

Trillingen en dynamica van spoorwegen

Presentatie voor de Nationale Wiskunde Dagen 2007

door dr.ir. Herke Stuit

The logo for Movares, featuring the word "Movares" in white text on a dark blue background, with a stylized orange and white arc above the letters "o" and "v".
Movares

vormgeven
aan
bereikbaarheid

Movares:

‘Vormgeven aan bereikbaarheid’

Movares is een advies- en ingenieursbureau op het gebied van mobiliteit en infrastructuur.

Movares genereert oplossingen voor vraagstukken betreffende capaciteit, veiligheid en inpassing.

- **Omzet 2006 ca. 140 miljoen euro, ca. 1300 fte werkzaam**
- **In Nederland**
 - hoofdkantoor in Utrecht
 - regiokantoren in Eindhoven, Weesp, Zoetermeer en Zwolle
- **In Europa**
 - vestigingen in Duitsland, Polen en Portugal
 - projecten o.a. in Frankrijk, Slowakije, Slovenië en Spanje

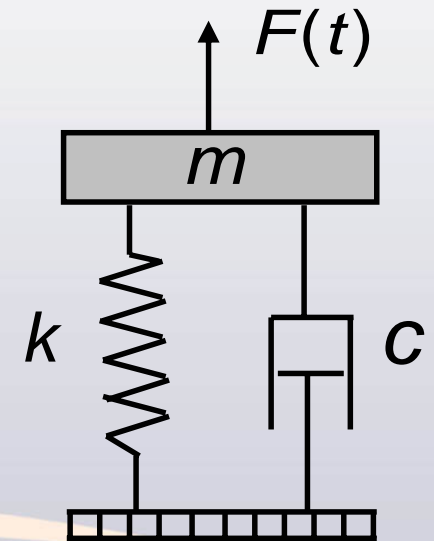
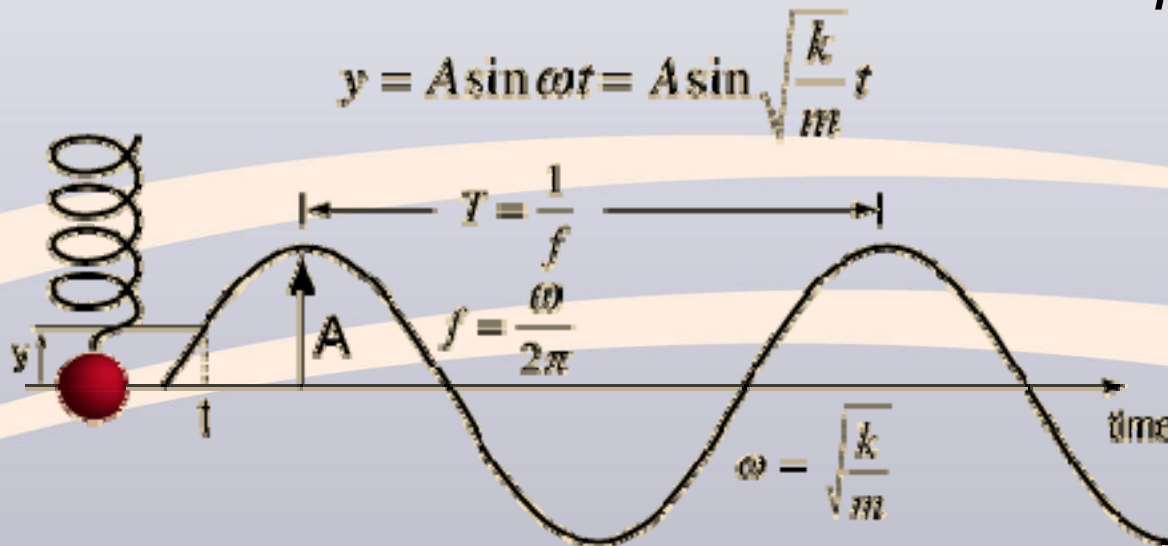


Inhoud

- **Inleiding trillingen**
- **Trillingen spoor**
- **Rekenmodellen**
- **Special: Kritieke treinsnelheid ZZL**
- **Project Trillingen**

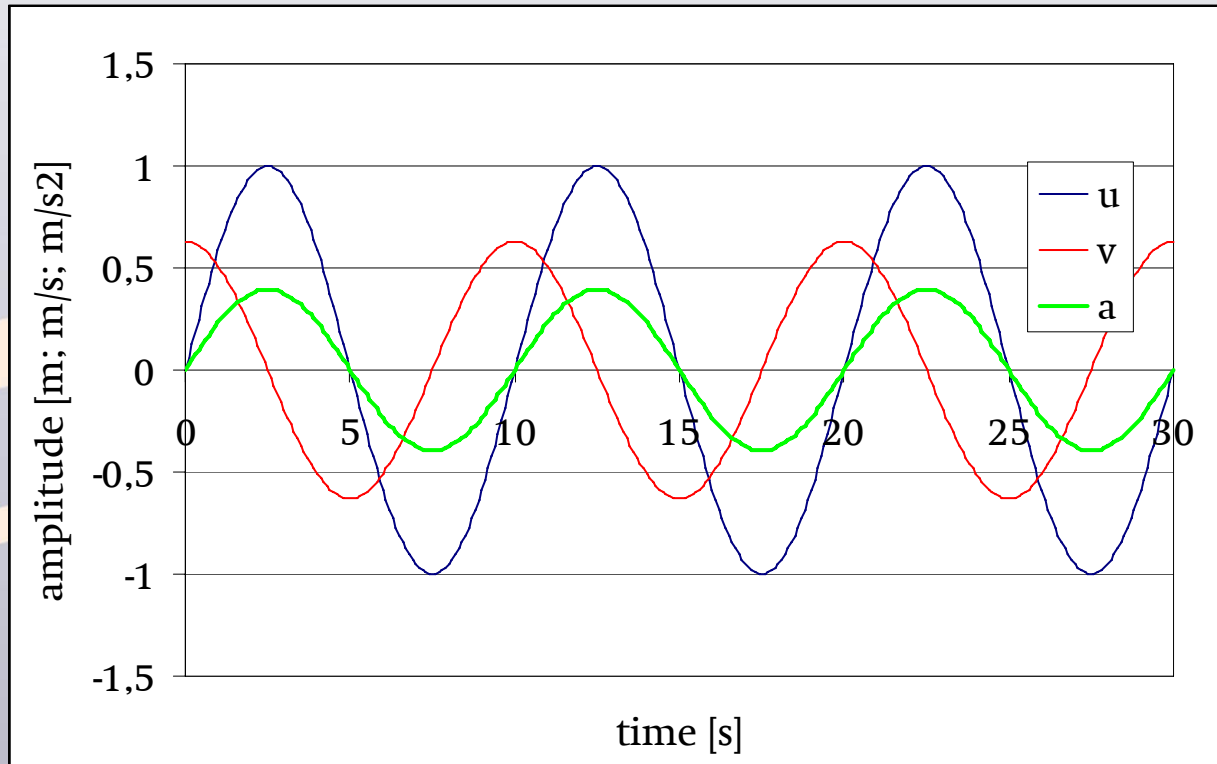
Voorbeeld massa-veer systeem

Harmonische beweging zonder demping



$$m \frac{d^2 u}{dt^2} + c \frac{du}{dt} + ku = F(t)$$

Verplaatsing – snelheid - versnelling



Relatie verplaatsing, snelheid, versnelling

De verplaatsing is: $u = A \sin(2\pi f t)$

- De afgeleide van de verplaatsing geeft de snelheid

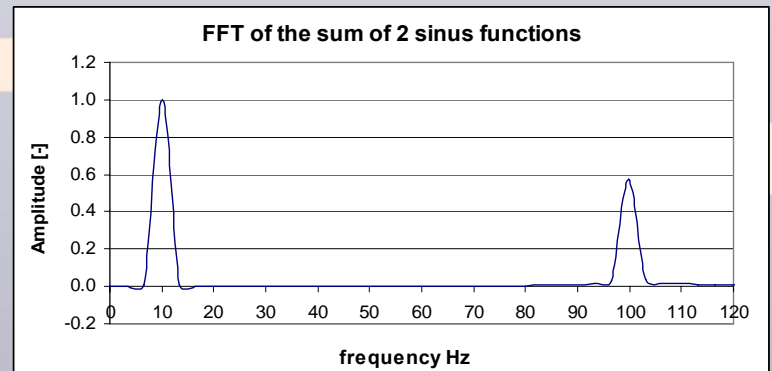
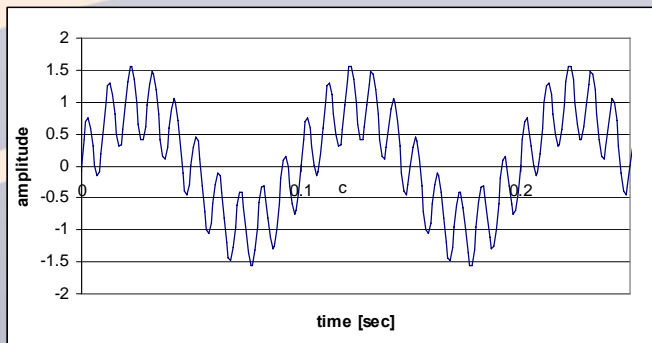
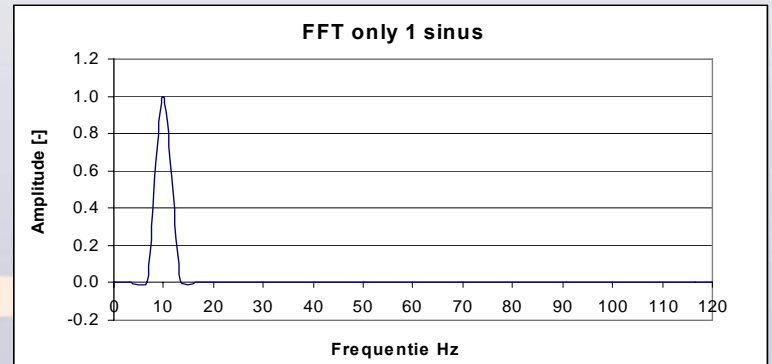
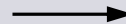
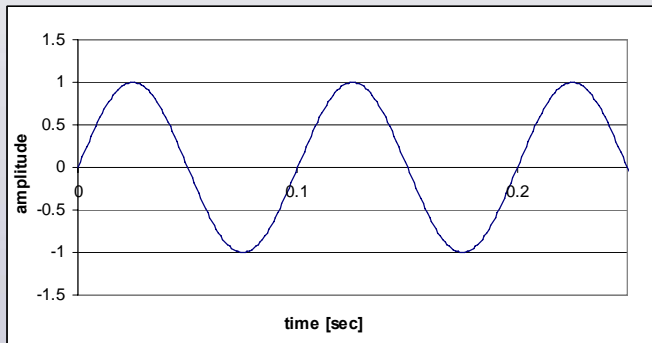
$$v = 2\pi f A \cos(2\pi f t)$$

- De afgeleide van de snelheid geeft de versnelling

$$a = -4\pi^2 f^2 A \sin(2\pi f t)$$

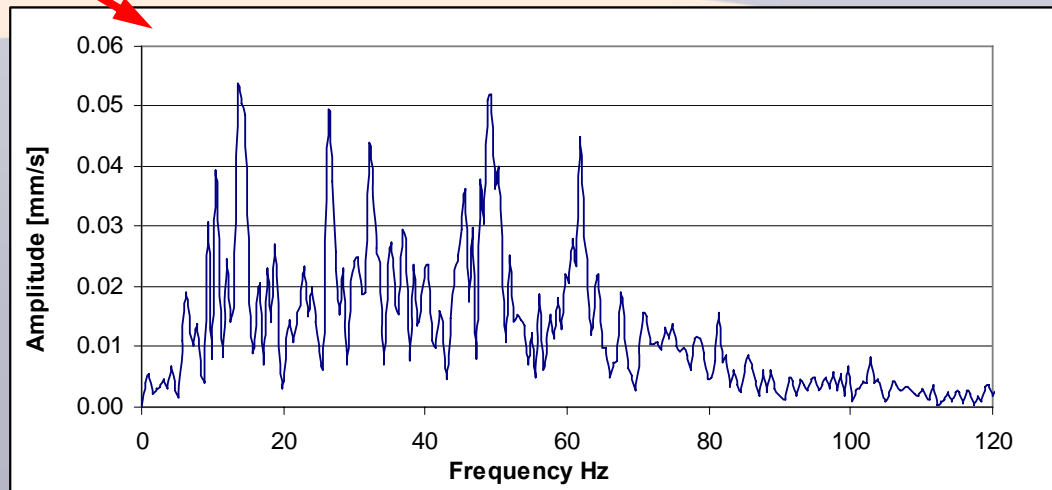
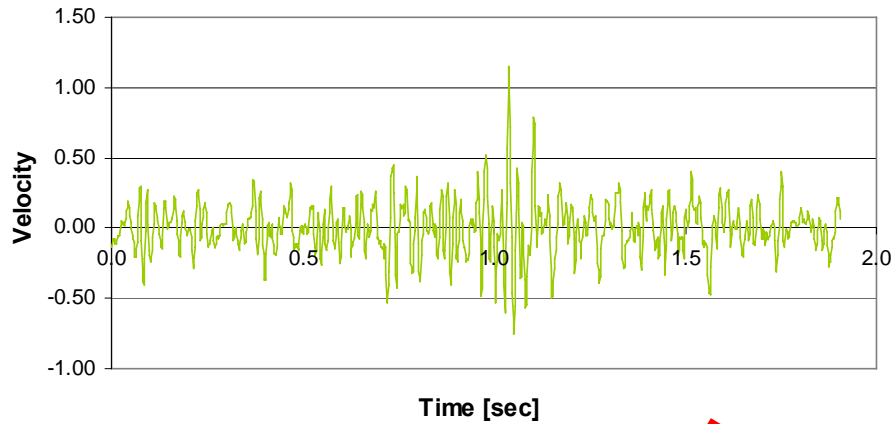
Frequentie response

FT = Fourier Transformation



Frequentie response van een trein

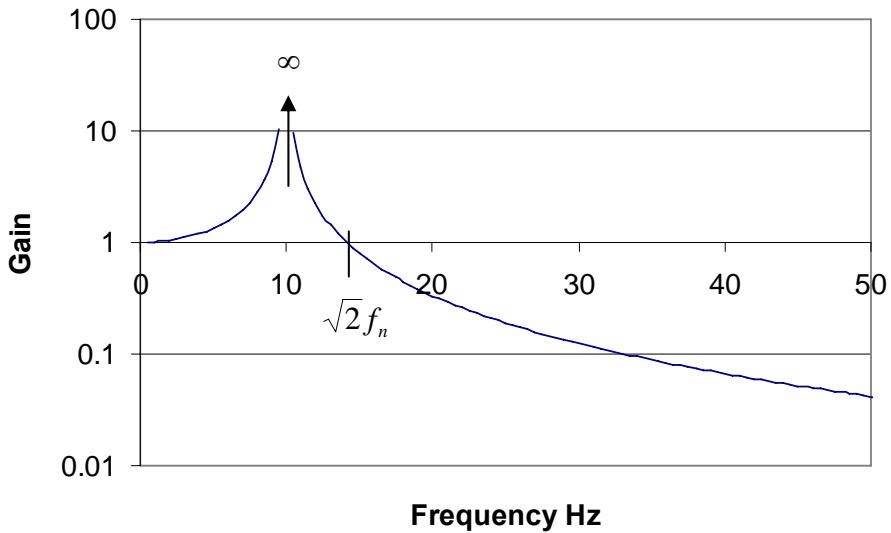
Measurment of vibration



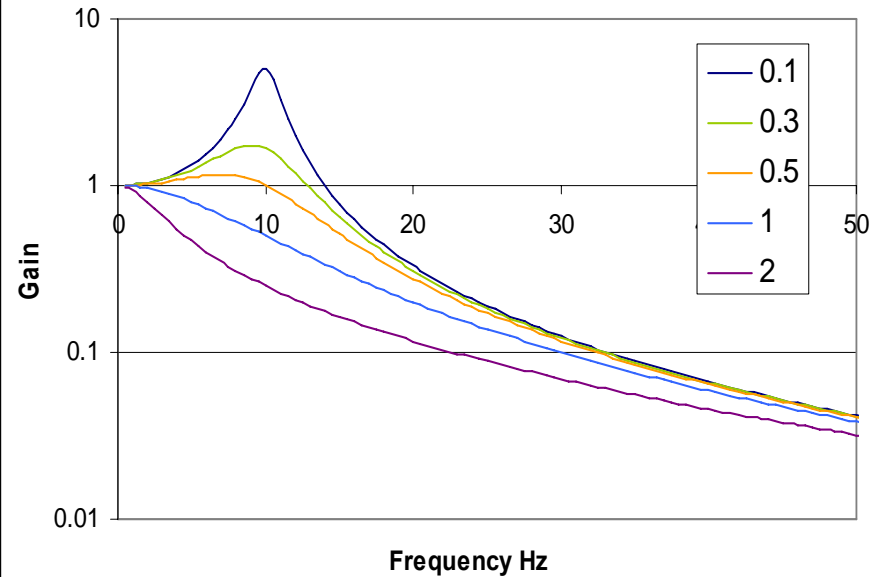
Frequentie response met / zonder damping

Massa-veer systeem

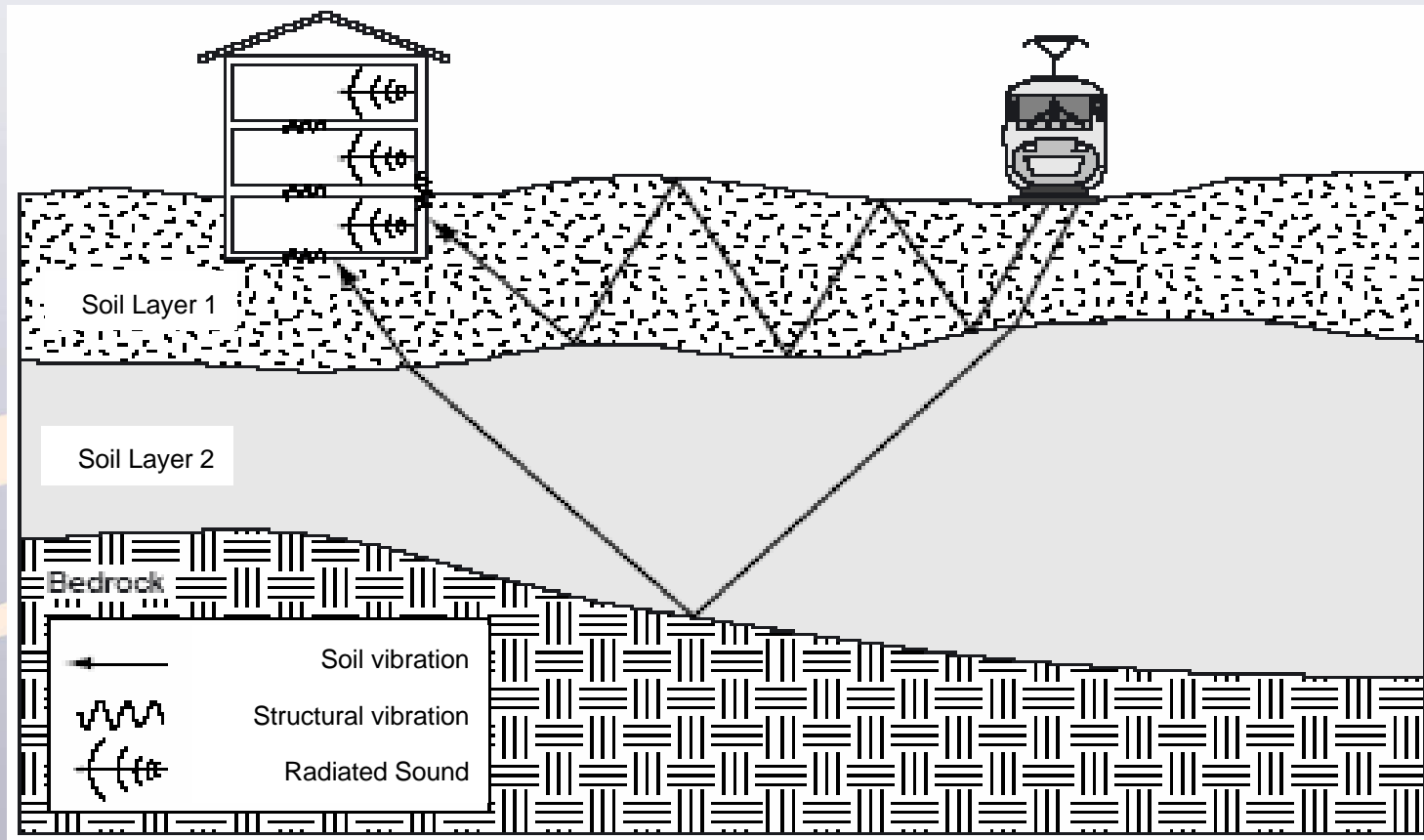
Frequency response without damping



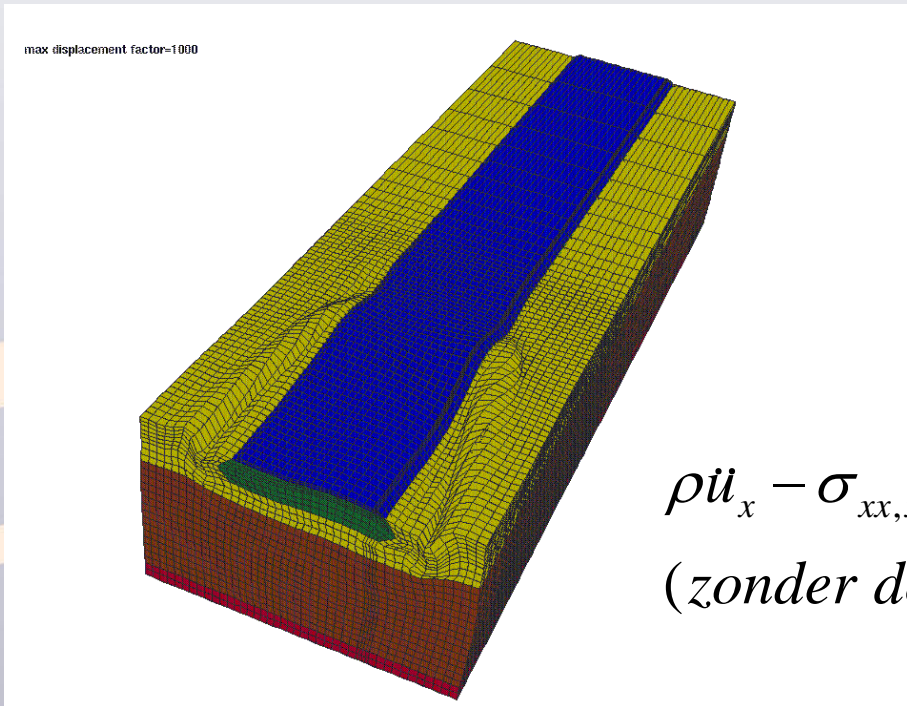
Frequency response with damping



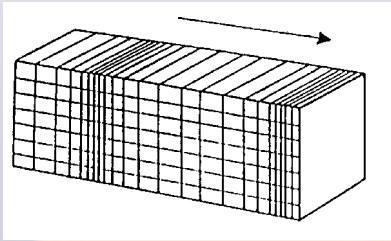
Trillingen spoor



En nu in de grond

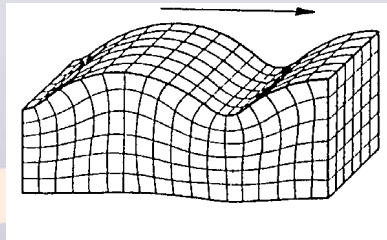


Verschillende golven in de grond



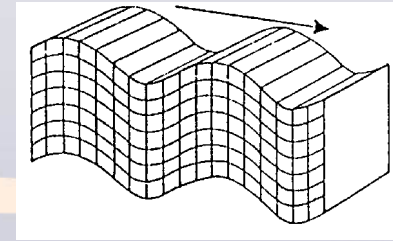
Druk golf

$$C_p = \sqrt{\frac{G_{dyn}}{\rho} \frac{2(1-\nu)}{(1-2\nu)}}$$



Schuif golf

$$C_s = \sqrt{\frac{G_{dyn}}{\rho}}$$



Rayleigh golf

$$C_R \approx 0.9 \cdot C_s$$

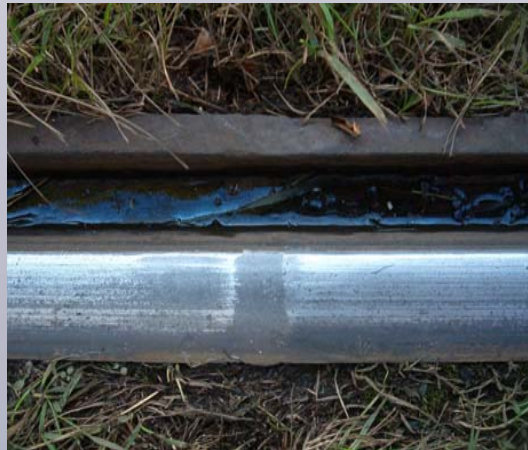
Factoren van invloed op trillingen



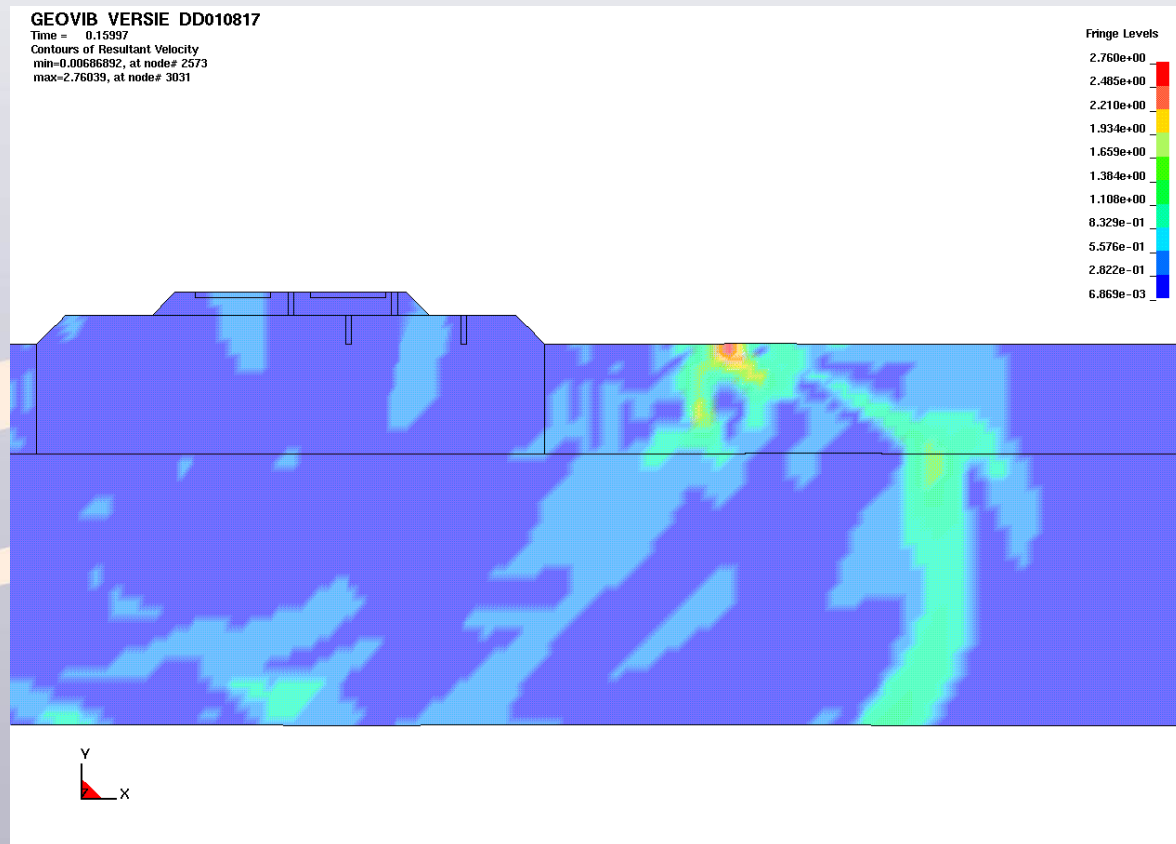
treintype
snelheid
rails
baanlichaam
kunstwerk

bodem
geometrie
afstand

hinder
schade
apparatuur



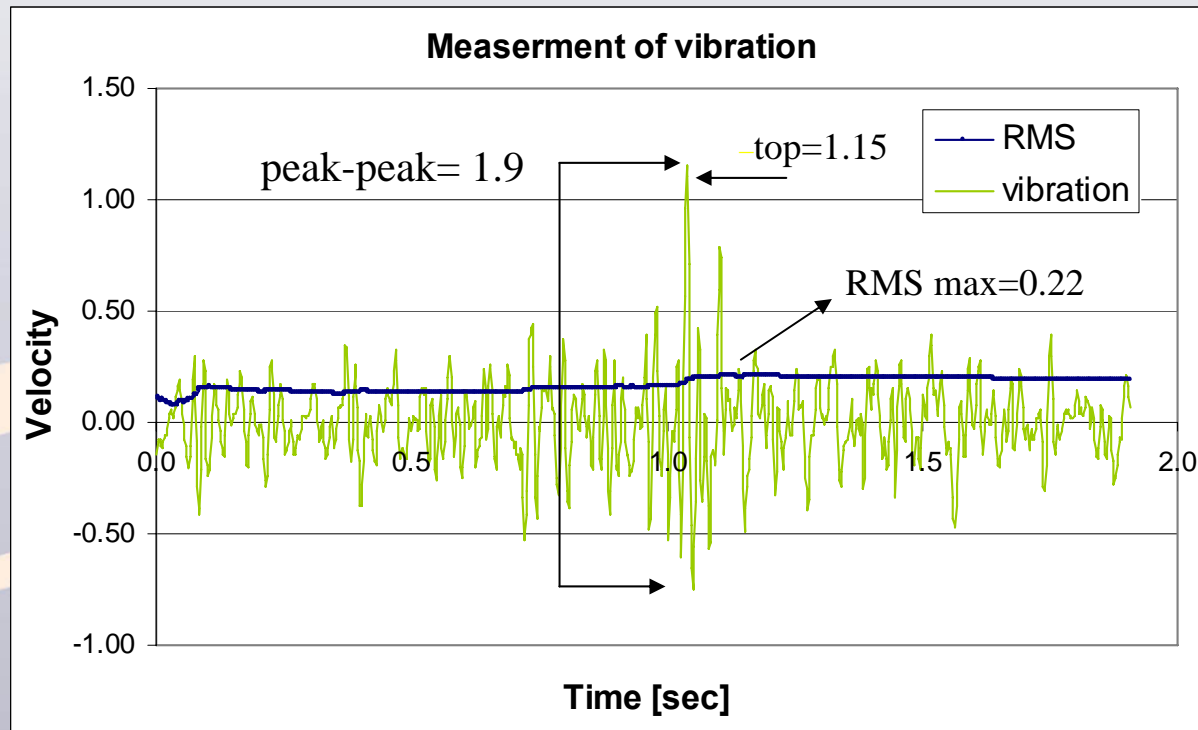
Trillingen onder het spoor



Schade/ hinder ?



Weergave amplitudes

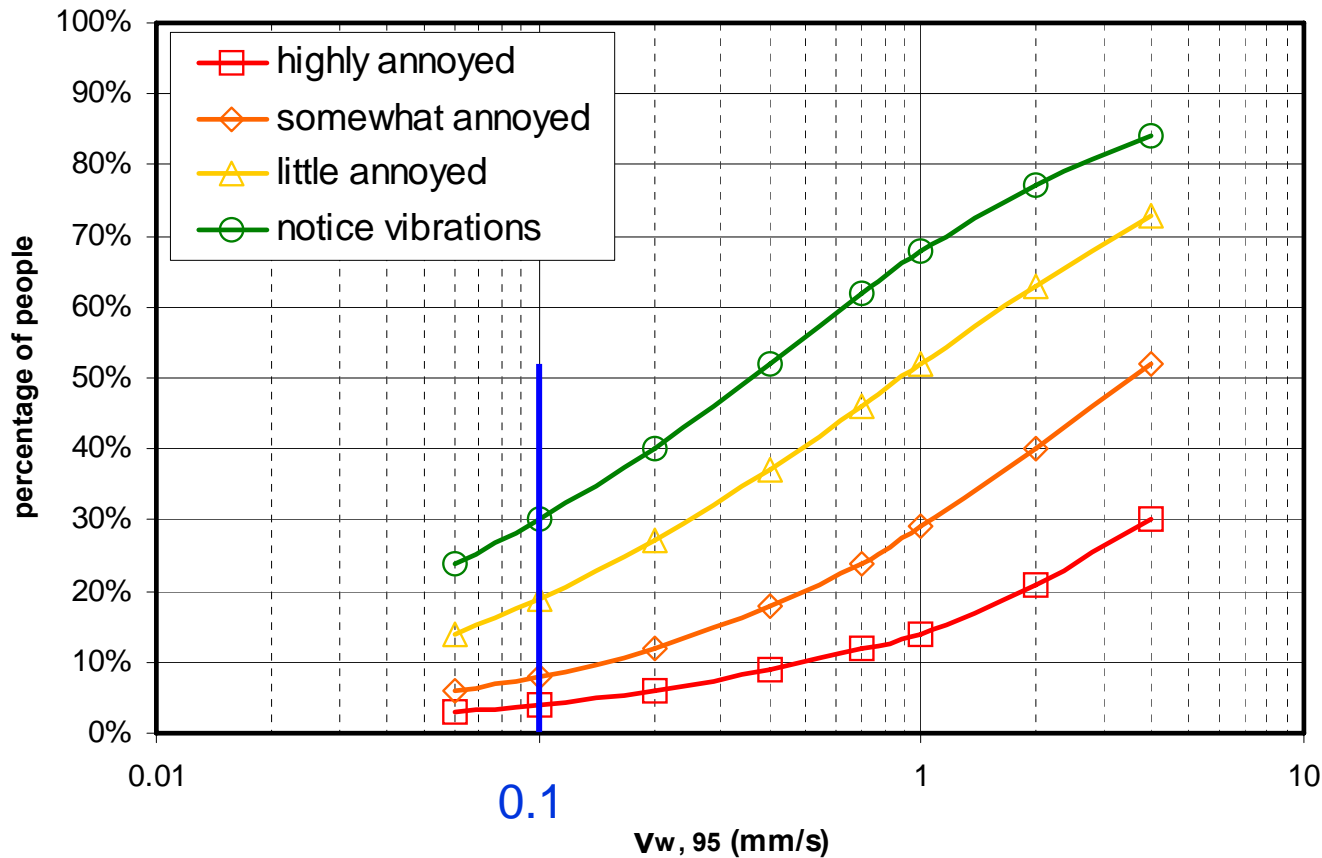


Classificatie van trillingen

<u>Human/Structural response</u>	<u>Velocity Level [mm/s]</u>	<u>Typical sources (approx. 15m from source)</u>
Threshold, minor cosmetic damage fragile buildings	2.500 2.000 1.500	Blasting from construction projects
Difficulty with tasks such as reading VDT screen	1.000 0.800 0.600	Bulldozers and other heavy construction equipment
Residential annoyance, infrequent events	0.500 0.330 0.250 0.200	Commuter rail, upper range Rapid transit, upper range
Residential annoyance, frequent events	0.150 0.100 0.080	Bus or truck over a bump Rapid transit, typical
Approx. threshold for human perception	0.060 0.050 0.033 0.025 0.020	Bus or truck, typical
sensitive equipment	0.015 0.010 0.008	typical background noise

Exposure effect relationships

Norwegian Socio-vibrational Survey

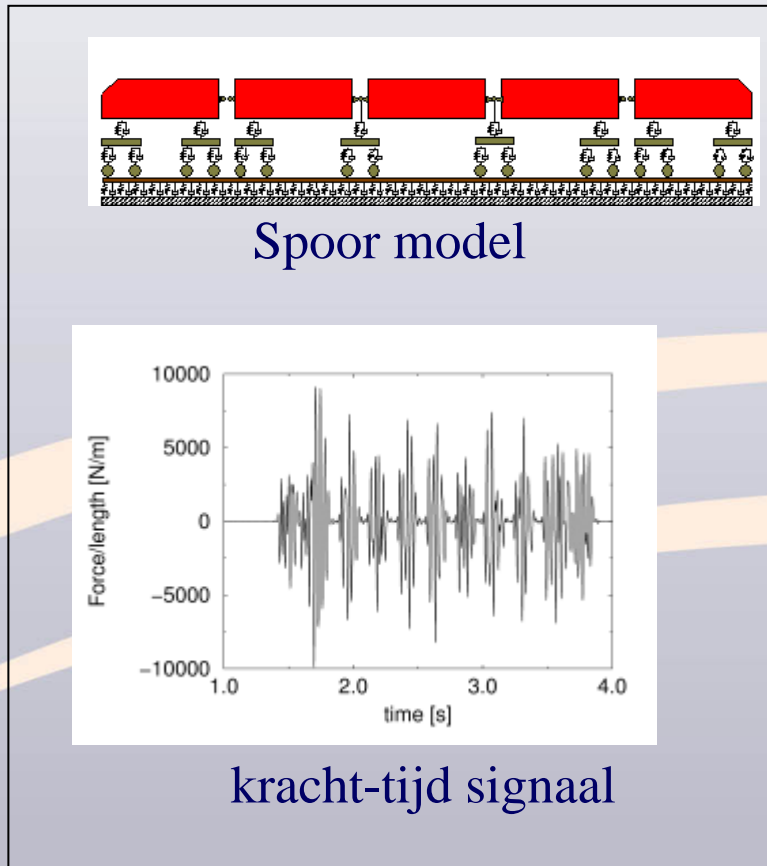


Nederland:
Beoordeling volgens
SBR richtlijnen

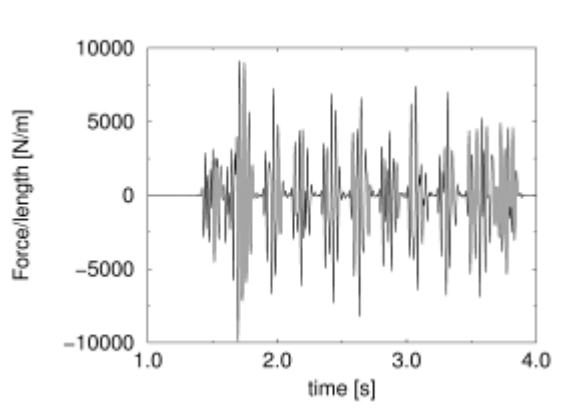
$V < 0.1$

Treinen in nieuwe
situaties.

Rekenmodellen



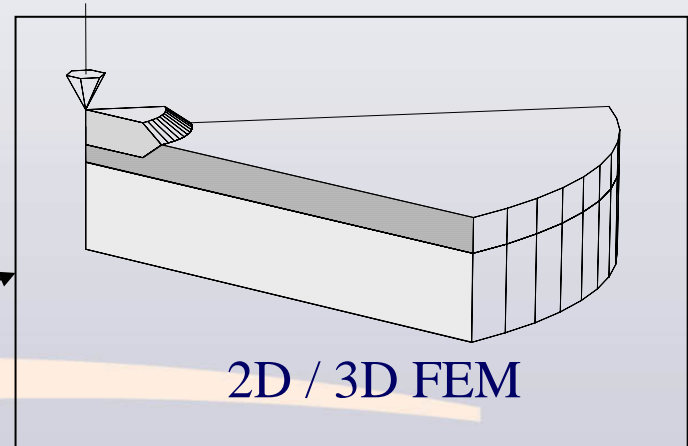
Spoor model



kracht-tijd signaal

bron

$F(t)$



2D / 3D FEM

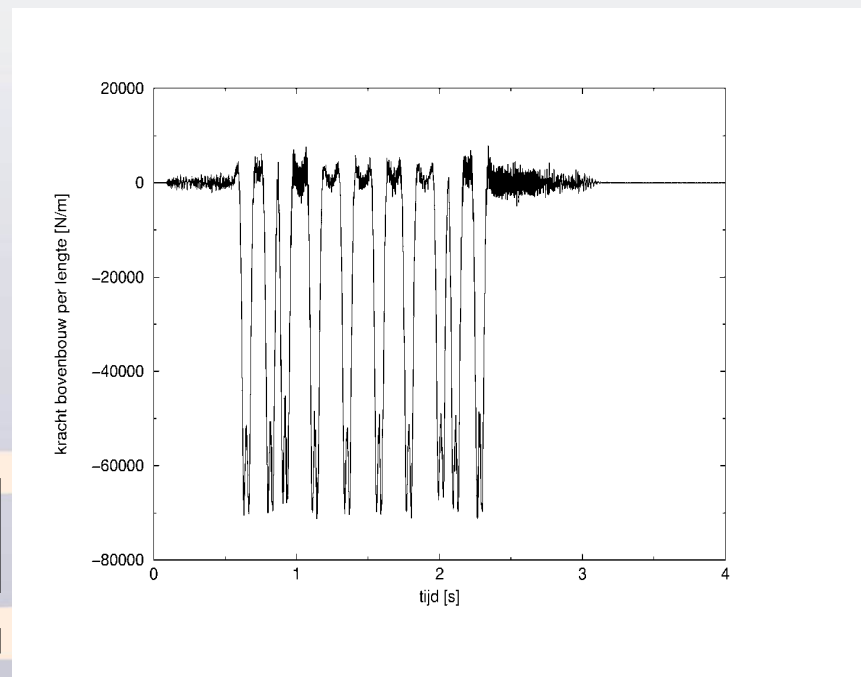
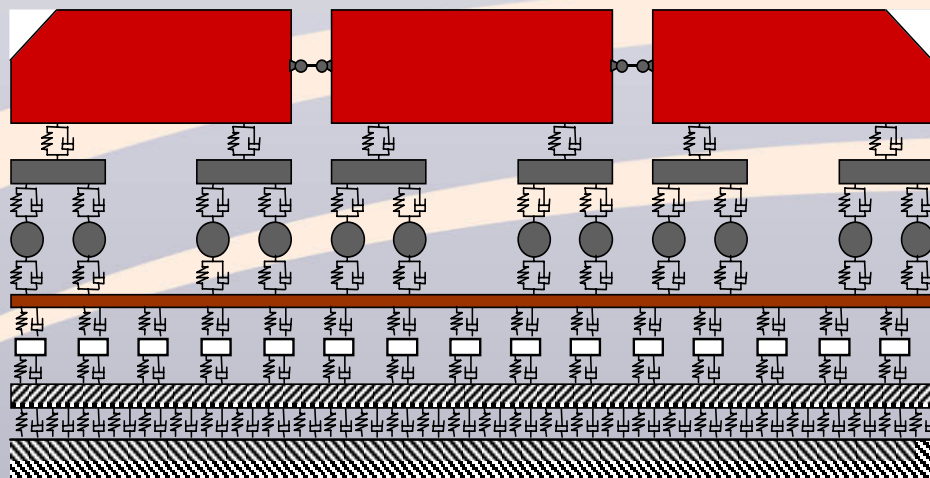
voortplanting

V_{\max} , V_{eff} , V_{per}

Check met SBR richtlijnen

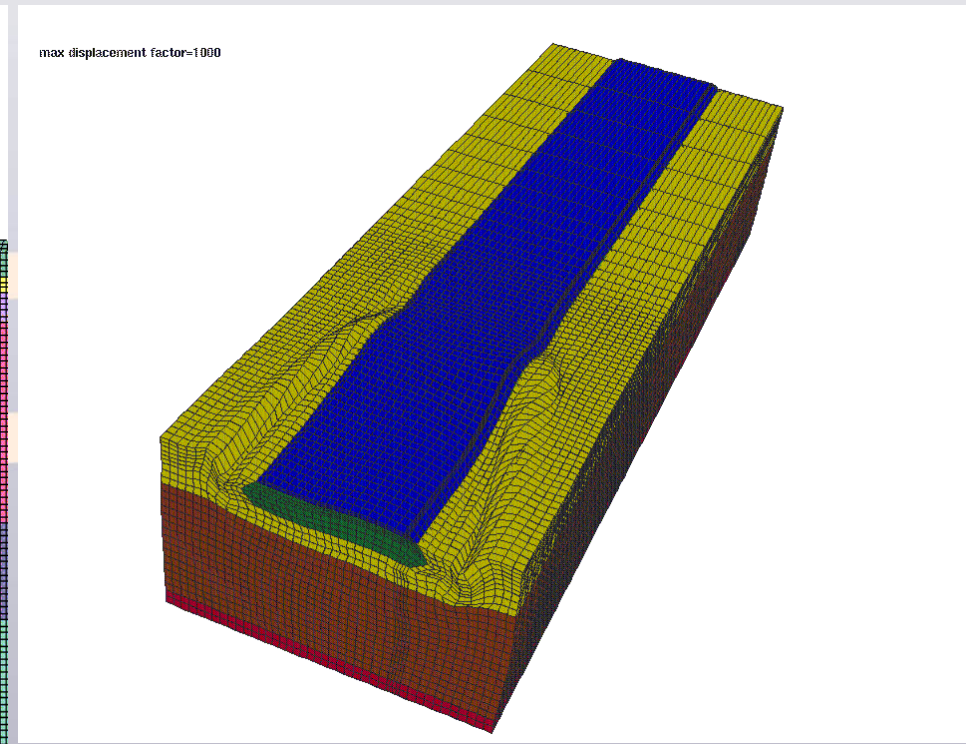
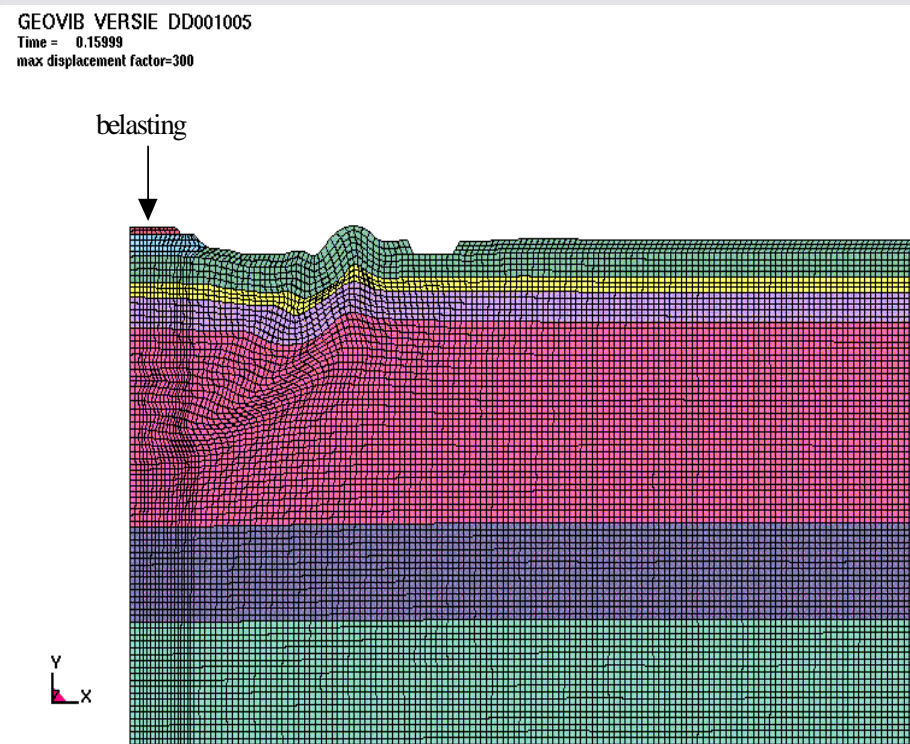
Schade / Hinder

Simulatie railverkeer



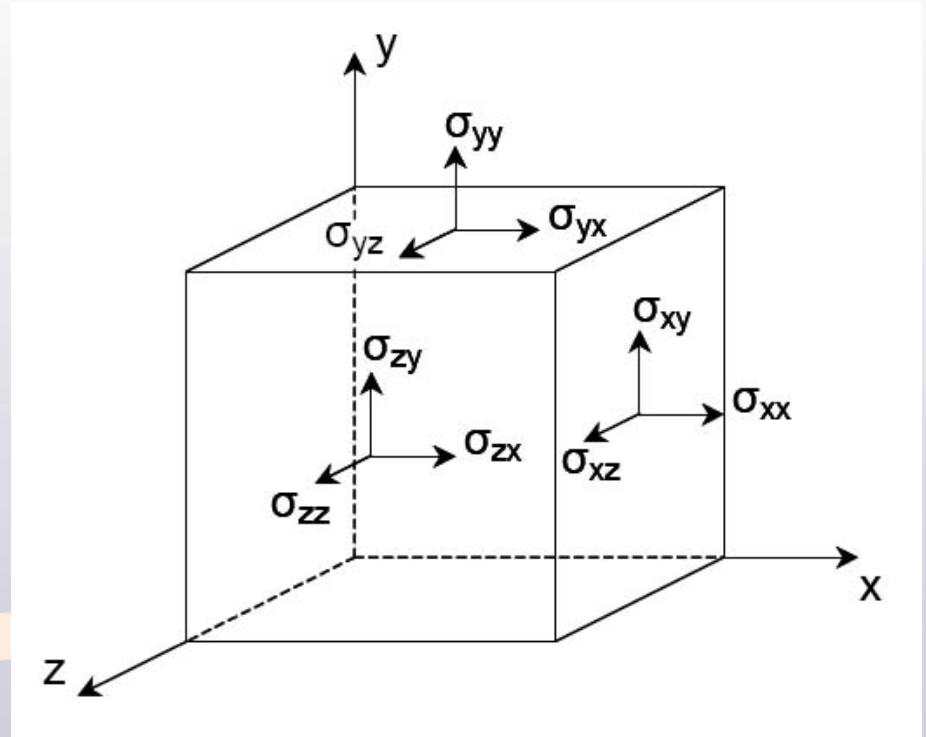
- Rails
- Ballast + sleepers
- Inlay tunnel
- Fixed subsoil

Golfvoortplanting bodem



Rekenmethode in elementen

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$



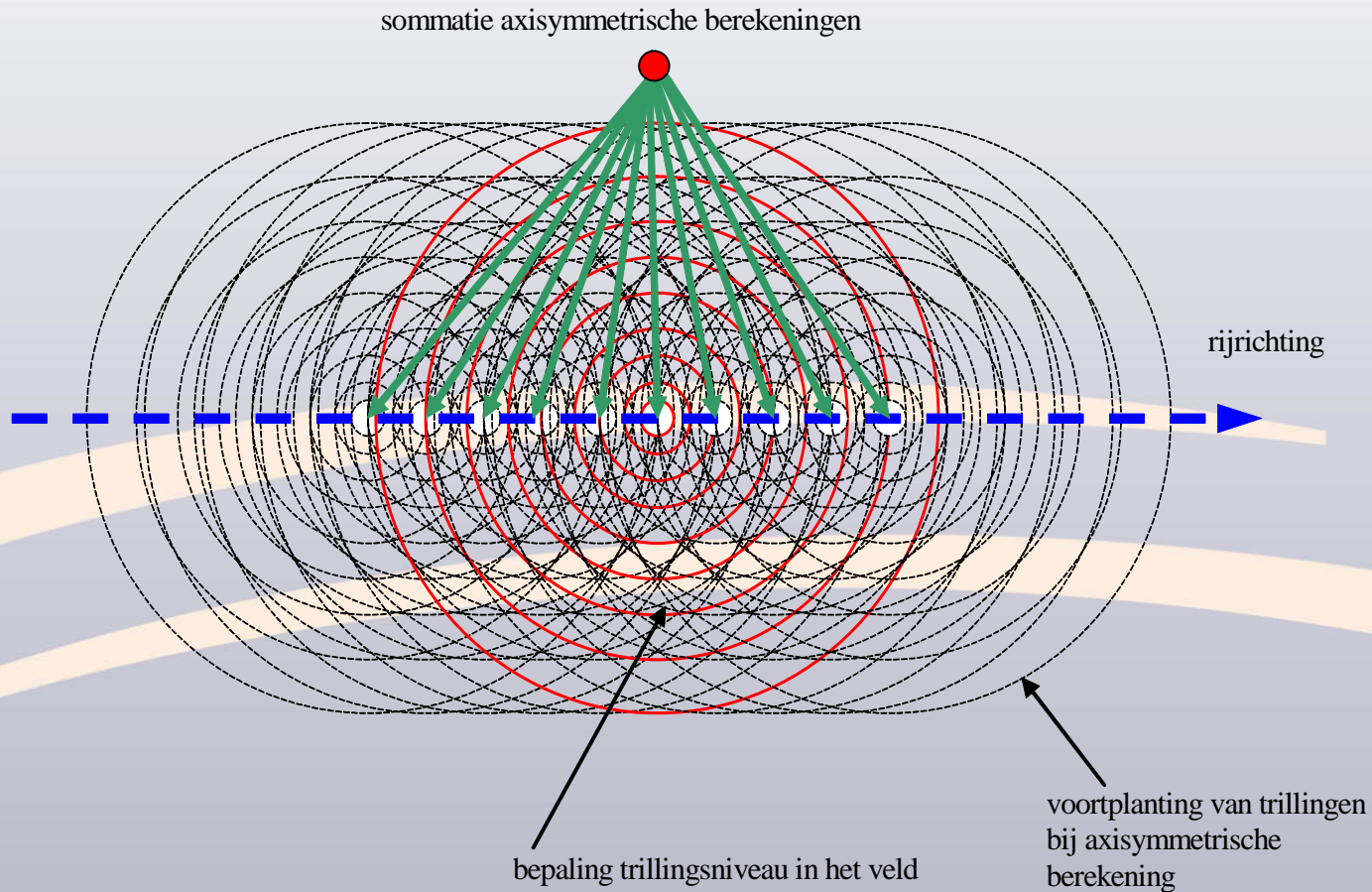
$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} & \gamma_{xy} & \gamma_{xz} \\ \gamma_{yx} & \varepsilon_{yy} & \gamma_{yz} \\ \gamma_{zx} & \gamma_{zy} & \varepsilon_{zz} \end{bmatrix} = \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{1}{2} \left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right) & \frac{1}{2} \left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x} \right) \\ \frac{1}{2} \left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y} \right) & \frac{\partial u_y}{\partial y} & \frac{1}{2} \left(\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y} \right) \\ \frac{1}{2} \left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z} \right) & \frac{1}{2} \left(\frac{\partial u_z}{\partial y} + \frac{\partial u_y}{\partial z} \right) & \frac{\partial u_z}{\partial z} \end{bmatrix}$$

Rekenmethode in de tijd

$$u^{t+\Delta t} = u^t + \dot{u}^t \Delta t + \left(\left(\frac{1}{2} - \alpha \right) \ddot{u}^t + \alpha \ddot{u}^{t+\Delta t} \right) \Delta t^2$$

$$\dot{u}^{t+\Delta t} = \dot{u}^t + \left((1 - \beta) \ddot{u}^t + \beta \ddot{u}^{t+\Delta t} \right) \Delta t$$

Sommatie meerdere bronnen



Kritieke treinsnelheid, een probleem ?

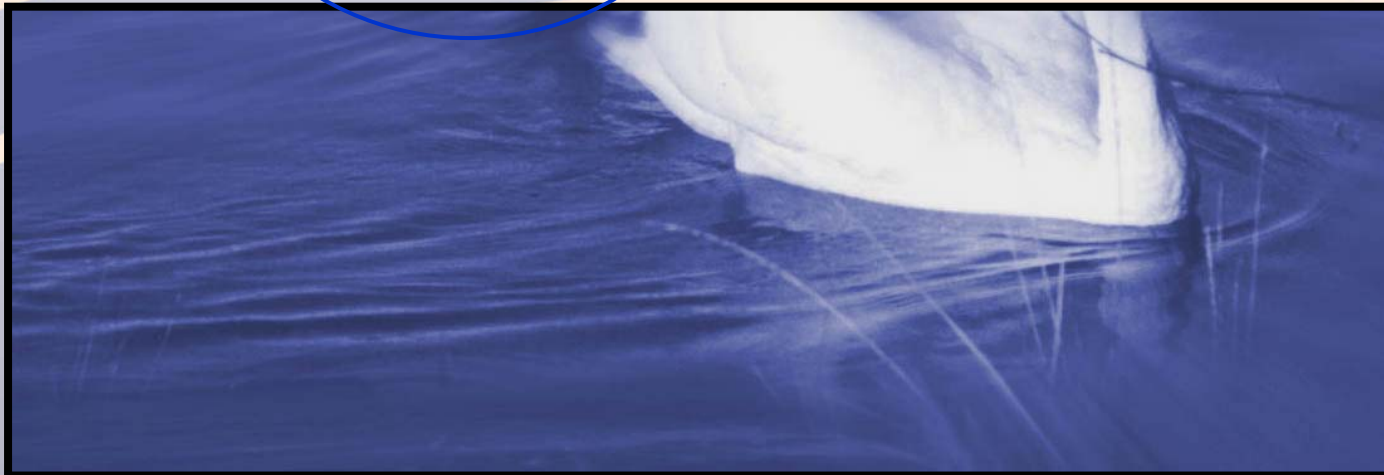
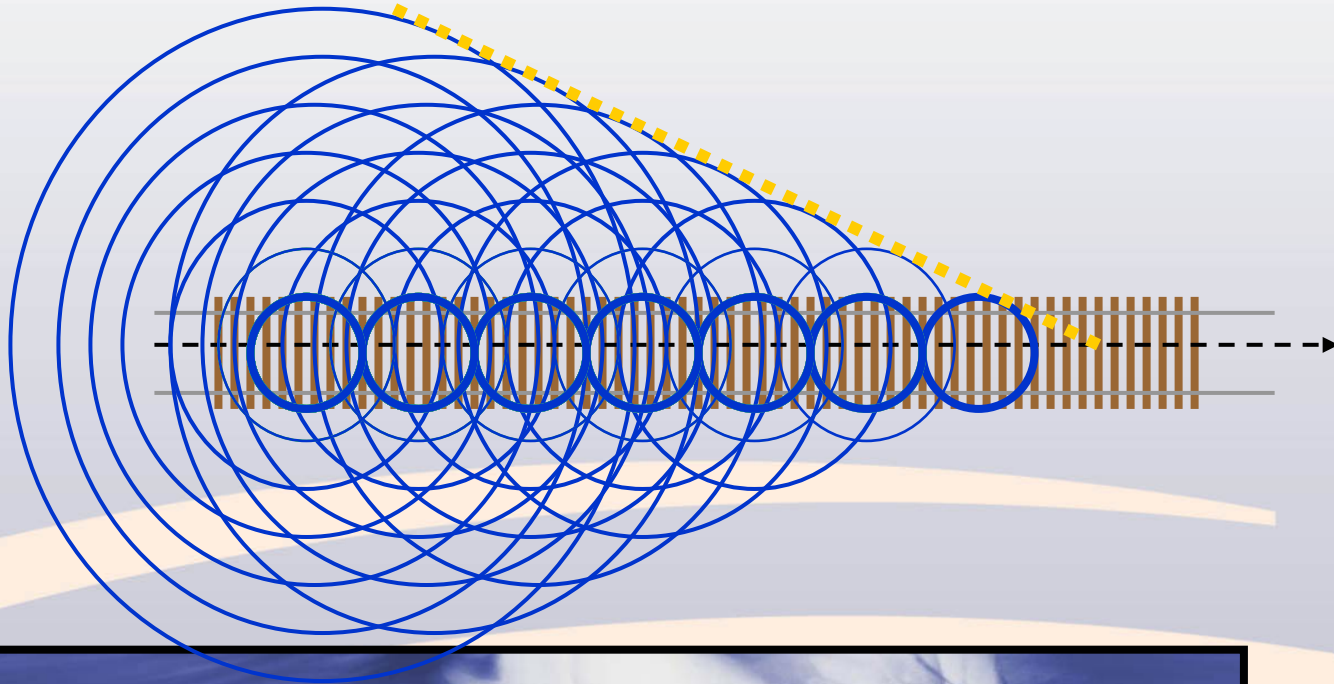
-
-
-
-
-
-



Voortplantingsnelheden bodem NL

Grondsoort	golfvoortplantingsnelheid	
	[m/s]	[km/h]
zand	100 - 250	360-900
klei	50 - 100	180-360
veen	40 - 80	140-300

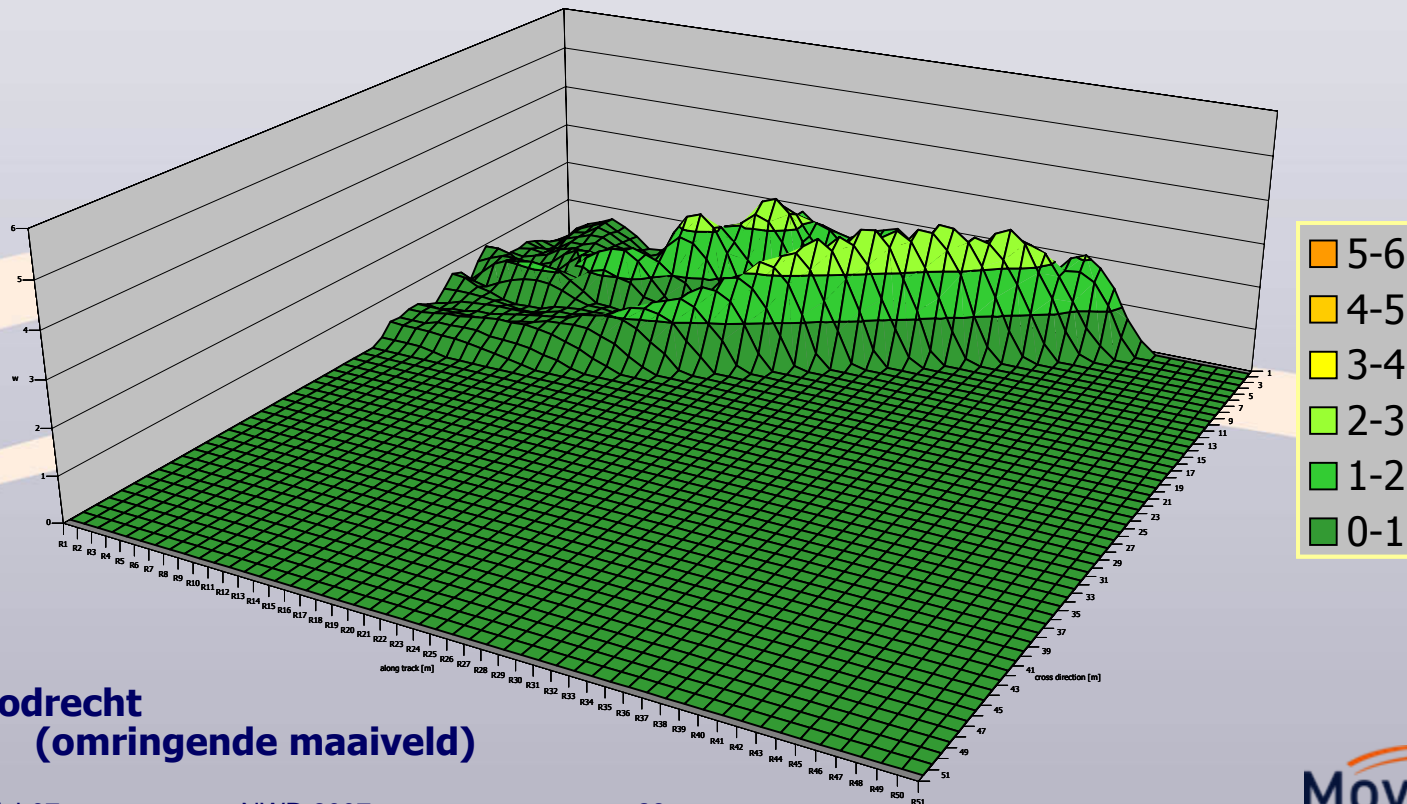
Kritieke treinsnelheid



Kritieke treinsnelheid

$$C_{\text{trein}} / C_{\text{bodem}} = 0.5; 0.75; 1.0; 1.5$$

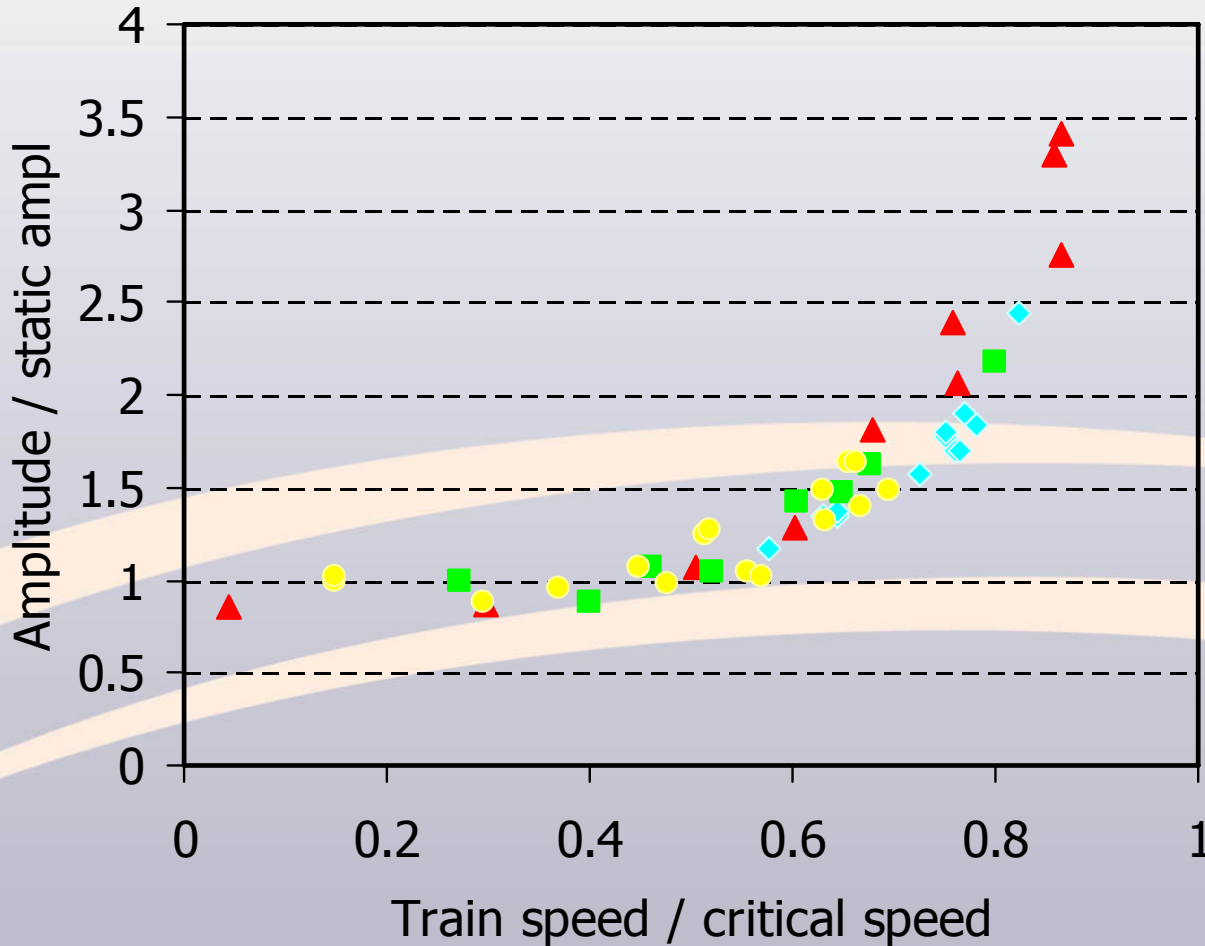
$c_{\text{source}} / c_{\text{soil}} = 2.0$ langs het spoor ↓



loodrecht
(omringende maaiveld)

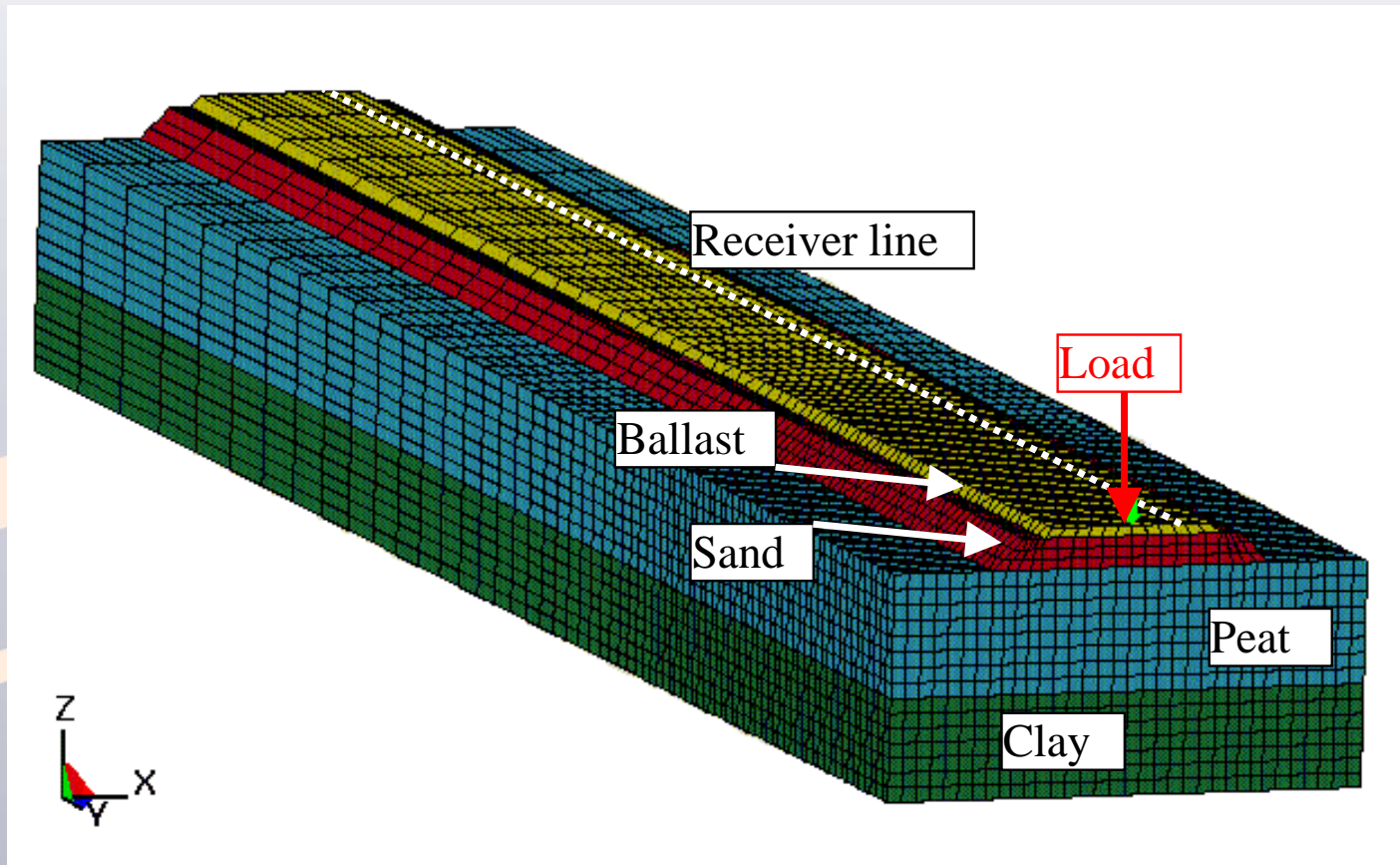
Kritieke treinsnelheid

UK 225 km/h
 S 235 km/h
 NL 150 km/h
 270 km/h



- ◆ Stilton Fen (UK)
- ▲ Ledsgard (S)
- Oosthuizen (NL)
- Maarssen (NL)

Rekenmodel van het baanlichaam



Rekenresultaten

- **EEM model**

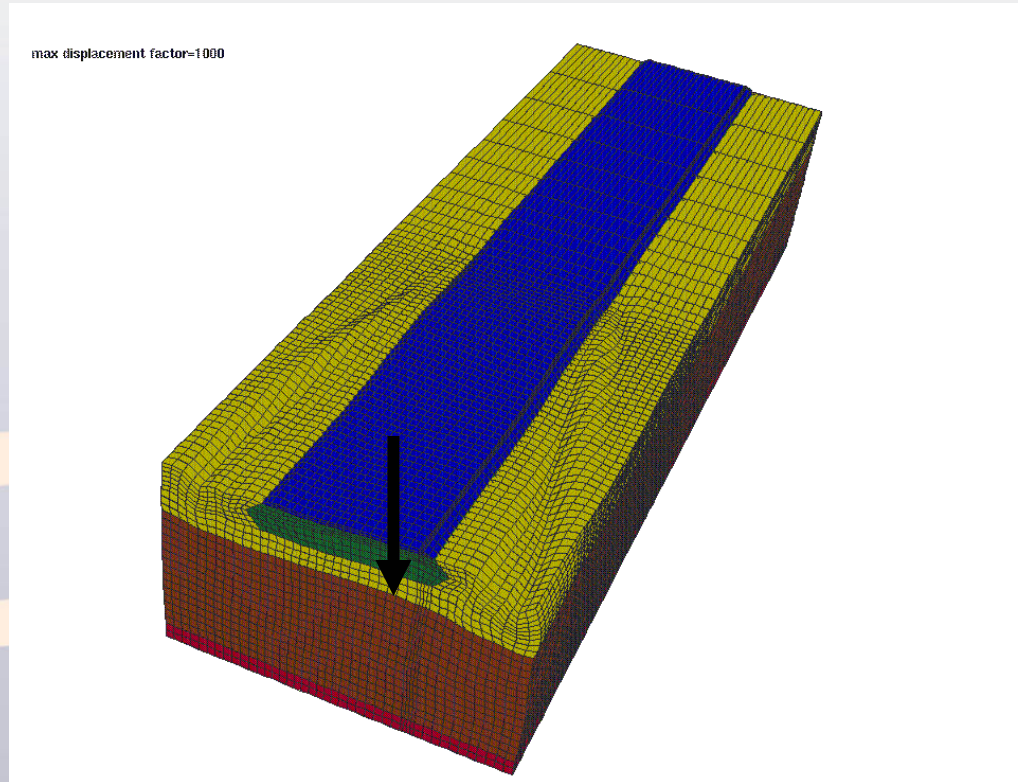
-

-

-

-

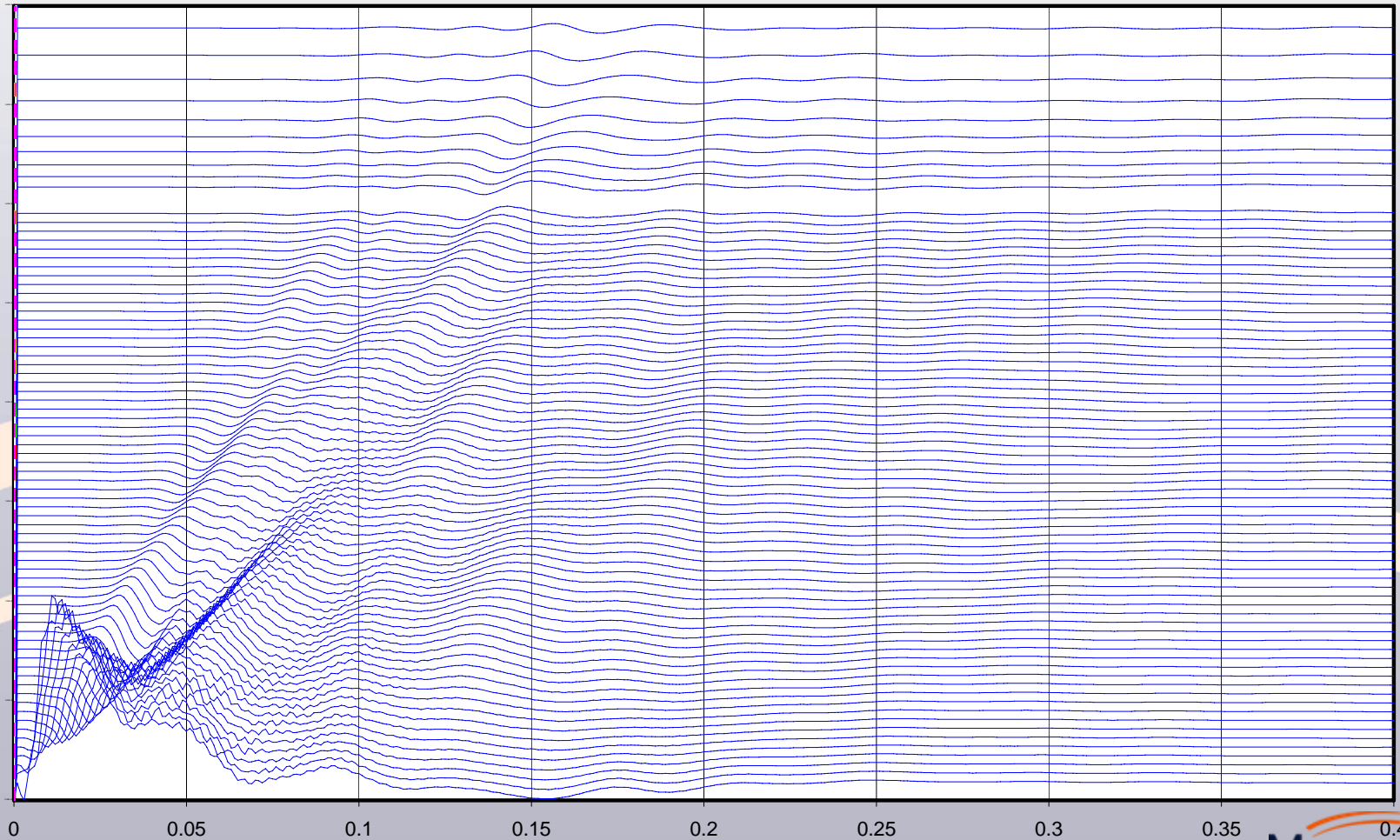
-



puls belasting

=> responsie

Resultaten



0

0.05

0.1

0.15

0.2

0.25

0.3

0.35

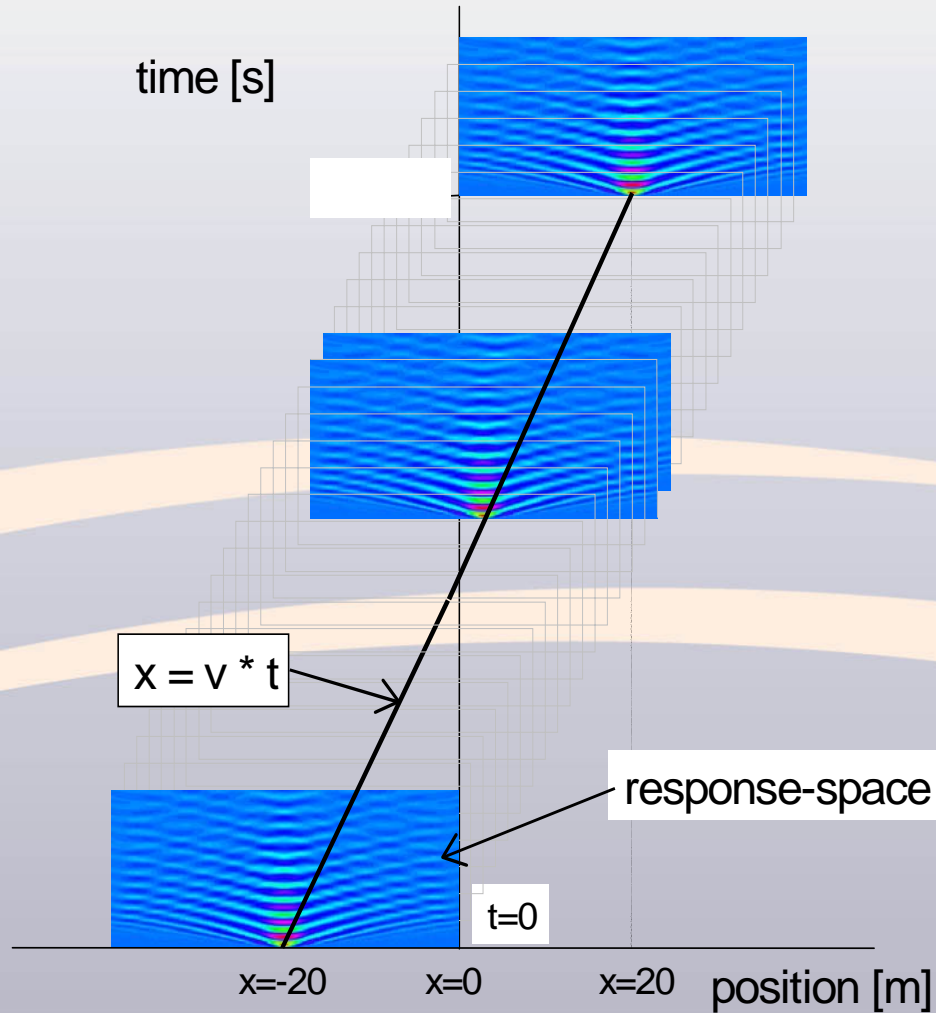
0.4

03feb07

NWD 2007

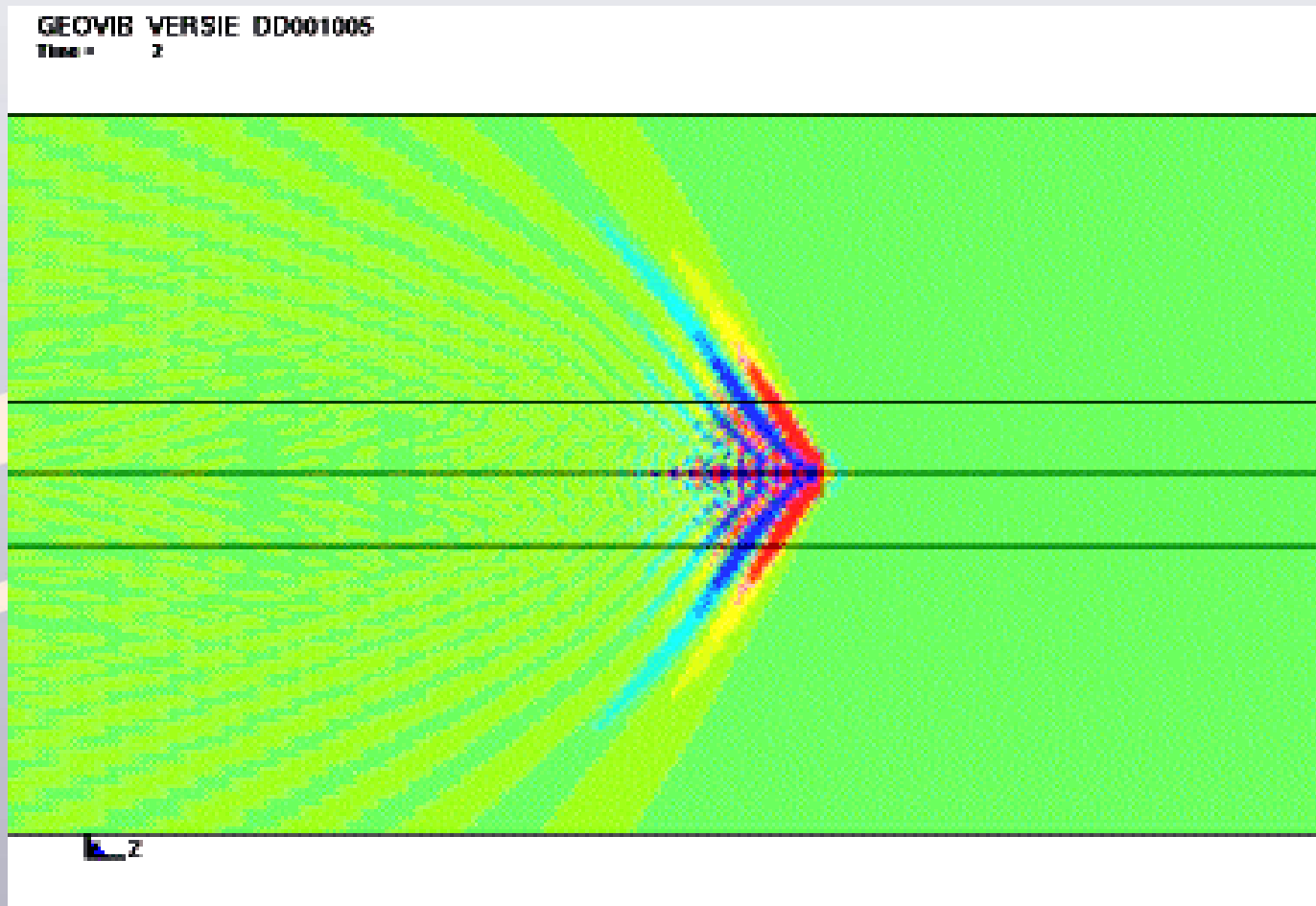
32

Response integratie



Kritieke treinsnelheid

top view (3D FEM)



ZZL

bodemprofiel

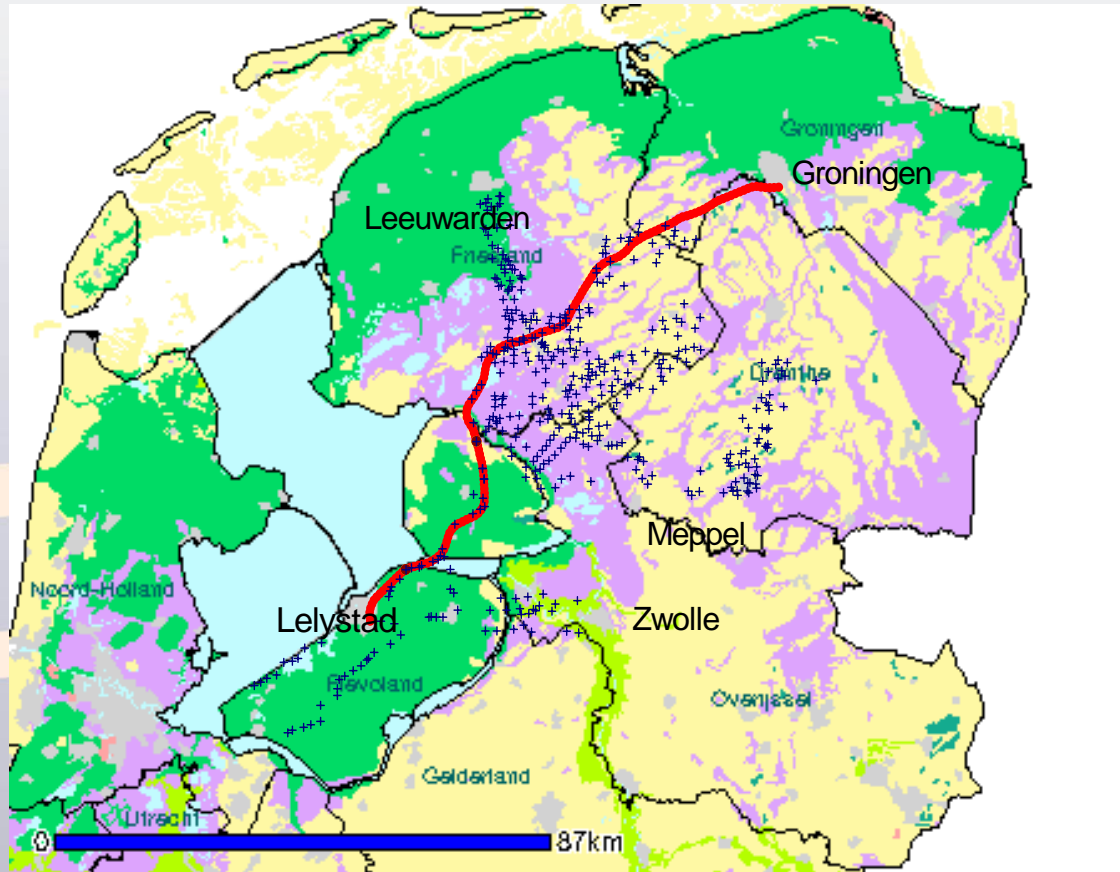
bodem voortpl. Snelh.
[km/u]

sand 360 - 900

clay 180 - 360

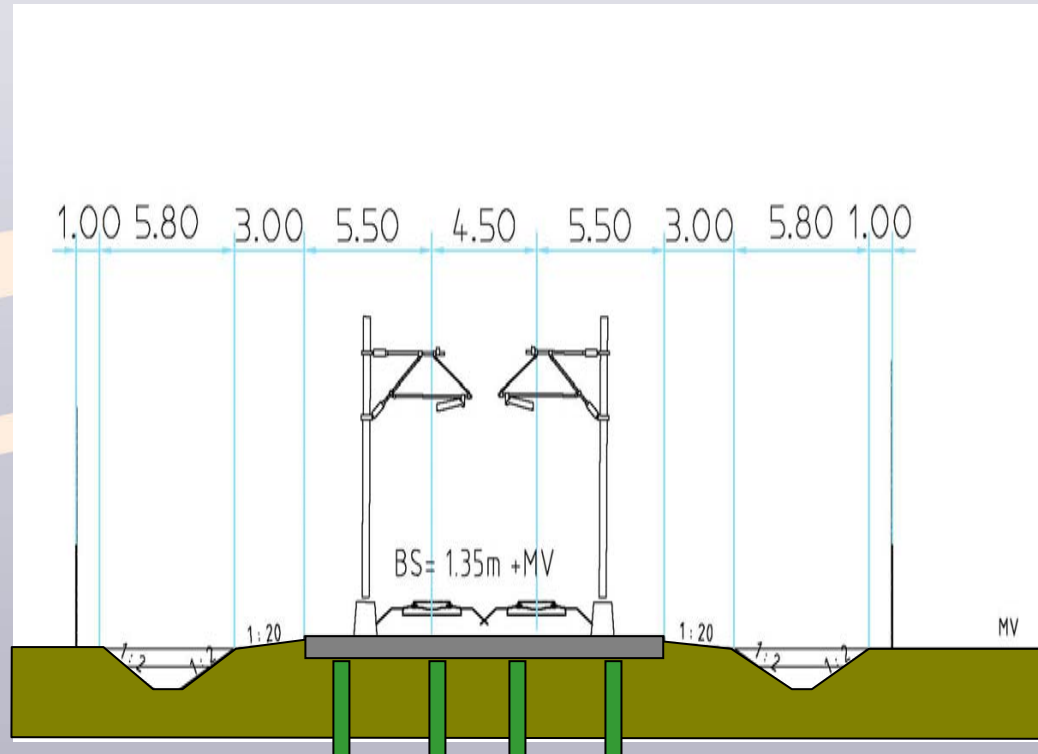
peat 140 - 300

ZZL : 200-250 km/u



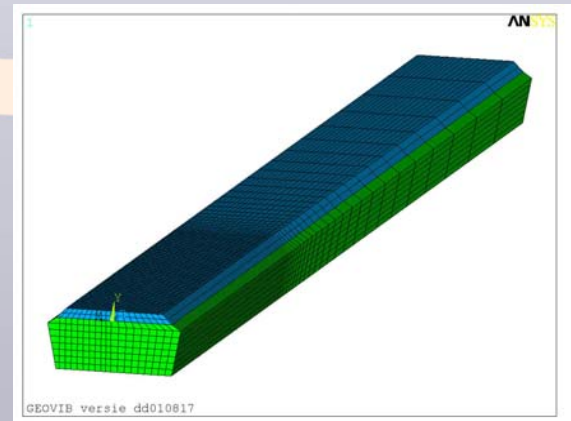
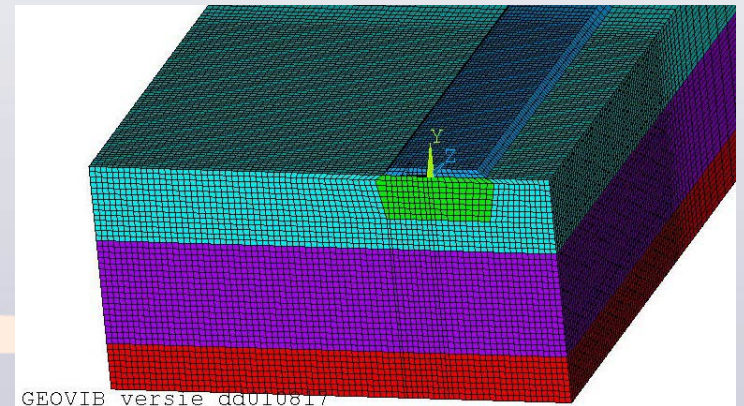
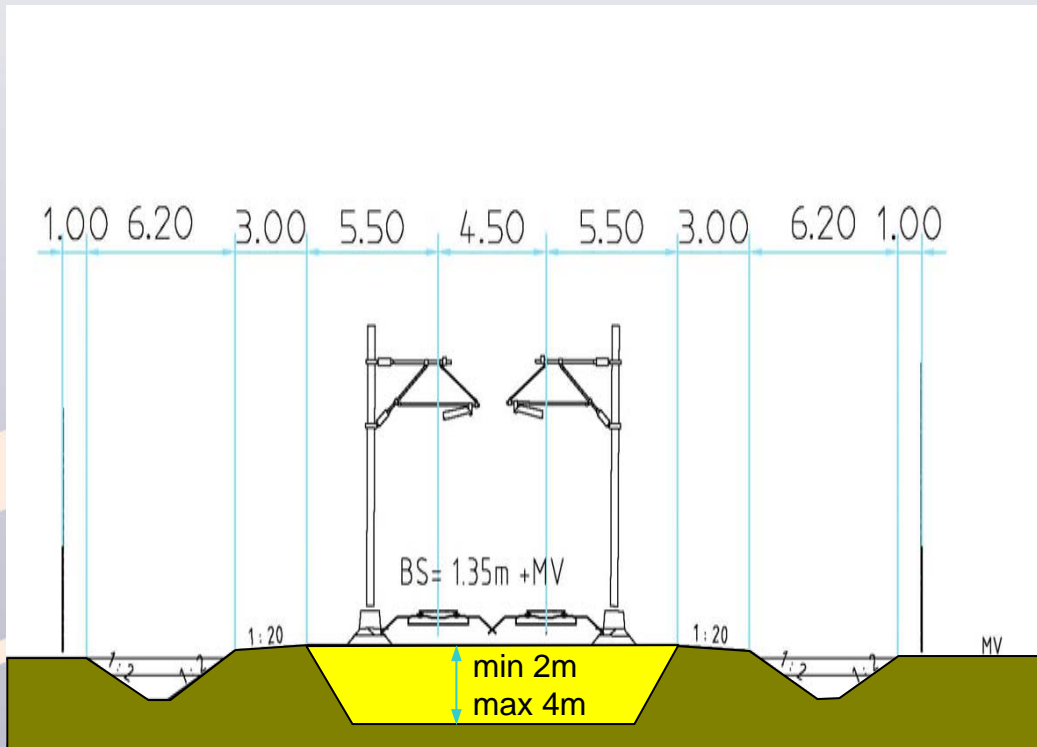
Doorsnede

Constructie HSL Zuid, plaat op palen



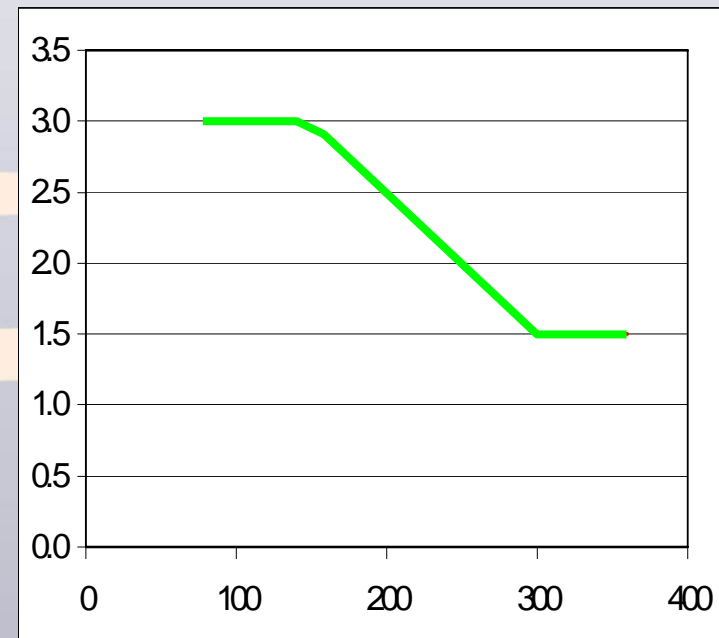
Doorsnede

Conventionele baanlichaam

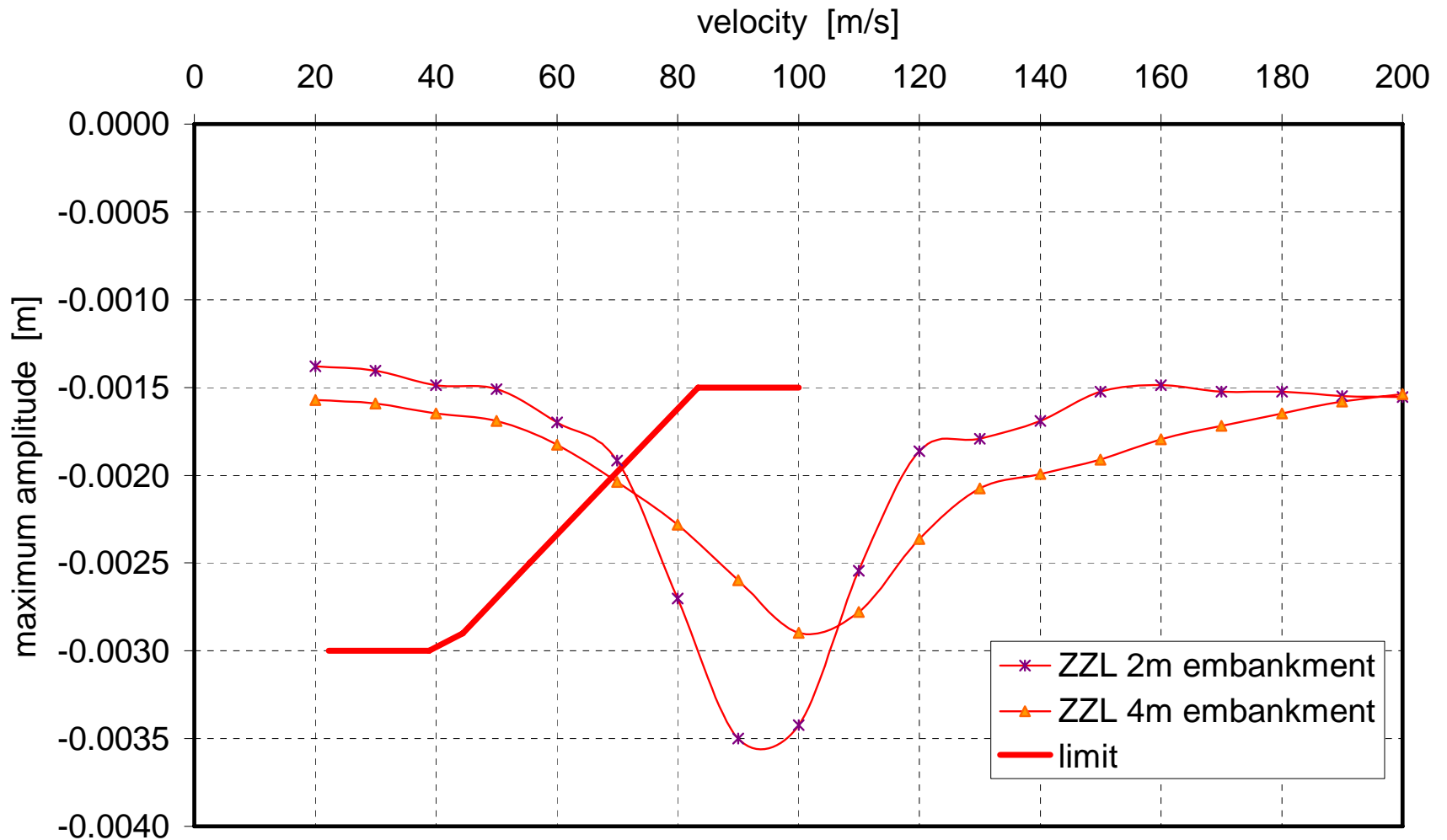


Toelaatbaar

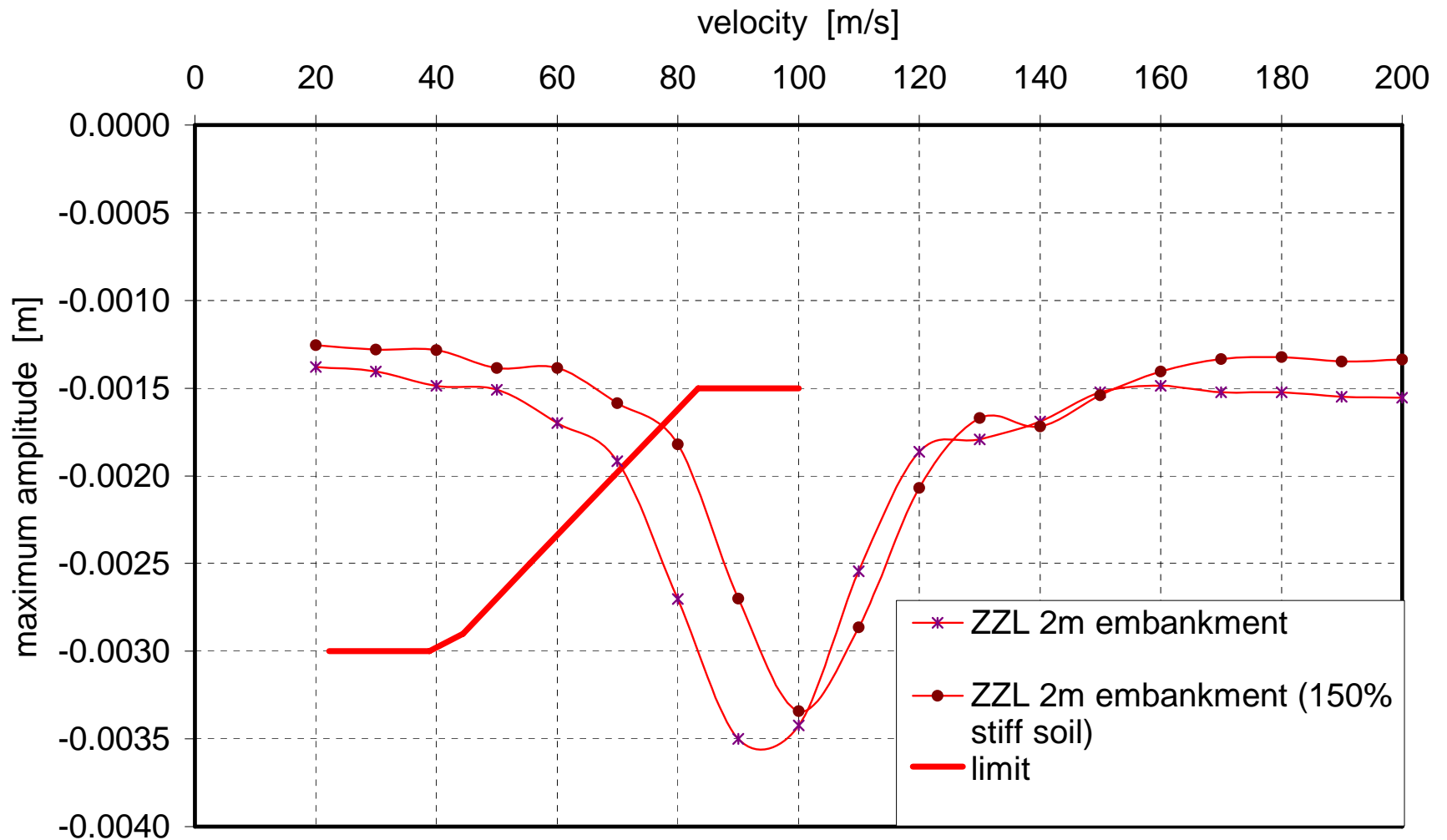
Trein snelheid [km/u]	Max. dyn. [mm]
80	3
100	3
140	3
160	2.9
200	2.5
250	2
300	1.5
360	1.5



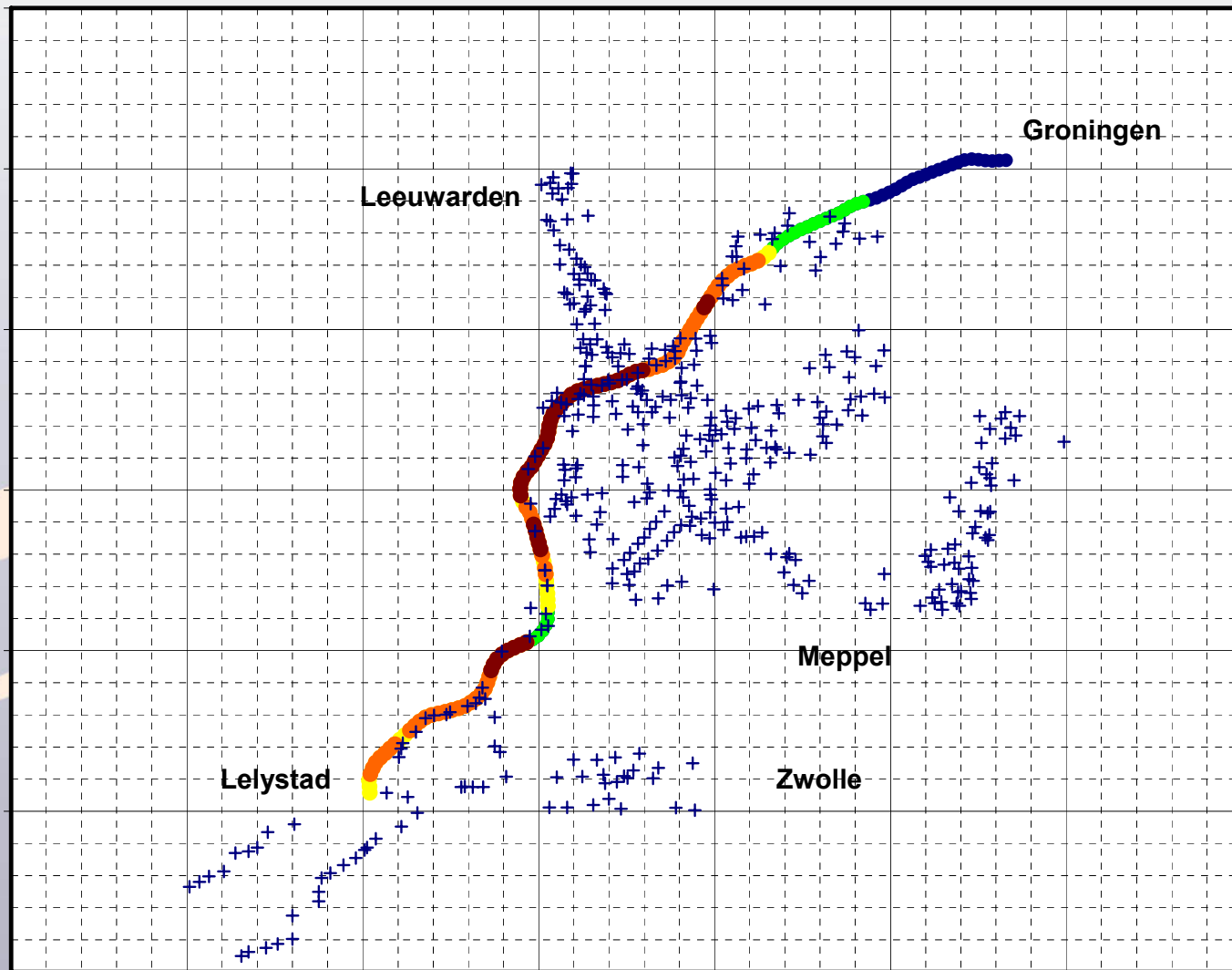
Resultaten baanlichaam 2m and 4m



Resultaten baanlichaam op slappe en stijve bodem



ZZL bij 250 km/h



baandikten bij
maximale snelheid
200 km/uur

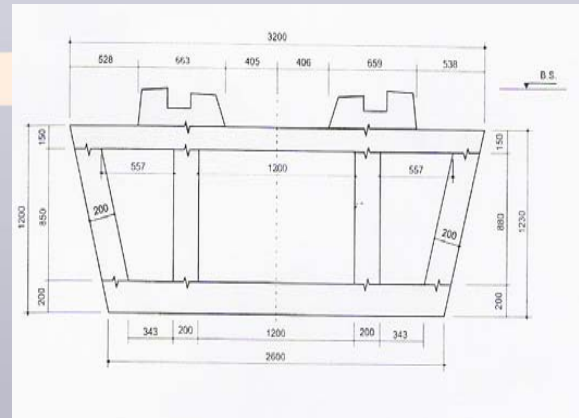
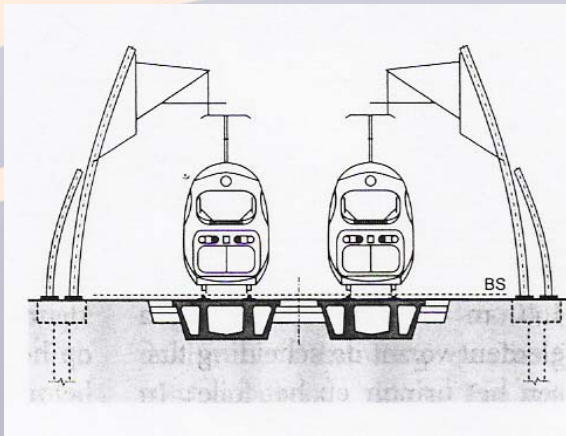
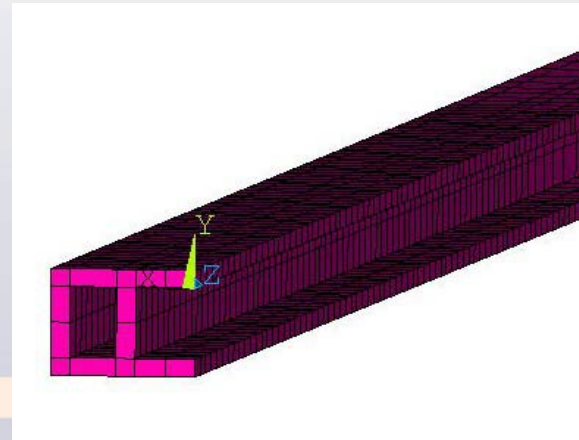
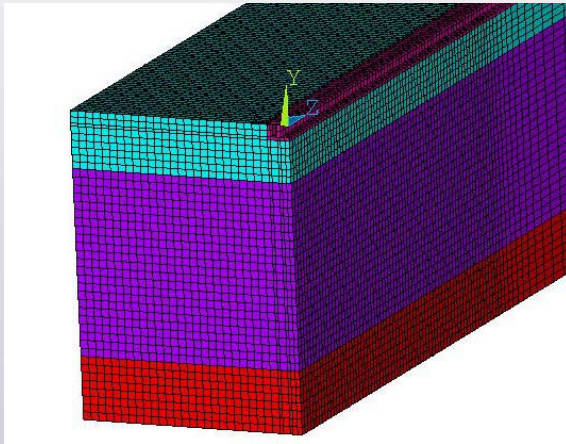
- ZZL variant 1
- 1.5 = baan 2m
- 2.5 = baan 3m
- 3.5 = baan 4m
- 4.5 = ander concept
- + punt x y

Innovatieve baanlichamen

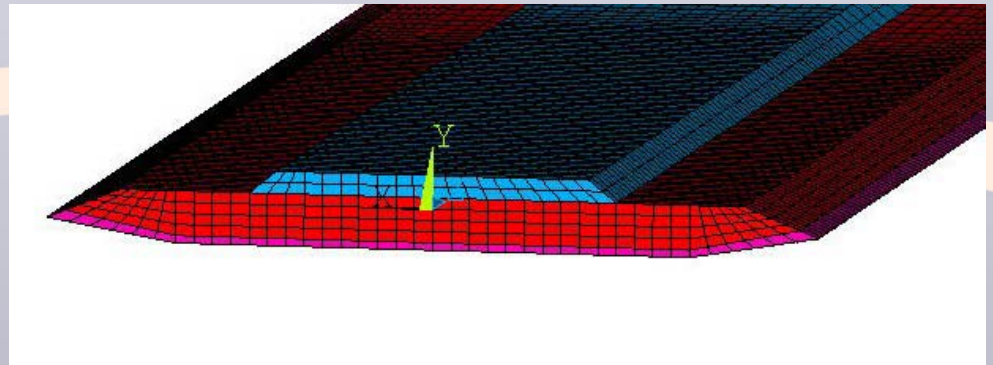
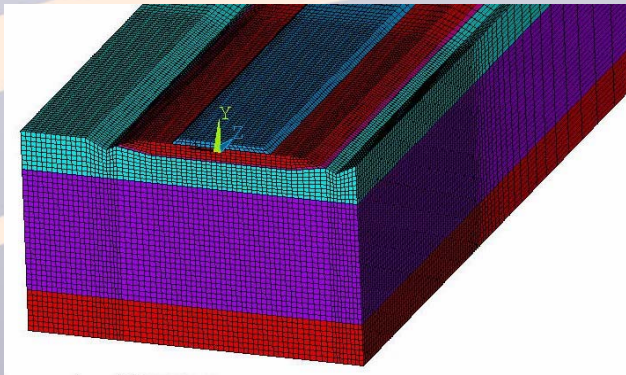
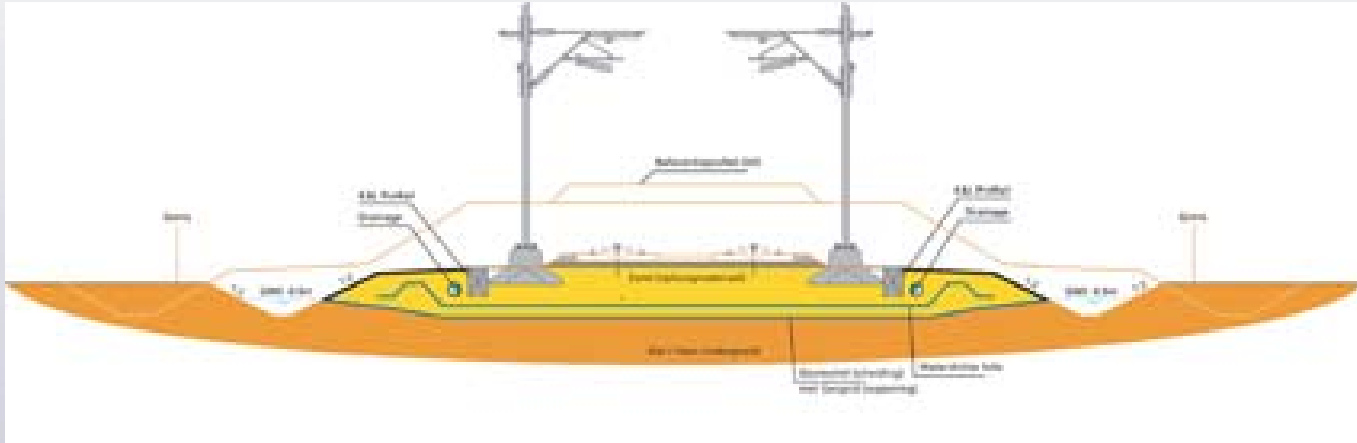
- Deck Track
- Polderbaan
- Grondmatras

4m dik baanlichaam = referentie

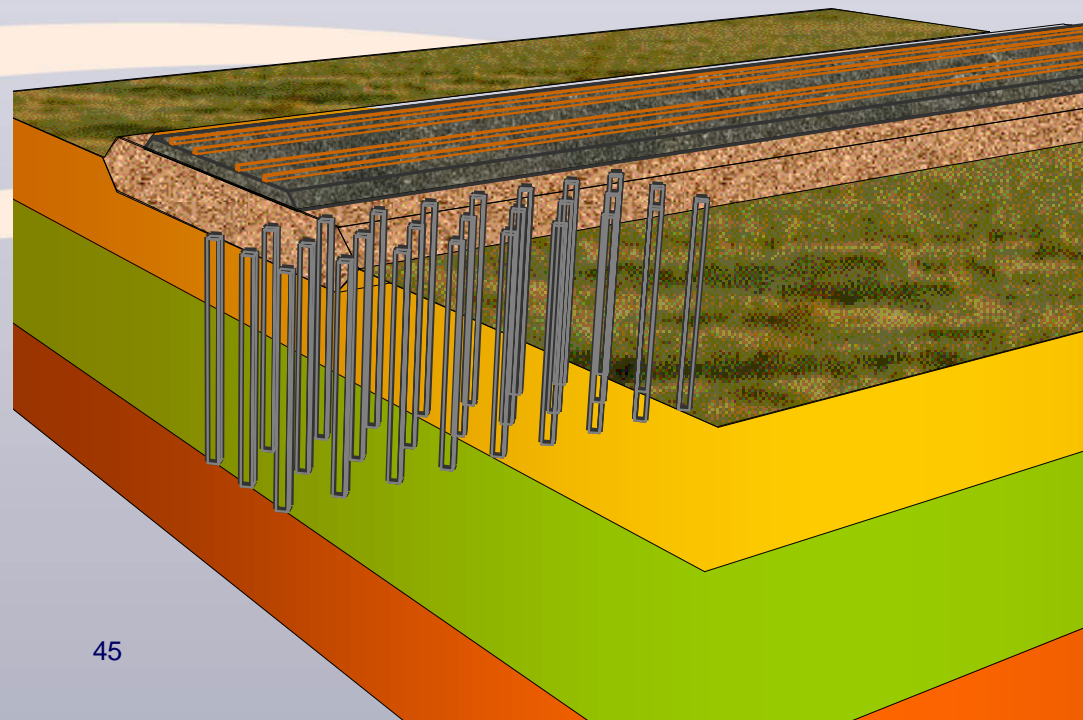
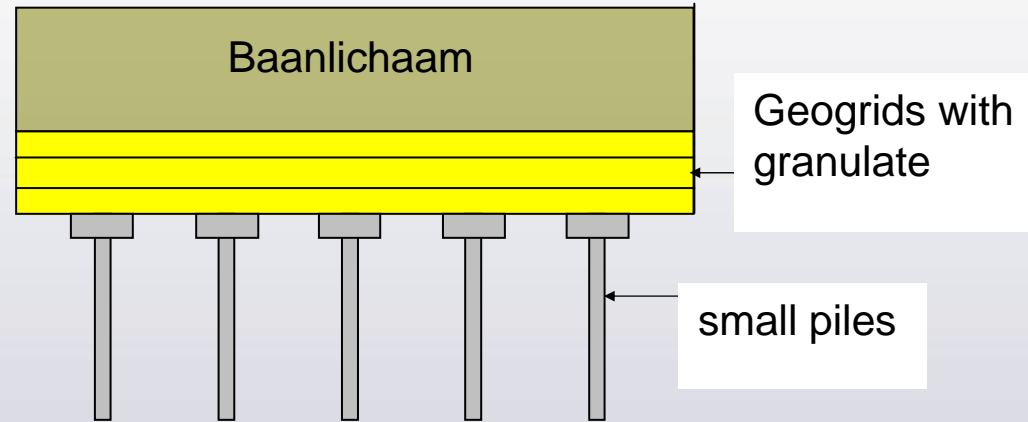
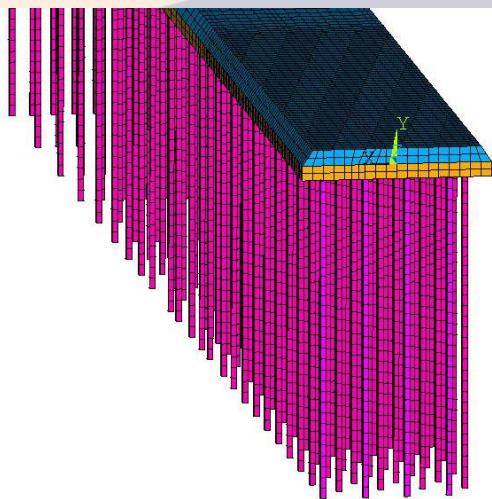
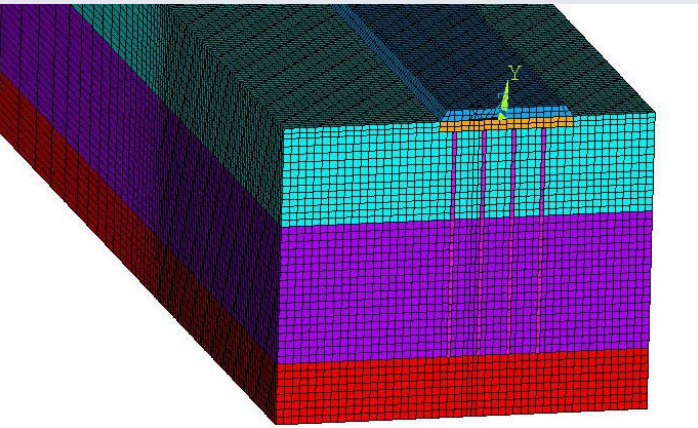
Deck Track



Polderbaan

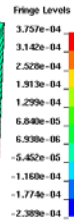
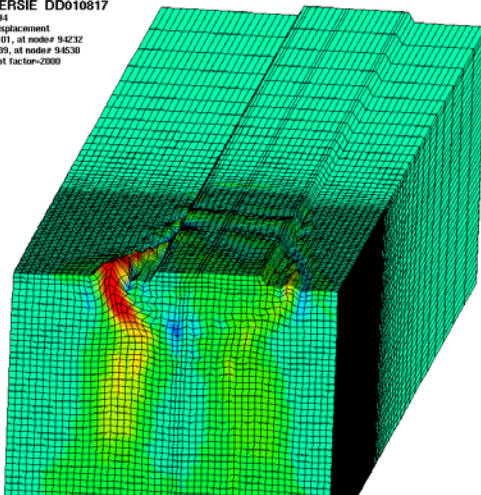


Grondmatras

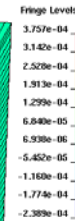
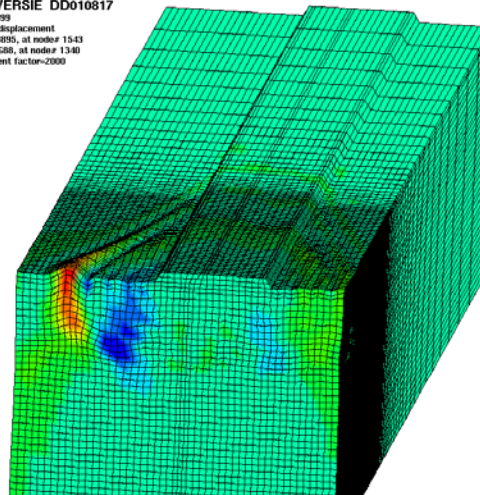


Resultaten Grondmatras

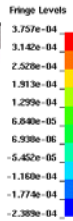
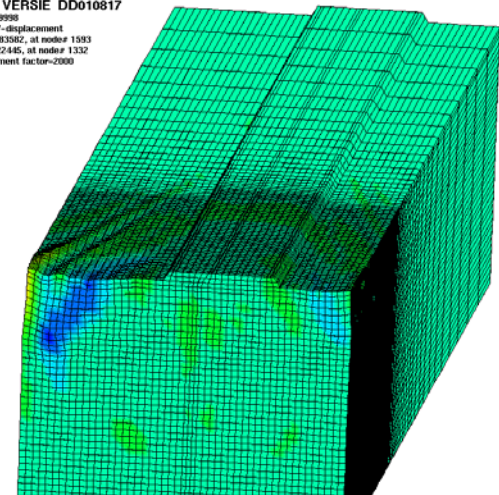
IB VERSIE DD010817
Time = 0.099914
Contours of Y-displacement
min=-0.000259101, at node# 94232
max=0.00024839, at node# 94530
max displacement factor=2000



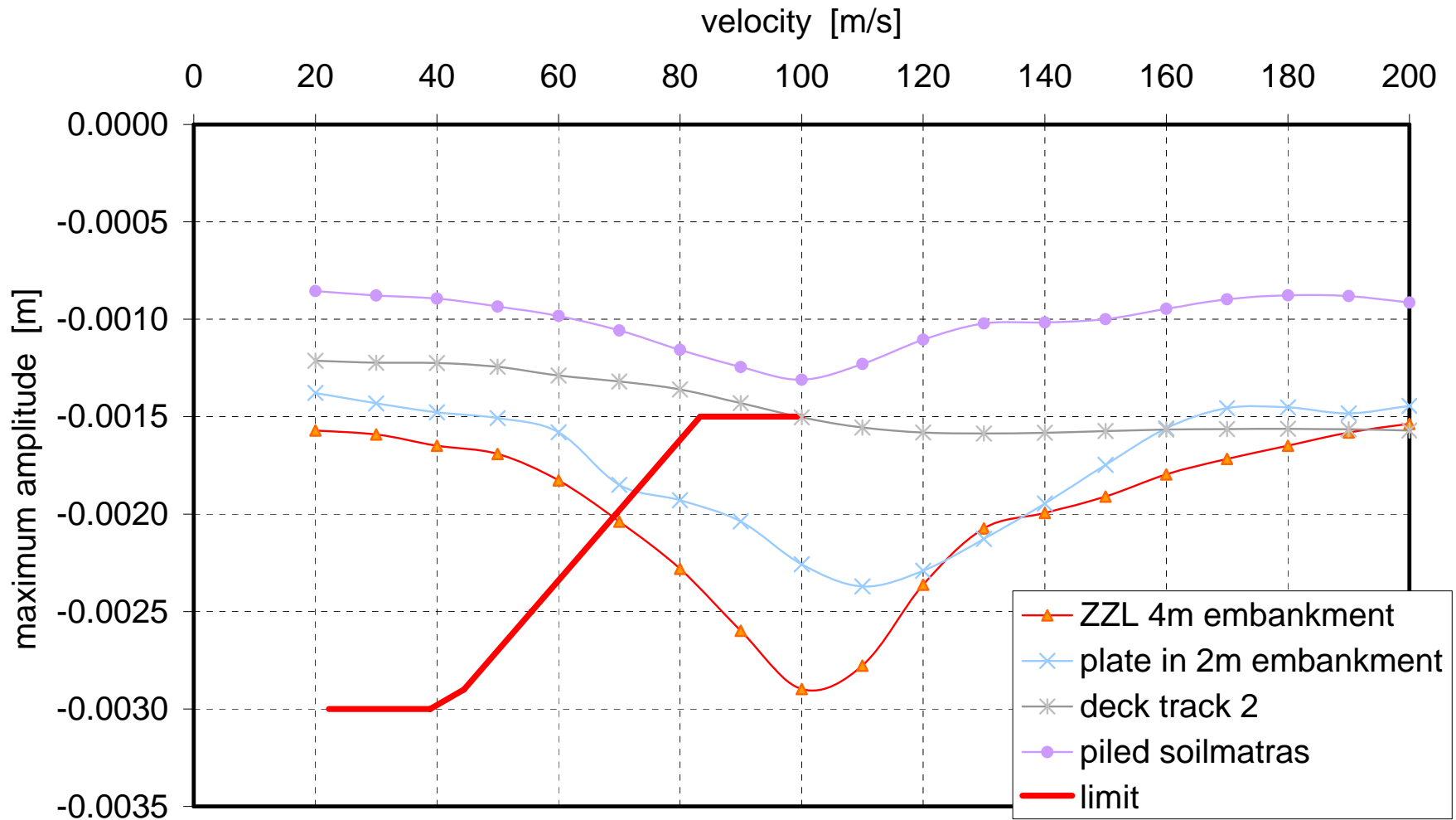
GEOVIB VERSIE DD010817
Time = 0.19993
Contours of Y-displacement
min=-0.00023895, at node# 1543
max=0.00037568, at node# 1340
max displacement factor=2000



GEOVIB VERSIE DD010817
Time = 0.29996
Contours of Y-displacement
min=-0.000183582, at node# 1593
max=0.00022445, at node# 1332
max displacement factor=2000



Results alle varianten



Project trillingen

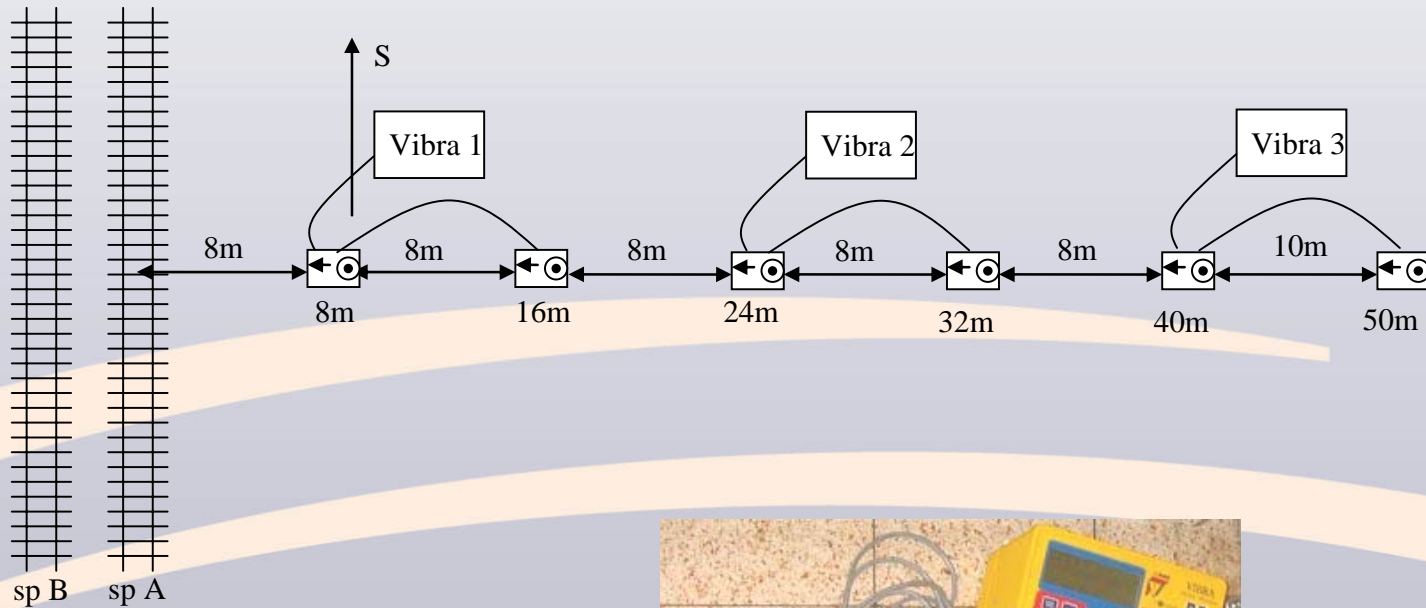


Opzet onderzoek

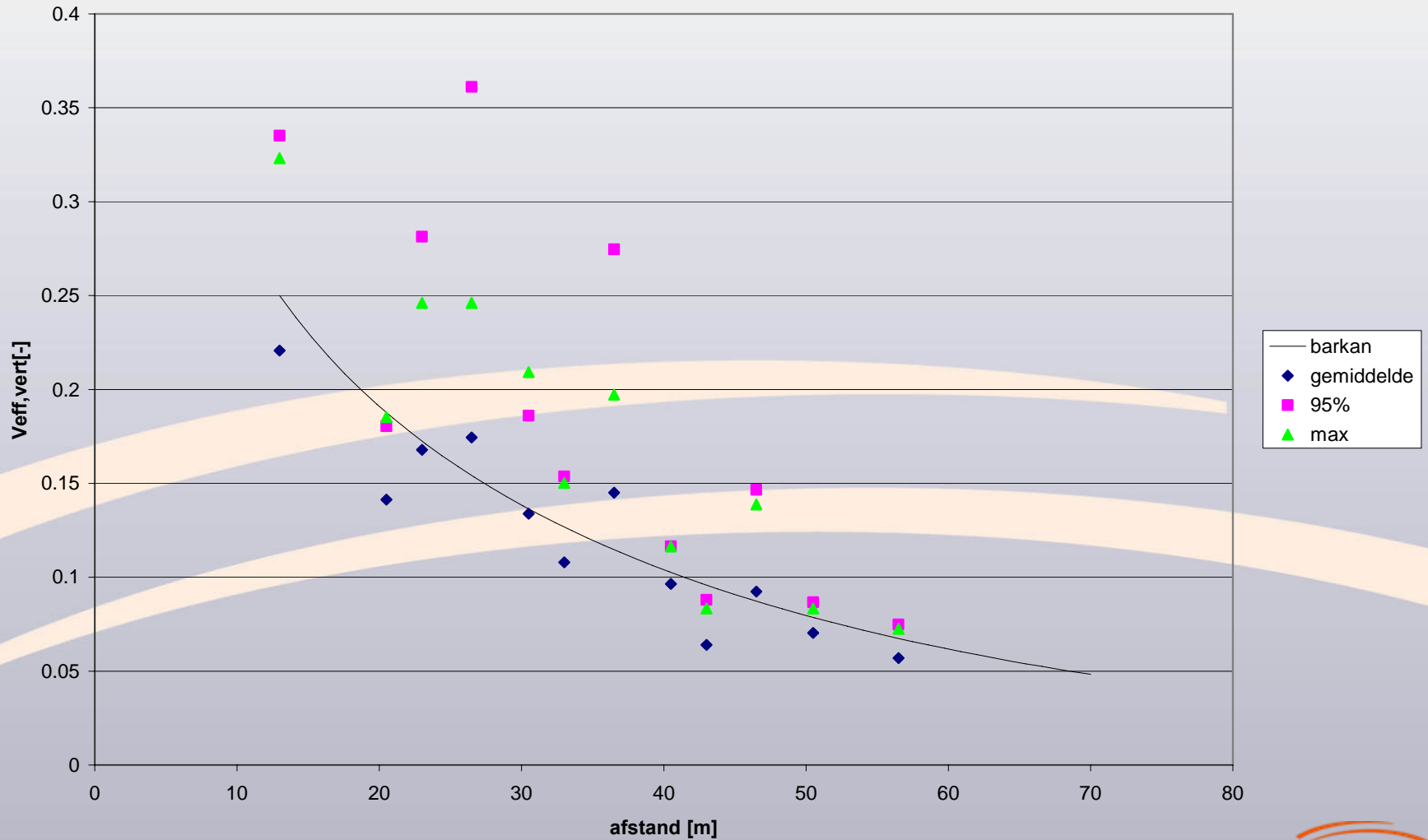
- inleiding probleem en achtergrond theorie
- zoeken meetlocatie
- uitvoeren meting
- verwerken meetresultaten
- rapportage



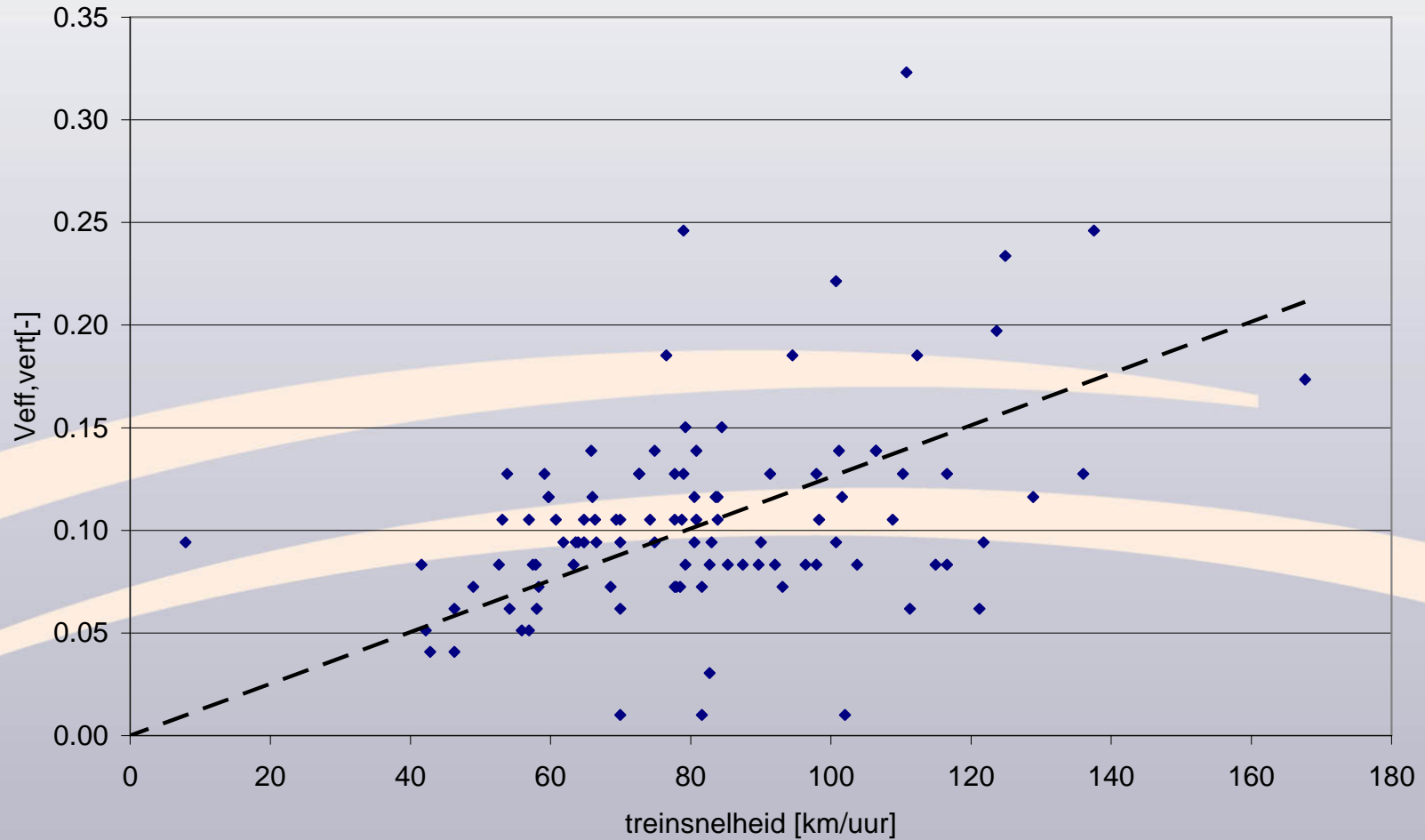
Opzet meetlocatie



Resultaten



Resultaten



Einde

- Vragen?