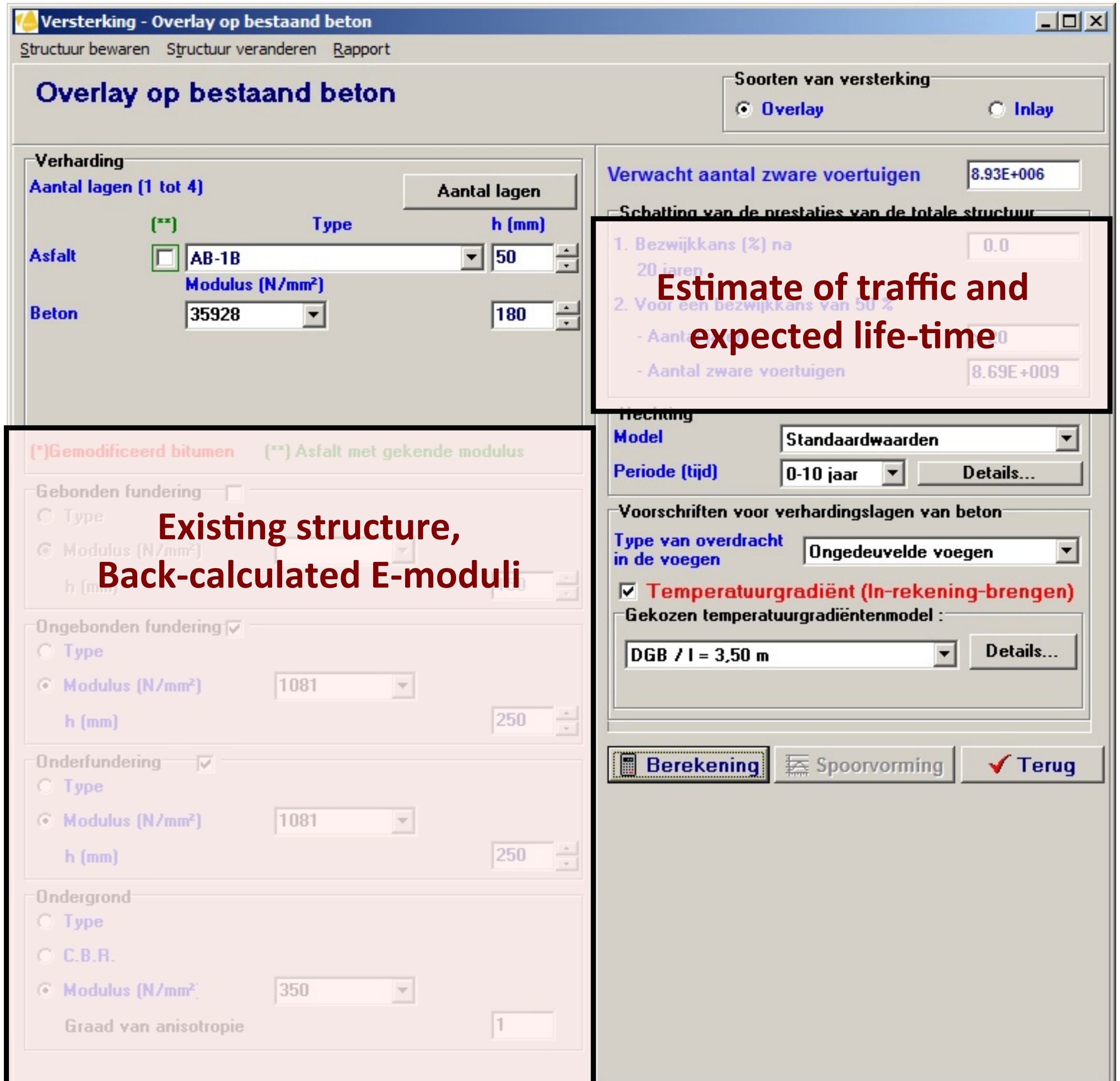
Qualidim



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Evaluation with a theoretical model

- Concept: Theoretical structure:

Layer/Type of material	Thickness (mm)	Modulus (N/mm2)	Poisson Ratio
Concrete slabs (no dowels)	Between 180 and 200	37661	0.20
Unbound base course, granular material Type I	400	650	0.45
subbase (stabilized with chalk)	200	2000	0.50
Clay ground		20	0.50

- Traffic: 100 trucks/day, 300 days/year, growth +2% per year:

Axle load:	50 kN	90 kN	120 kN
100 trucks per day, 300 days per year	20%	60%	20%

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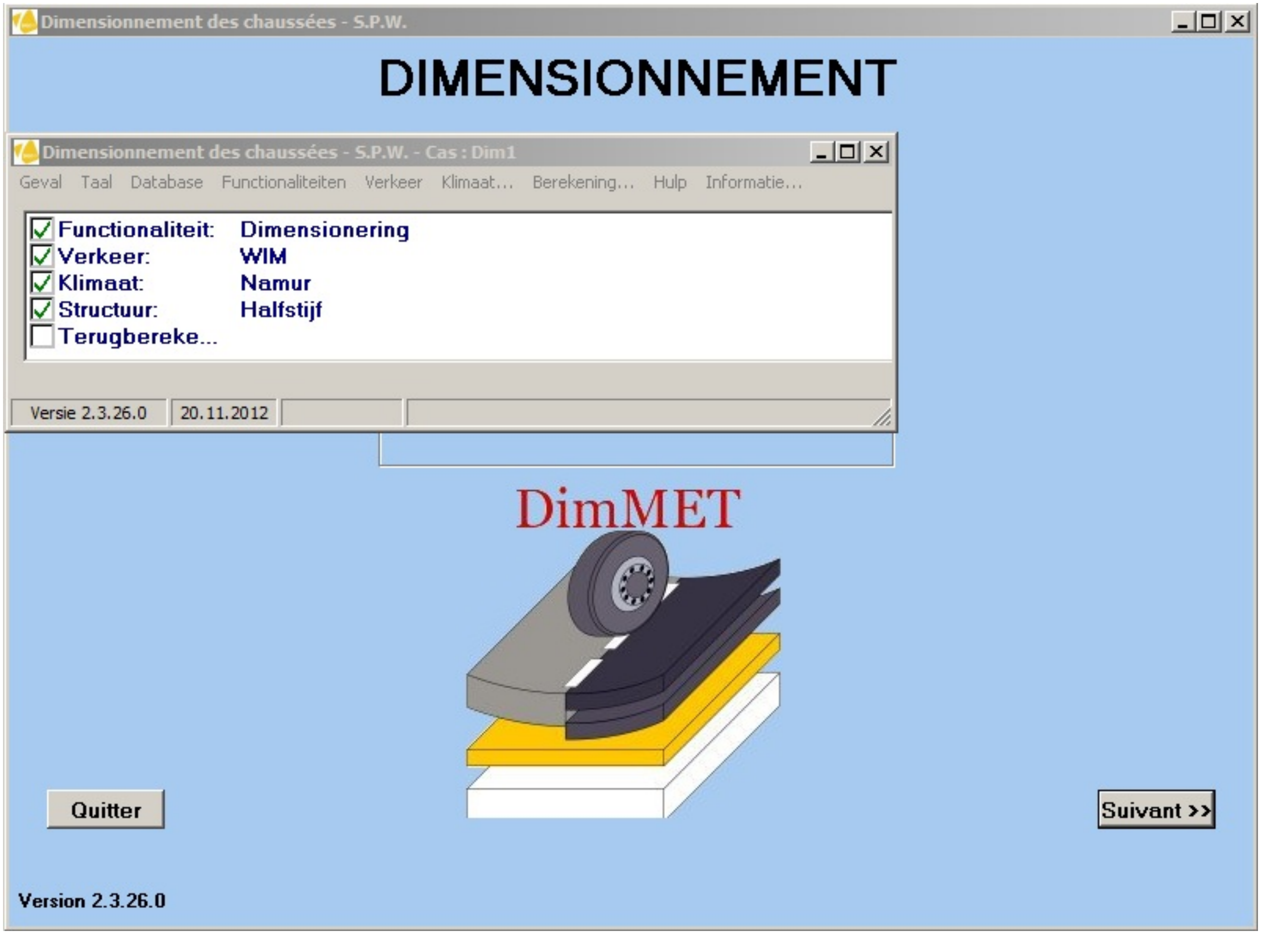
Study of the influence of thickness on the road lifetime…



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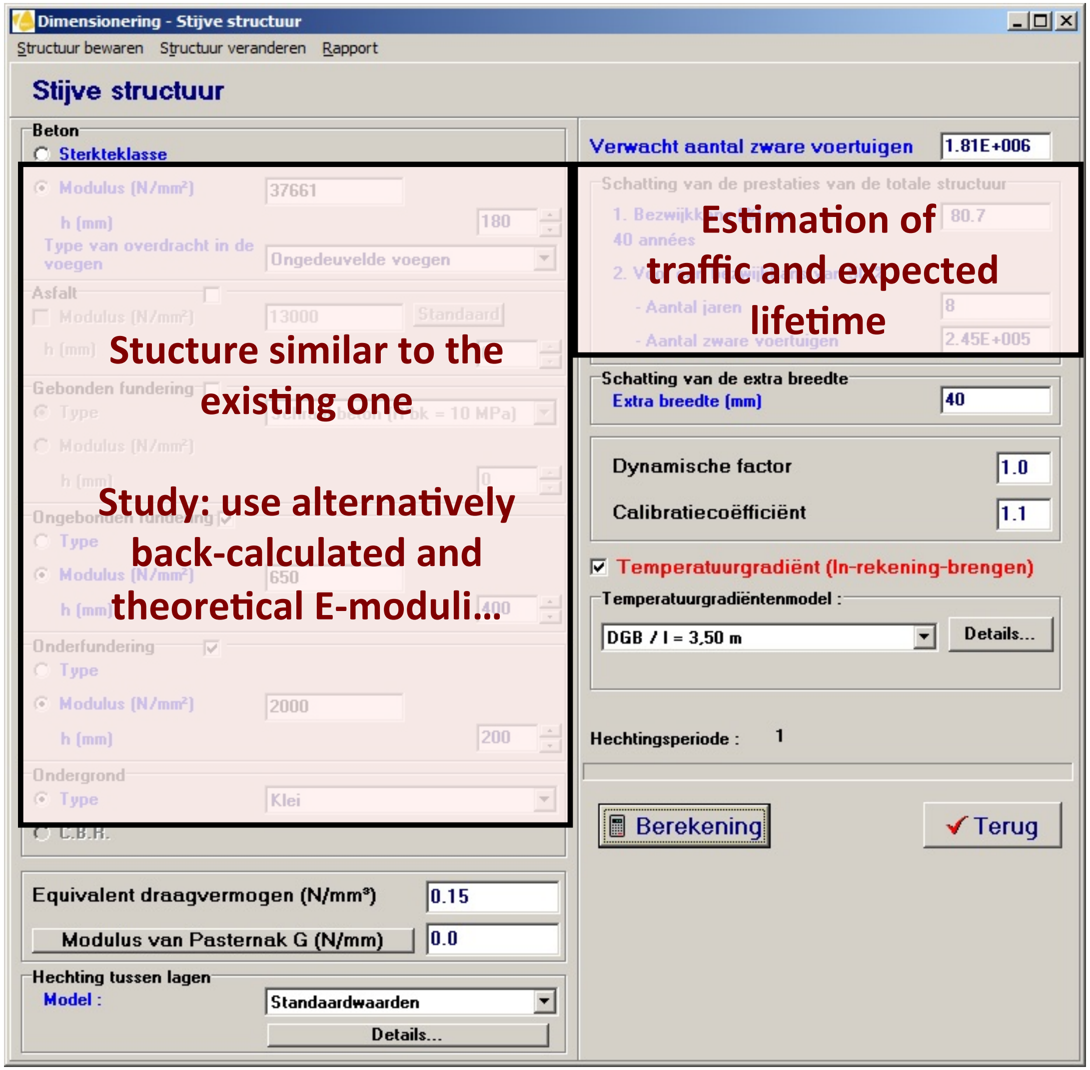
Study of the influence of thickness on the road lifetime…



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2 cm extra thickness is important!

- Lowering the thickness of the concrete slab in the theoretical model makes the estimated lifetime drop drastically

Thickness of concrete slab (mm)	200	190	180
Number of standard axles N_c that can go over the road	$2.45*10^6$	$6.60*10^5$	$1.52*10^5$
Estimated life-time (in years)	> 40	18	5

> Note: this does not mean that the thicknesses of the layers underneath are of no significance…

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Author

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In 1996, Carl Van Geem earned the doctoral degree in technical sciences from the Research Institute on Symbolic Computation (RISC-Linz), Johannes Kepler University, Linz, Austria.

The BRRC has several devices for the evaluation of road surface properties (roughness, skid resistence), for pavement management (visual inspection device "SAND"), and for measuring the bearing capacity of roads (FWD, curviameter, GPR). The main topic of Carl's research is the interpretation of data obtained with these monitoring devices for an optimal management of road maintenance. Carl participated in several national and international research projects, including a "national pre-normative research project on the indicators of roughness", the COST Action 354 "Performance Indicators for Road Pavements", the PIARC technical committee D1 "Management of Road Infrastructure Assets", and the FP7 project "Tomorrow's Road Infrastructure Monitoring and Management (TRIMM)".

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