Norconsult

NGV 2022 - 5th Nordic Ground Vibration Day

24 October 2022, Aarhus, Denmark

Ground vibration from high-speed lines on soft ground: site characterization, numerical modelling, and countermeasures

Bengt B. Broms Lecture

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NTNU, Trondheim, Norway

Conference in Singapore in honor of Prof. Bengt Broms, 1995

Acknowledgement

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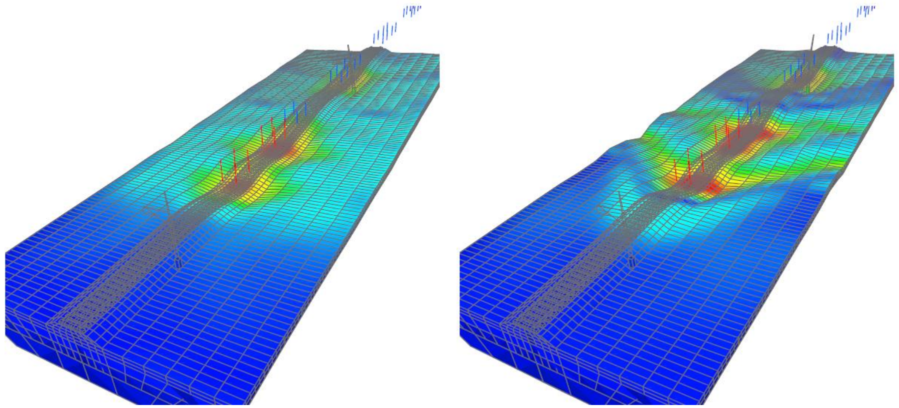
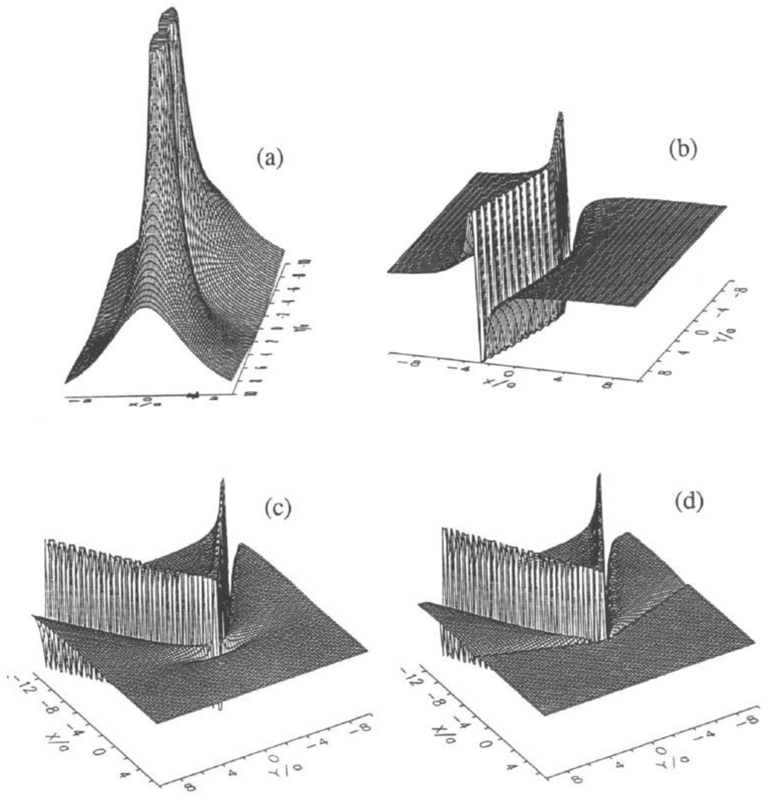
- **NGI colleagues** - (Christian Madshus, Karin Norén-Cosgriff, Joonsang Park, Jörgen Johansson)
- **EU projects** *SUPERTRACK* and *Destination-Rail*



Ekevid & Wiberg,
IABSE Symp. 2003

Historical note on the problem of moving load

- 2-D solutions, i.e. solutions for a moving line load, have been presented by Sneddon (1951), Cole and Huth (1958), Ang (1960), Craggs (1960), Payton (1964), Eringen and Suhubi (1975) by various Mathematical techniques (Potential theory, Fourier/Laplace transform, Helmholtz decomposition, etc.).
- A comprehensive review of earlier work (before 1970) was presented by Frýba (1973)
- 3-D solutions have been developed for loads on half-space or beam/plate over half space by, among others, Achenbach et al. (1967), Pan and Atluri (1995), Krylov (1995), Aubry et al. (1994), de Barros and Luco (1995).
- Cole and Huth (1958) defined Mach numbers $M_P = C_P/V$ and $M_S = C_S/V$ to represent the speed of the moving load, V, relative to the pressure wave velocity, C_P, and shear wave velocity, C_S, of the medium.



de Barros and Luco, Wave Motion, 1994

Dynamisk respons av bane/bakke ved "Critical Speed"

For me, and perhaps for the modern era of high-speed rail, it started about 25 years ago when large ground vibrations were observed at Ledsgård as Trafikverket decided to increase the speed to above 140 km/h and subsequently initiated a comprehensive research program => *Critical Speed*

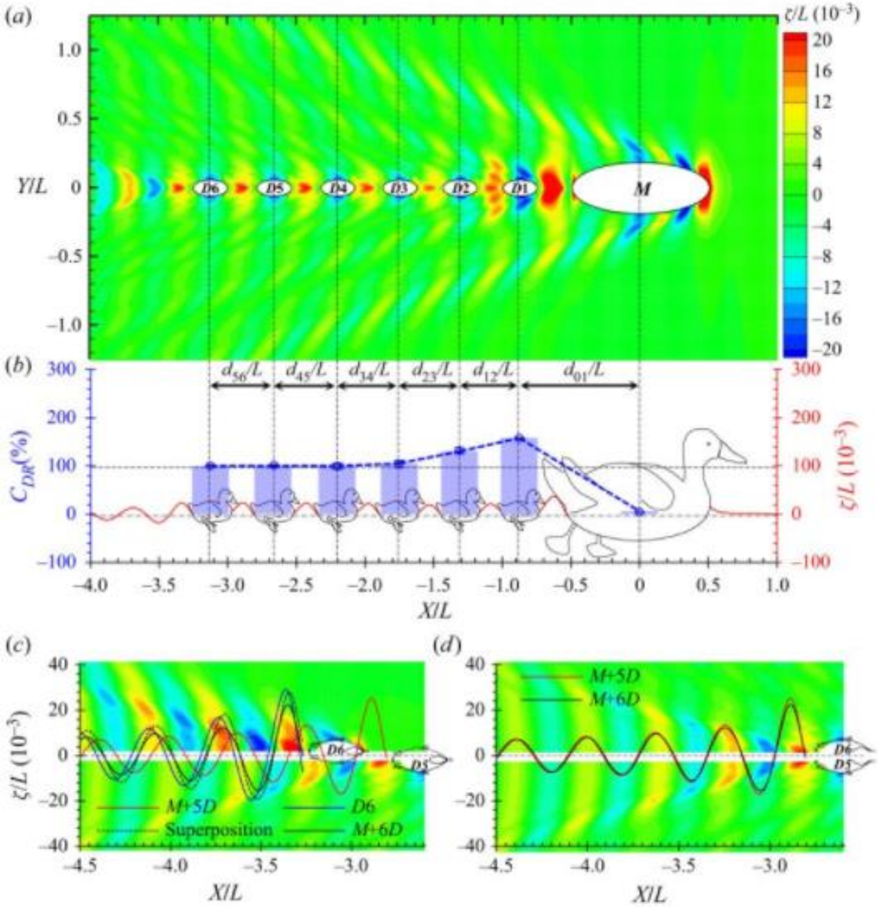
The community owes to the openness of Trafikverket in sharing their data and findings with the outside.

More recent measurements at Lammhultsmosse, Sweden

©Eric Berggren,
EBER Dynamics AB

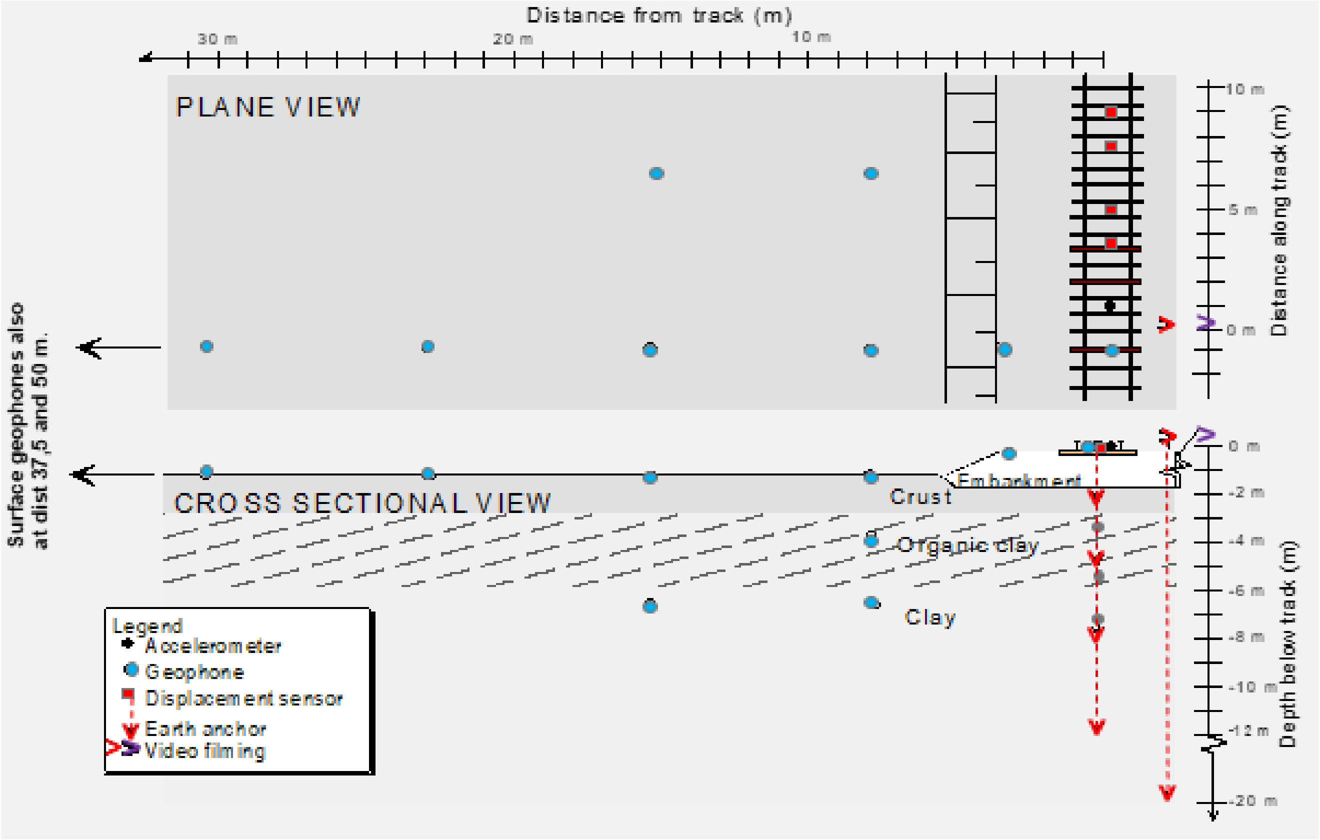
Critical Speed in other media

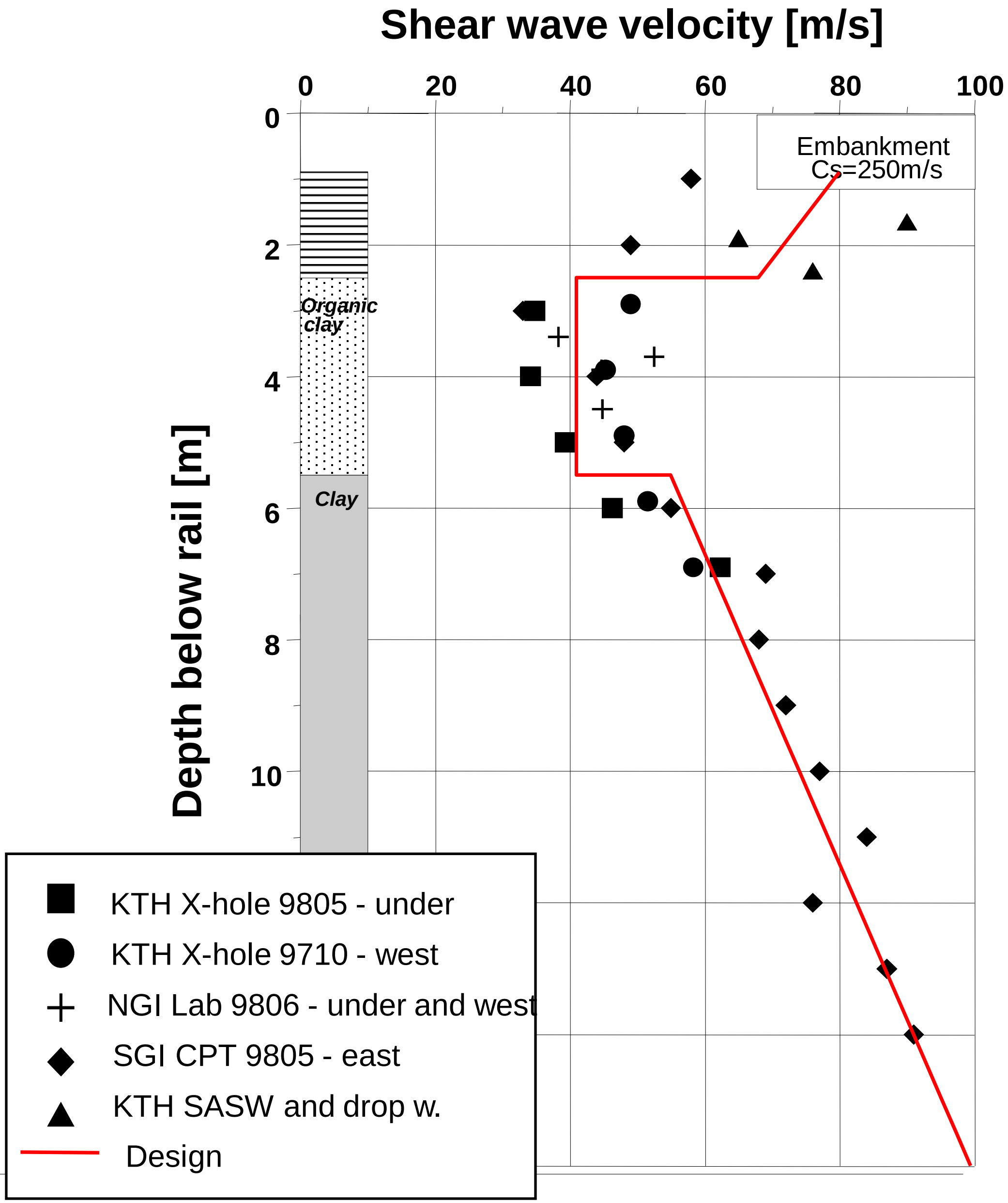
- Aerospace
- Fluid Dynamics: Ducklings learn very early in their lives about the Critical Speed and how to swim effectively (https:/lnkd.in/dKp8BZ3Q)



1. Site Characterization

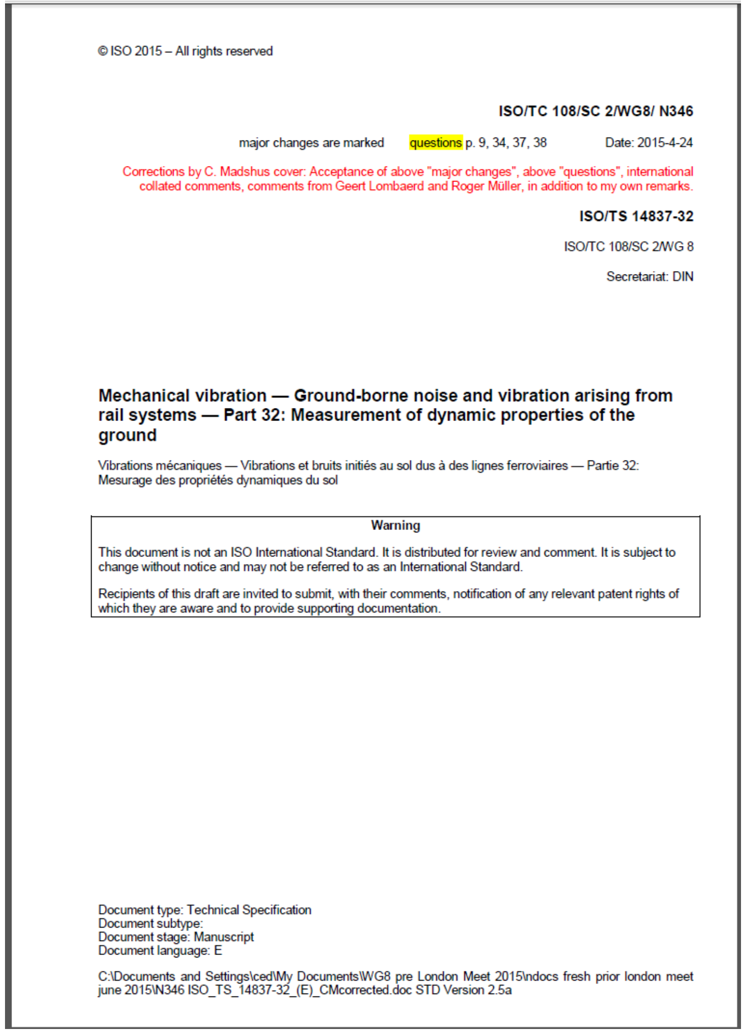
Ledsgård: Site characterization & Instrumentation





The key are the dynamic soil parameters

- ISO/DTS 14837-32:2015 - Mechanical vibration - Ground-borne noise and vibration arising from rail systems - Part 32: Measurement of dynamic properties of the ground
- Direct measurements in lab and field
- Correlations with other soil parameters



ISO/TC 108/SC 2/WG8/ N346

major changes are marked questions p. 9, 34, 37, 38 Date: 2015-4-24

Corrections by C. Madshus cover: Acceptance of above "major changes", above "questions", international collated comments, comments from Geert Lombaerd and Roger Müller, in addition to my own remarks.

ISO/TS 14837-32

ISO/TC 108/SC 2/WG 8

Secretariat: DIN

Mechanical vibration — Ground-borne noise and vibration arising from rail systems — Part 32: Measurement of dynamic properties of the ground

Vibrations mécaniques — Vibrations et bruits initiés au sol dus à des lignes ferroviaires — Partie 32: Mesurage des propriétés dynamiques du sol

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Document stage: Manuscript
Document language: E

C:\Documents and Settings\ced\My Documents\WG8 pre London Meet 2015\ndocs fresh prior london meet june 2015\N346 ISO_TS_14837-32_(E)_CMcorrected.doc STD Version 2.5a

Dynamic soil parameters – Correlations, sand

Empirical equations to estimate G_{max}

Granular soils (1): $$G_{\mathrm{max}} = 625 \frac{1}{0,3 + 0,7e^2} \sqrt{p_{\mathrm{a}} \sigma'_{\mathrm{m}}}$$

Granular soils (2): $$G_{\mathrm{max}} = 22\, K_{2,\mathrm{max}} \sqrt{p_{\mathrm{a}} \sigma'_{\mathrm{m}}}$$

$$\sigma'_{\mathrm{m}} = \frac{1}{3}(\sigma'_1 + \sigma'_2 + \sigma'_3)$$

Dr (%)	$K_{2,max}$
30	34
40	40
45	43
60	52
75	59
90	70

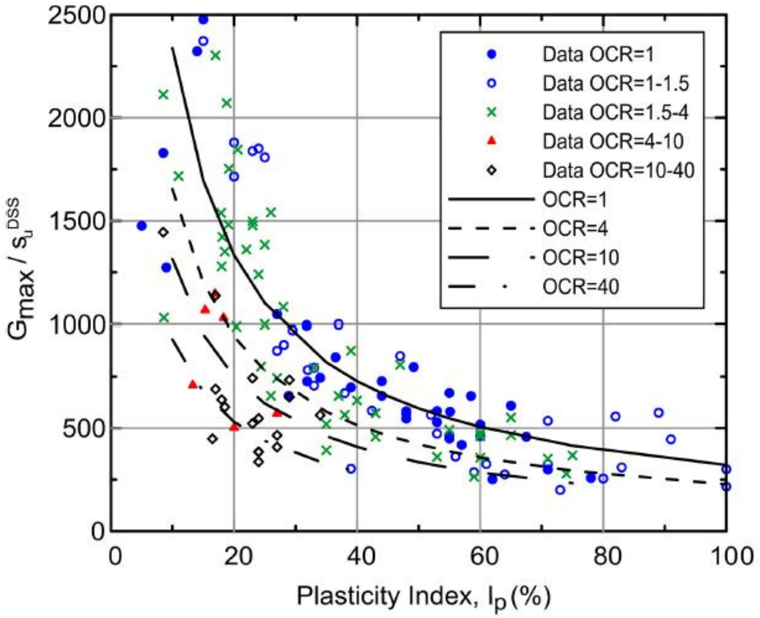
e	$K_{2,max}$
0,4	70
0,5	60
0.6	51
0,7	44
0,8	39
0,9	34

Dynamic soil parameters – Correlations, clay

Cohesive soils:

$$G_{max}/s_u^{DSS} = (30+300/(I_p/100+0.03))\cdot OCR^{-0.25}$$

$$G_{max}/\sigma_{ref}' = (30+75/(I_p/100+0.03))\cdot OCR^{0.5}$$



Andersen, ISFOG, 2015

$$G_{max} = \left[250 + \left(208/\left(I_p/100\right)\right)\right]\cdot S_u \qquad I_p > 10\%$$

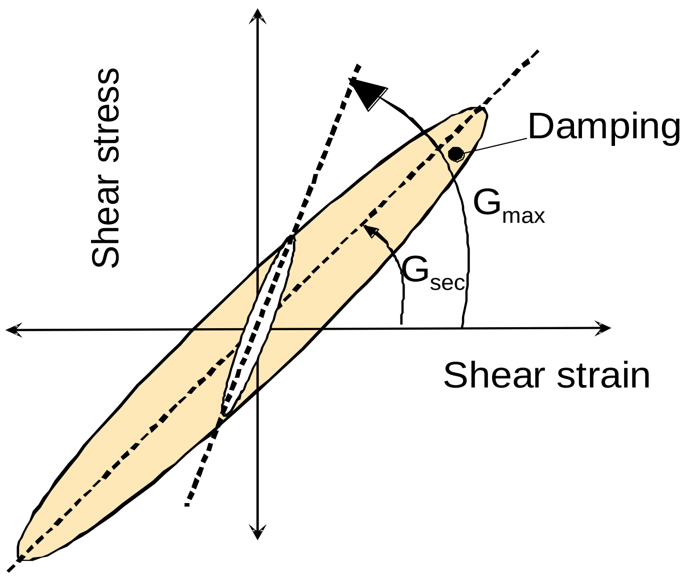
Note: I_p inserted in %

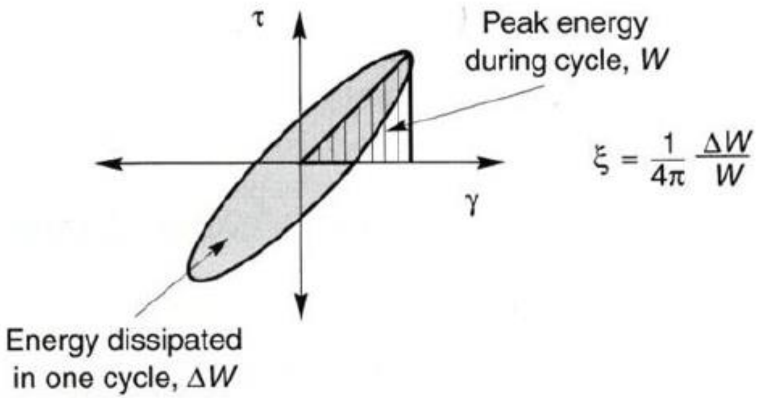
Larsson & Mulabdic´ (1991)
SGI Report No 40.

Very sensitive clays: $G_{max}/S_u^{DSS} = 800 - 900$

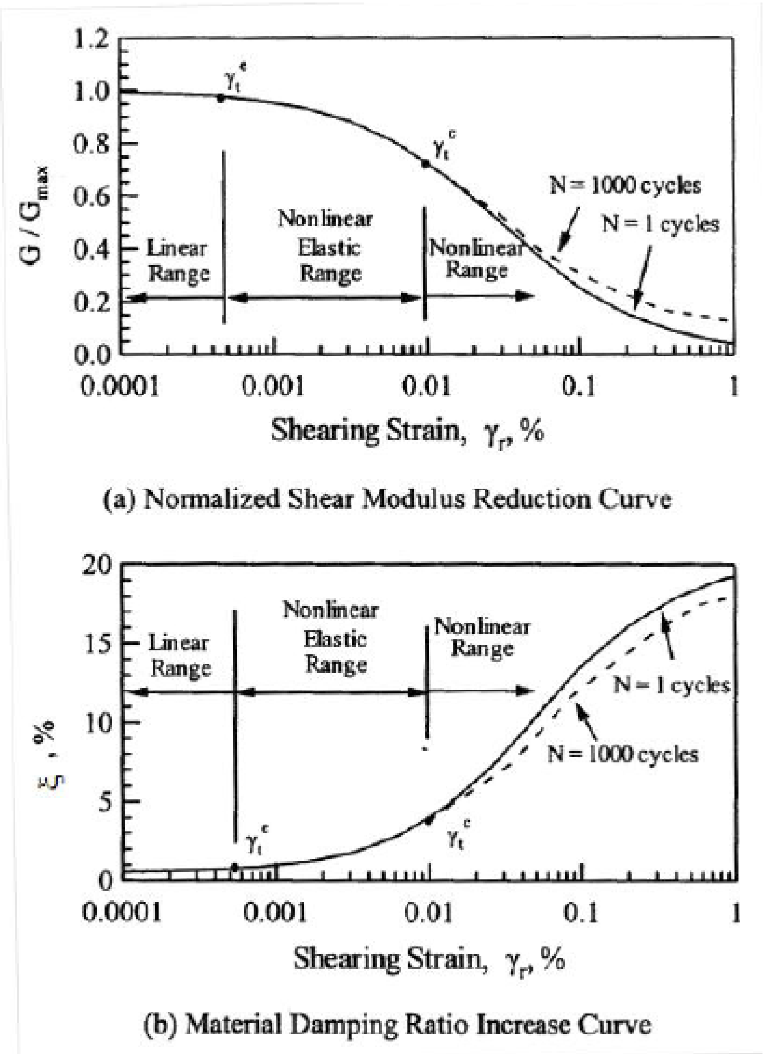
NC Quick Clay ~40% clay content
Ref. Andersen K.H. (2007).

Dynamic soil parameters – Nonlinearity and damping



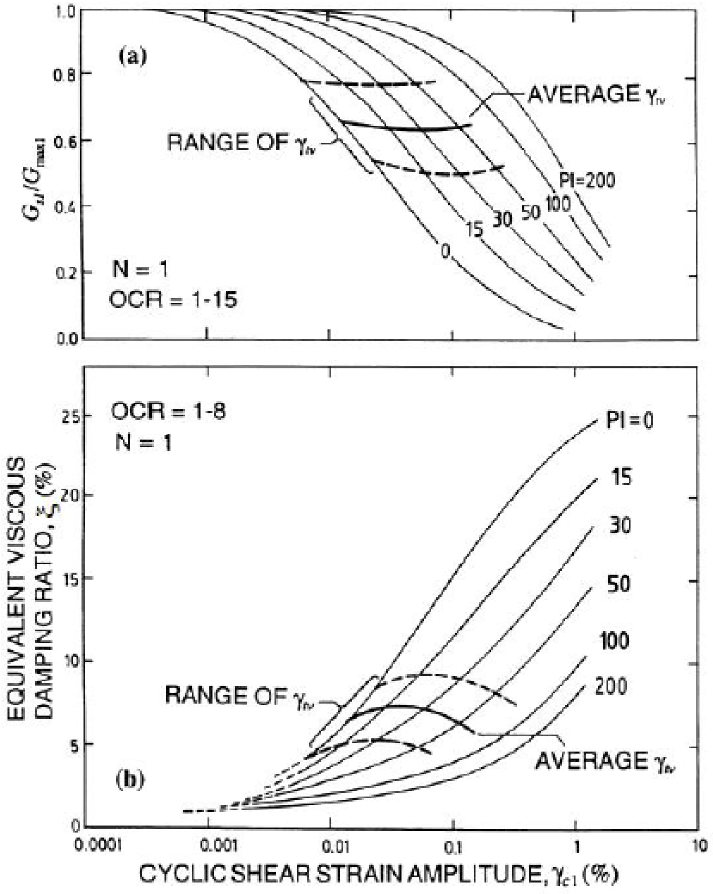


a) Definition of hysteretic damping ratio, $\xi = \eta/2$



Strain-dependent shear modulus and damping

Vucetic & Dobry (clay)



$$\frac{G}{G_{max}} = \frac{1}{1+\left(\frac{\gamma}{\gamma_r}\right)^a}$$

$$\gamma_r = (\phi_1 + \phi_2 * PI * OCR^{\phi_3}) * \sigma_o'^{\phi_4}$$

$$a = \phi_5$$

$$D_{Adjusted} = b * \left(\frac{G}{G_{max}}\right)^{0.1} * D_{Masing} + D_{min}$$

$$D_{min} = (\phi_6 + \phi_7 * PI * OCR^{\phi_8}) * \sigma_o'^{\phi_9} * [1 + \phi_{10} * \ln(frq)]$$

$$b = \phi_{11} + \phi_{12} * \ln(N)$$

$$D_{Masing} = c_1 D_{Masing,a=1.0} + c_2 D_{Masing,a=1.0}^{\;2} + c_3 D_{Masing,a=1.0}^{\;3}$$

where:

$$D_{Masing,a=1.0}(\%) = \frac{100}{\Pi}\left[4\frac{\gamma - \gamma_r \ln\left(\frac{\gamma+\gamma_r}{\gamma_r}\right)}{\frac{\gamma^2}{\gamma+\gamma_r}} - 2\right]$$

$$c_1 = -1.1143a^2 + 1.8618a + 0.2523$$

$$c_2 = 0.0805a^2 - 0.0710a - 0.0095$$

$$c_3 = -0.0005a^2 + 0.0002a + 0.0003$$

Darendeli, 2001 (clay, silt, sand)

Darendeli equations (from Darendeli PhD Thesis 2001)

INPUT

PI	20	%
OCR	10	
frq	0.3	Hz
σo'	1	atm (kPa/100)
N	10	cycles

gammar	0.077892479
a	0.919
b	0.619967368
Dmin	0.650164774
c1	1.022199878
c2	-0.00676184
c3	6.15195E-05

Values from Table 8.12	
ϕ1	0.0352
ϕ2	0.00101
ϕ3	0.325
ϕ4	0.348
ϕ5	0.919
ϕ6	0.801
ϕ7	0.0129
ϕ8	-0.107
ϕ9	-0.289
ϕ10	0.292
ϕ11	0.633
ϕ12	-0.00566
ϕ13	-4.23
ϕ14	3.62
ϕ15	-5
ϕ16	-0.25
ϕ17	5.62
ϕ18	2.78

Shearing Strain (%	G/Gmax	D	Dmasing	Dmasing,a=1.0
0.0001	0.998	0.667	0.028	0.027
0.000316	0.994	0.705	0.088	0.086
0.001	0.982	0.821	0.276	0.271
0.00316	0.950	1.179	0.858	0.844
0.01	0.868	2.224	2.575	2.562
0.0316	0.696	4.854	7.031	7.198
0.1	0.443	9.703	15.841	17.136
0.316	0.216	15.292	27.523	31.642
1	0.087	19.259	38.300	45.492
3.16	0.032	20.809	45.846	54.814
10	0.011	20.507	50.097	59.793

dD

Correlations with field test data (CPT)

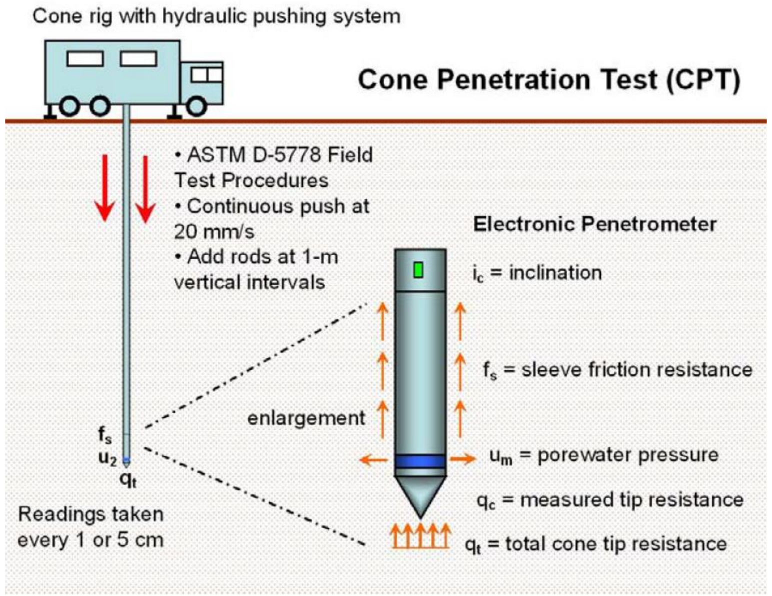
- Many different models for different soil types
- Generic models for all soils are:

$$V_s = 2.62 * q_t^{0.395} * I_c^{0.912} * z^{0.124}$$ Andrus et al. (2007)

$$V_s = 118.8 * log(f_s) + 18.5$$ Mayne (2007)

$$V_s = (10^{0.55*I_c+1.68} * (q_t - \sigma_v)/p_a)^{0.5}$$ Robertson (2009)

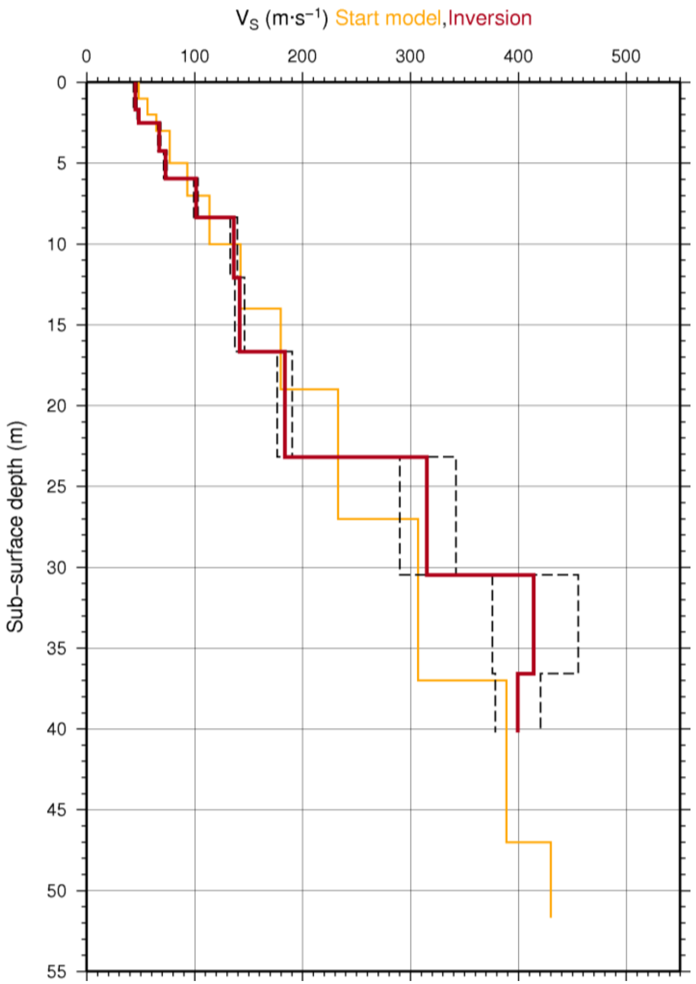
$$G_{\text{max}} = 1634(q_c)^{0,250}(\sigma'_v)^{0,375}$$

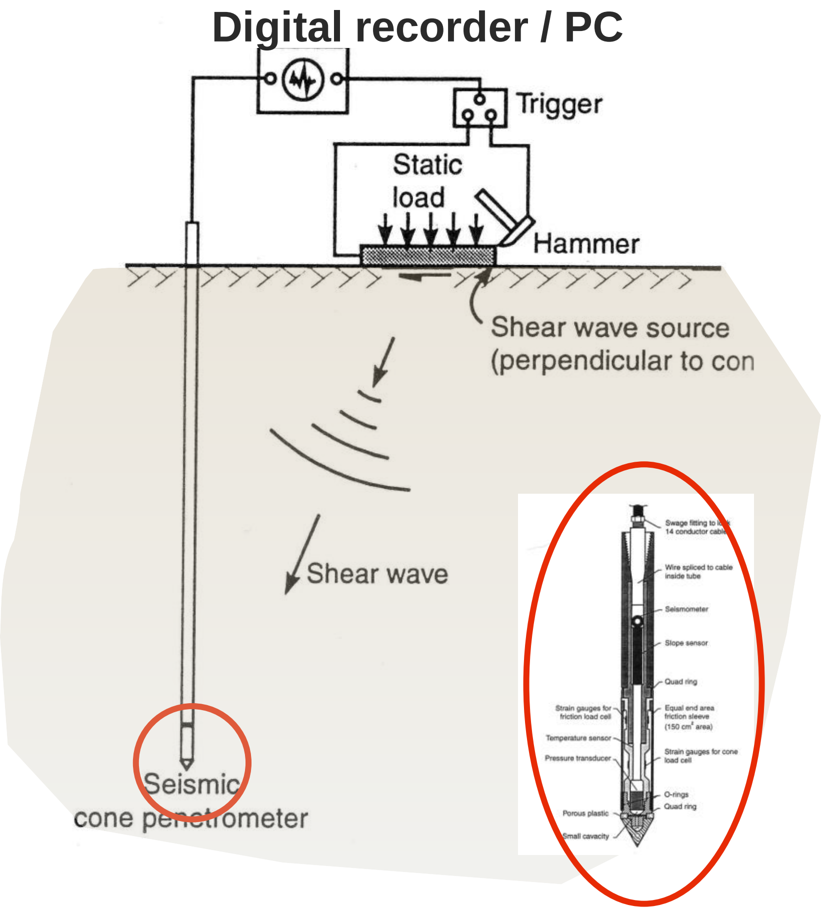


q_t = corrected cone resistance, I_c = soil behaviour type index, z = depth, f_s = unit sleeve friction resistance, σ_v = total vertical stress, and p_a = 100 kPa

In-situ Seismic (geophysical) methods

- Seismic CPT
- Cross hole
- Down hole
- SASW/MASW
- Seismic refraction

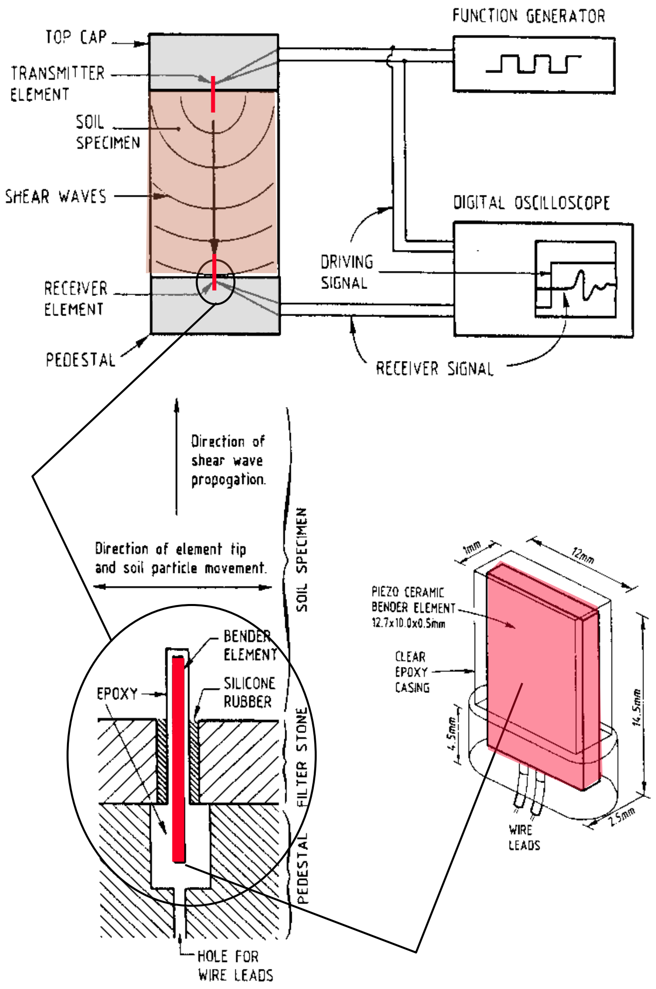




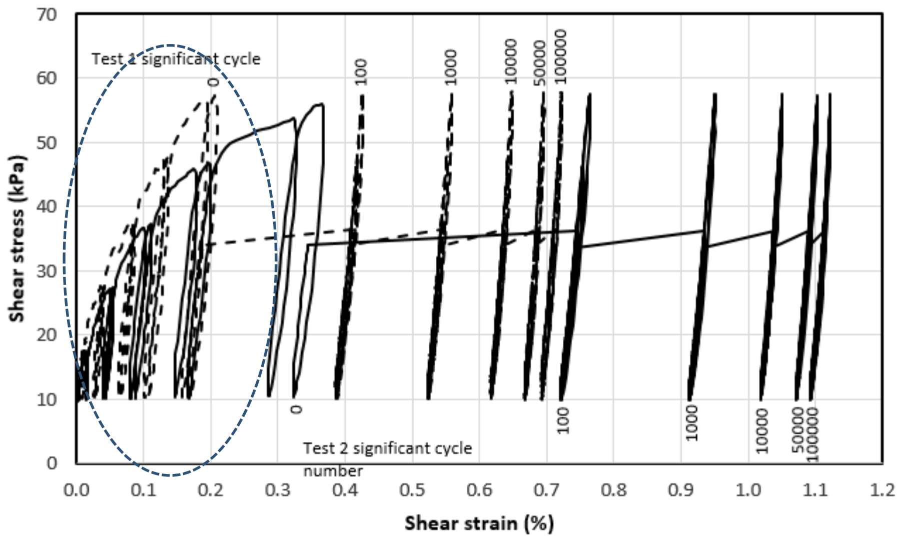
Soil parameters – Lab testing

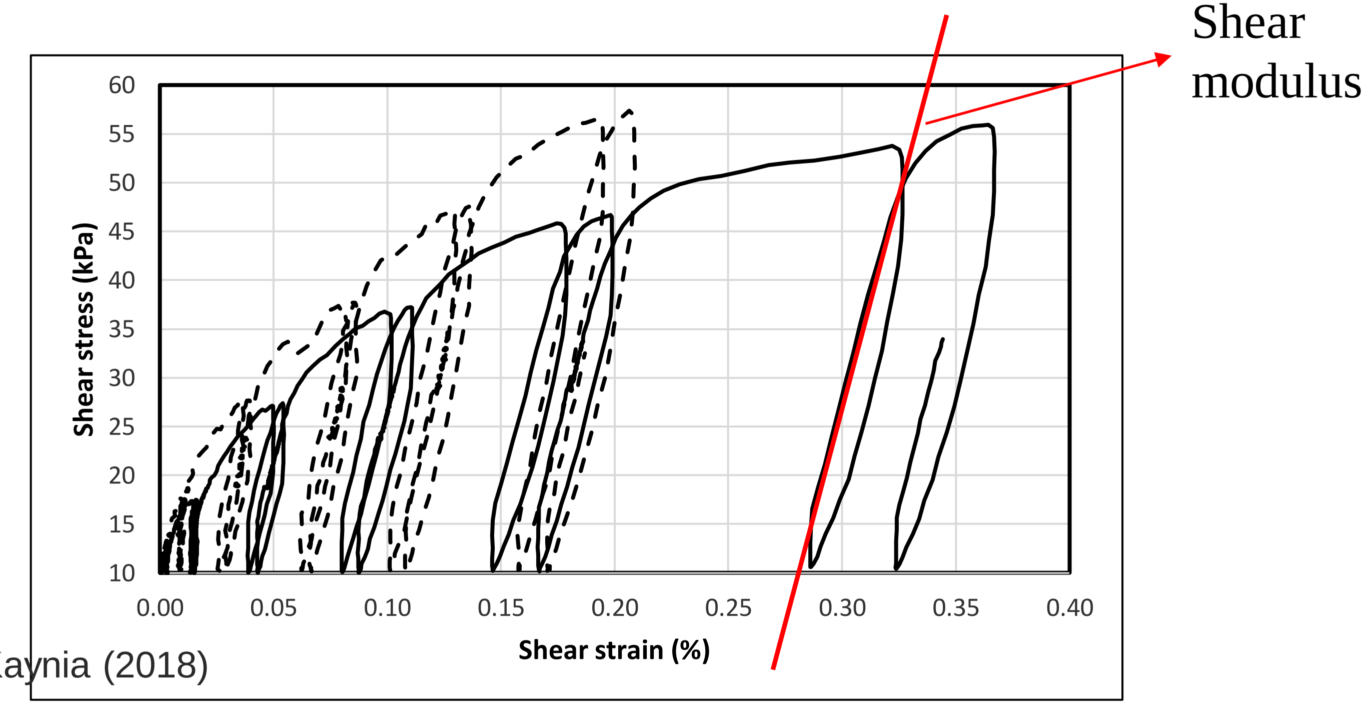
Piezo-bender device in triaxial testing

S-wave “seismic investigation” in laboratory scale



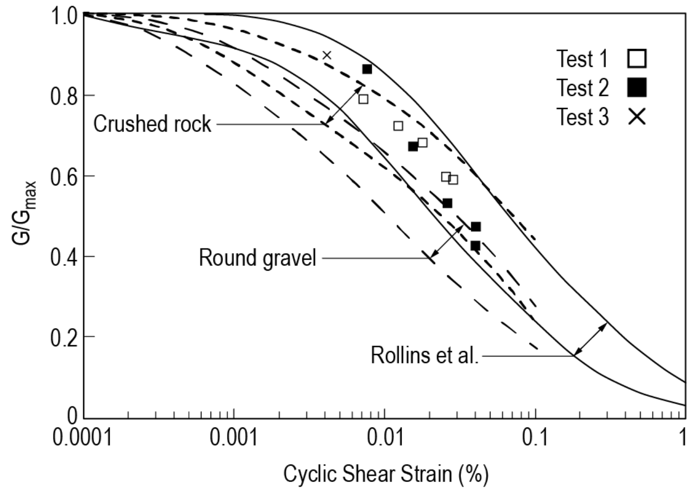
Cyclic triaxial testing (vacuum tri-axial)

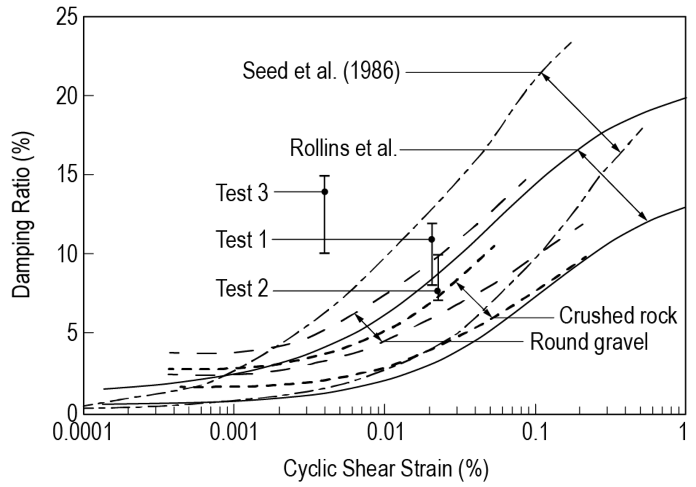




Dyvik & Kaynia (2018)

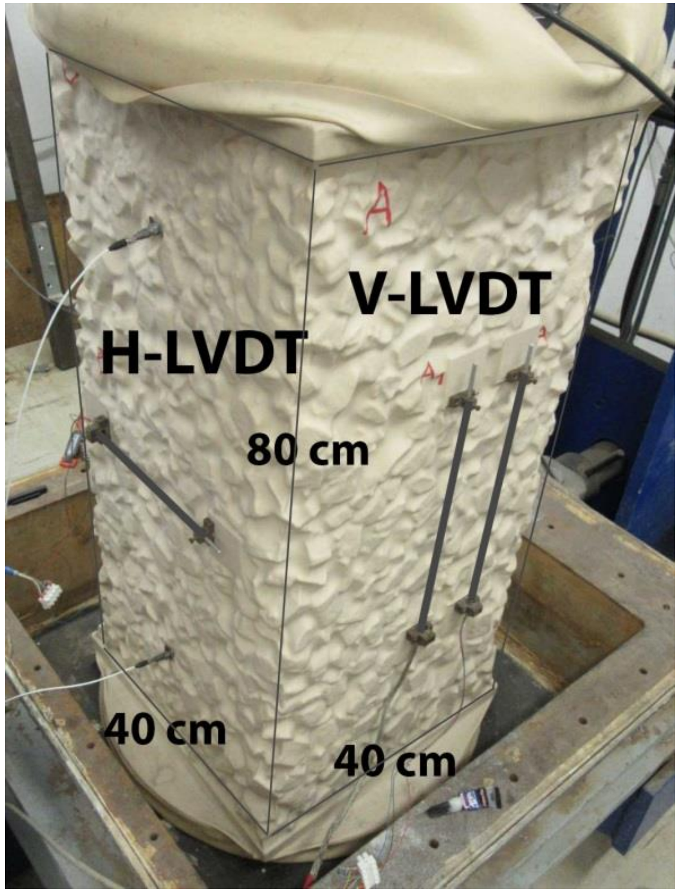
Cyclic test results compared to literature data



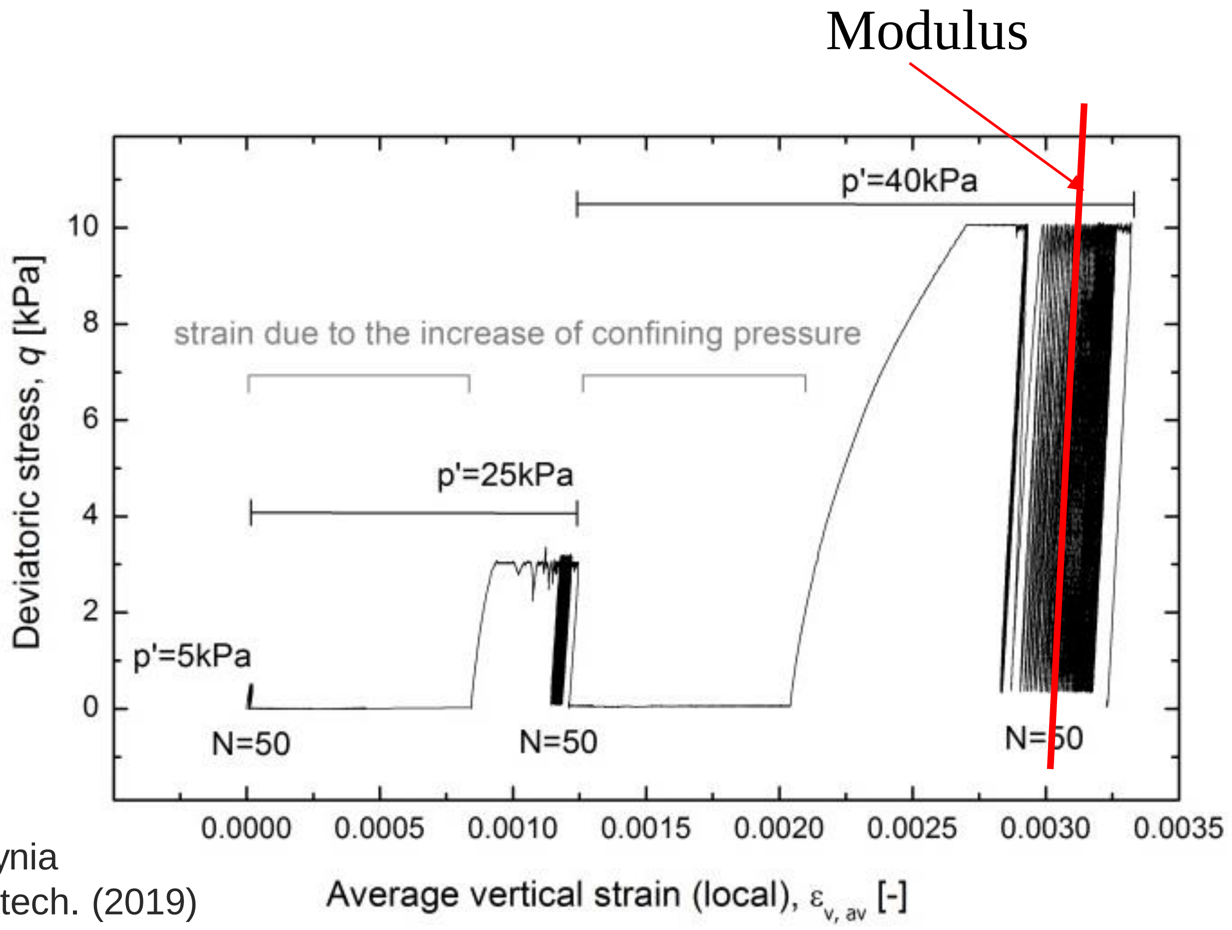


Dyvik & Kaynia (2018)

Similar tests on lightweight large aggregates



Tests performed at ZAG (Slovenia)



Lenart & Kaynia
Transp. Geotech. (2019)

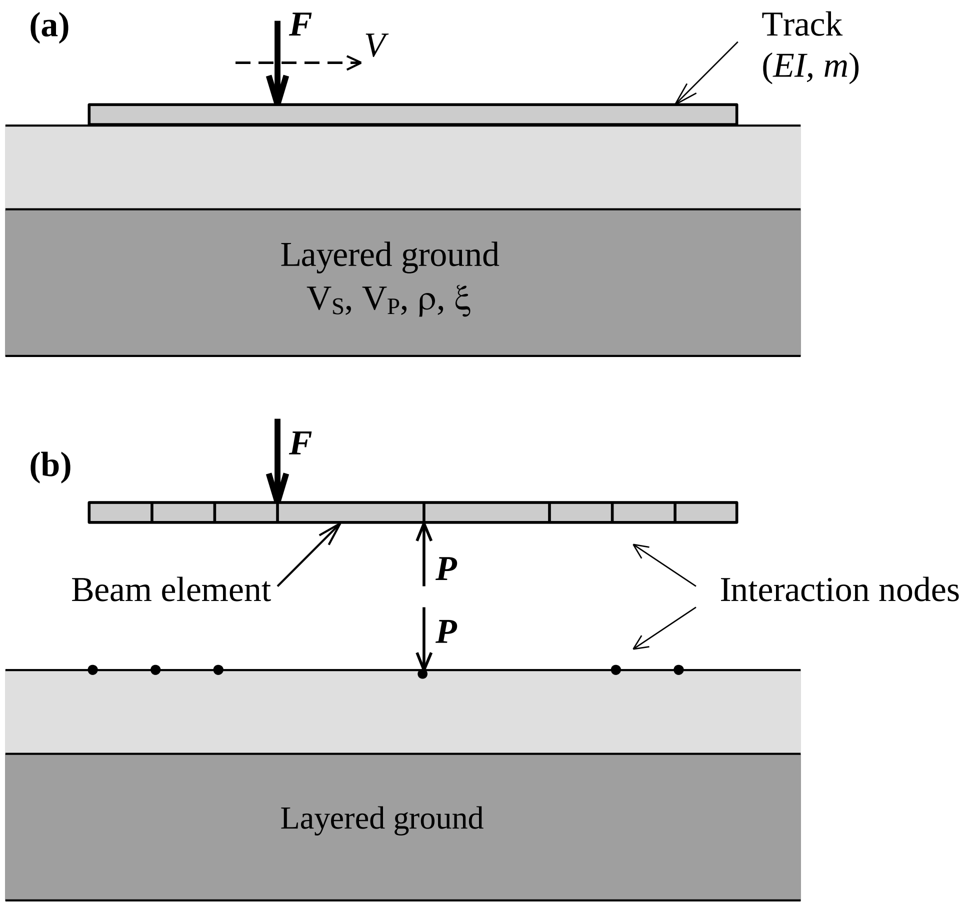
2. Numerical Modelling

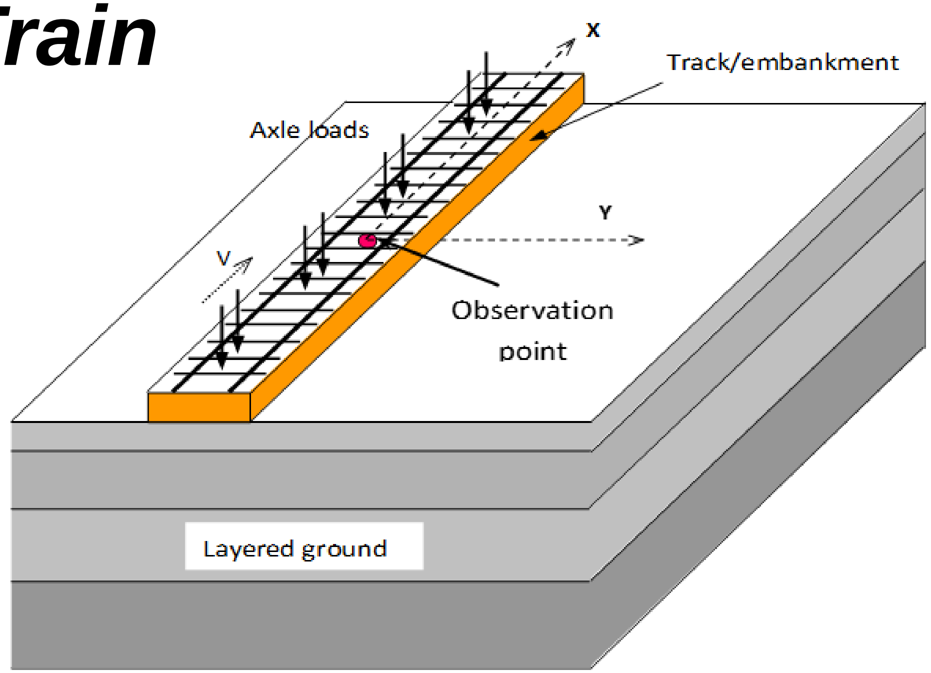
Existing solutions can be placed in the following categories:

1. Semi-analytical solutions based on Green's functions of layered ground (e.g. Kaynia et al. 2000).
2. 3D FE (or FD) solutions, Flac, Comsol, Abaqus (e.g. Hall and Bodare 2000)
3. Hybrid FE and semi-analytical (e.g. Correia dos Santos et al. 2017)
4. So-called 2.5D solutions, that is, 3D using 2D geometry (e.g. Lombaert et al. 2015).
5. 2D solutions, discussed in session on countermeasures (e.g. Norén-Cosgriff et al. 2019).
6. Empirical prediction methods (e.g. Madshus et al. 1996)
7. Special industry tools (e.g. VAMPIRE)

Numerical simulation model *VibTrain*

(Kaynia et al. 2000)





VibTrain (Hybrid model):
FE model of track coupled to analytical dynamic model of layered soil using **"Green's Functions"**

Ground: $W = G\,P$

$P = G^{-1}\,W = K_S\,W$

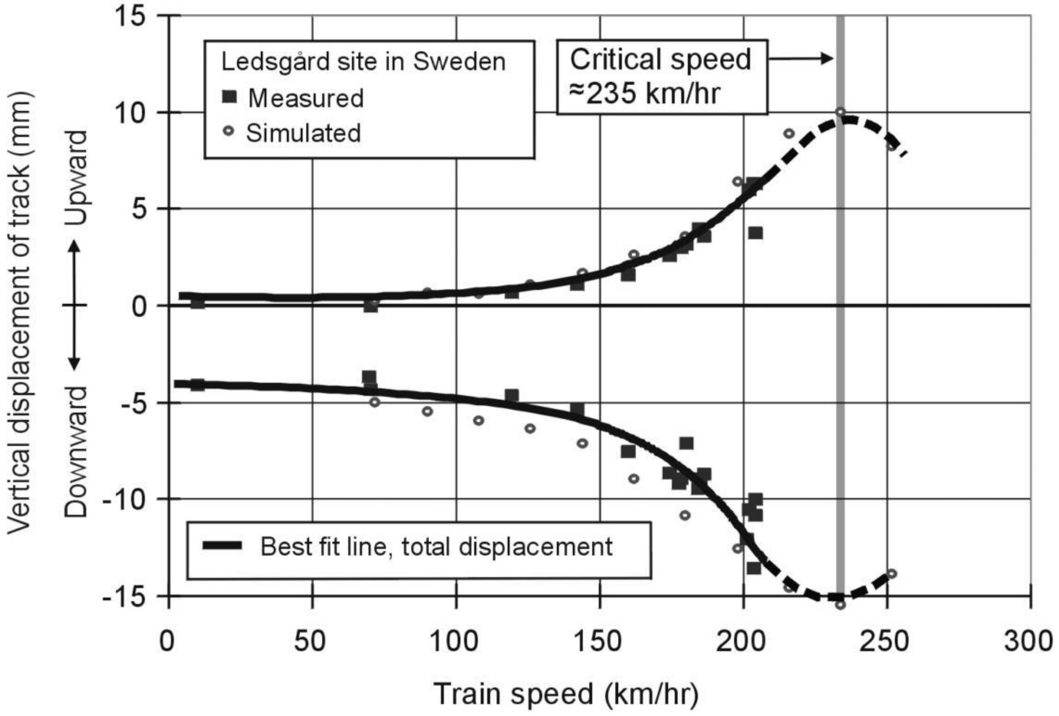
Track: $F - P = K_B\,W$

Total model: $F = (K_S + K_B)\,W$

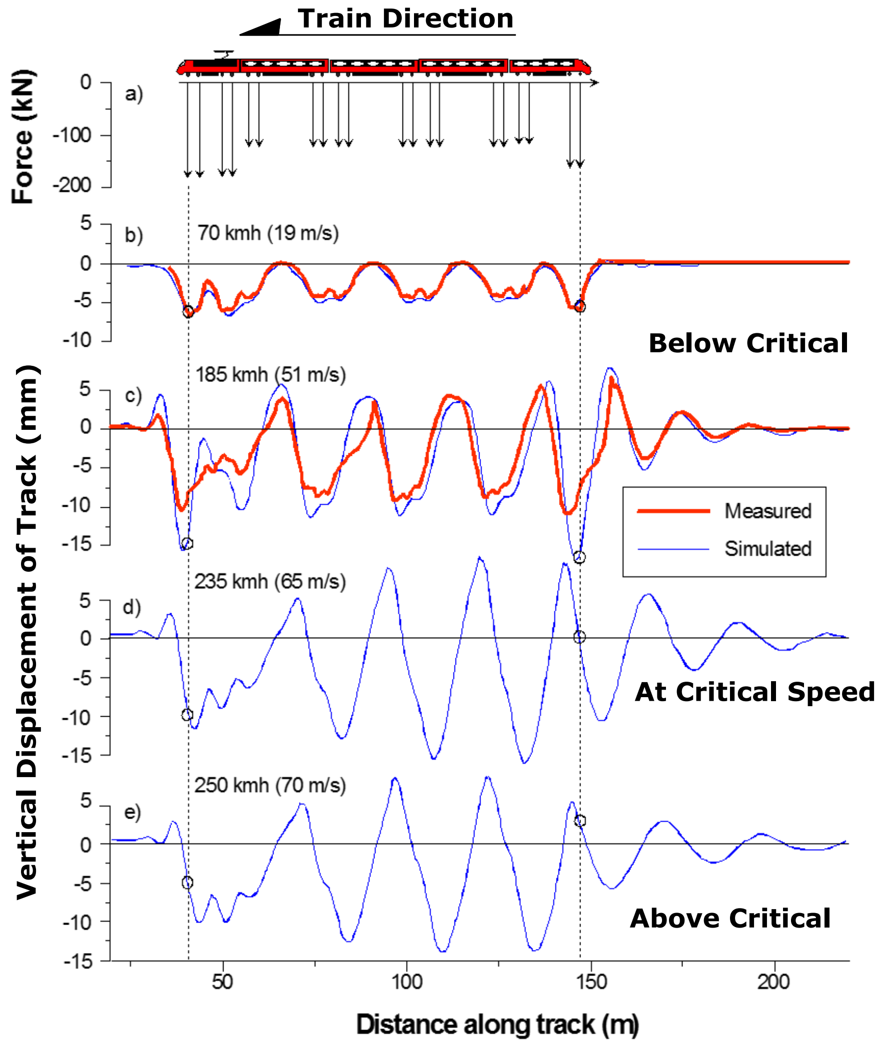
Green's Function G :

$$u_Z(r,z) = \frac{1}{\pi}\int_0^{\infty} \bar{u}_z\, J_0(kr)\,\frac{J_1(kR)}{kR}\,kdk$$

Simulations and comparisons

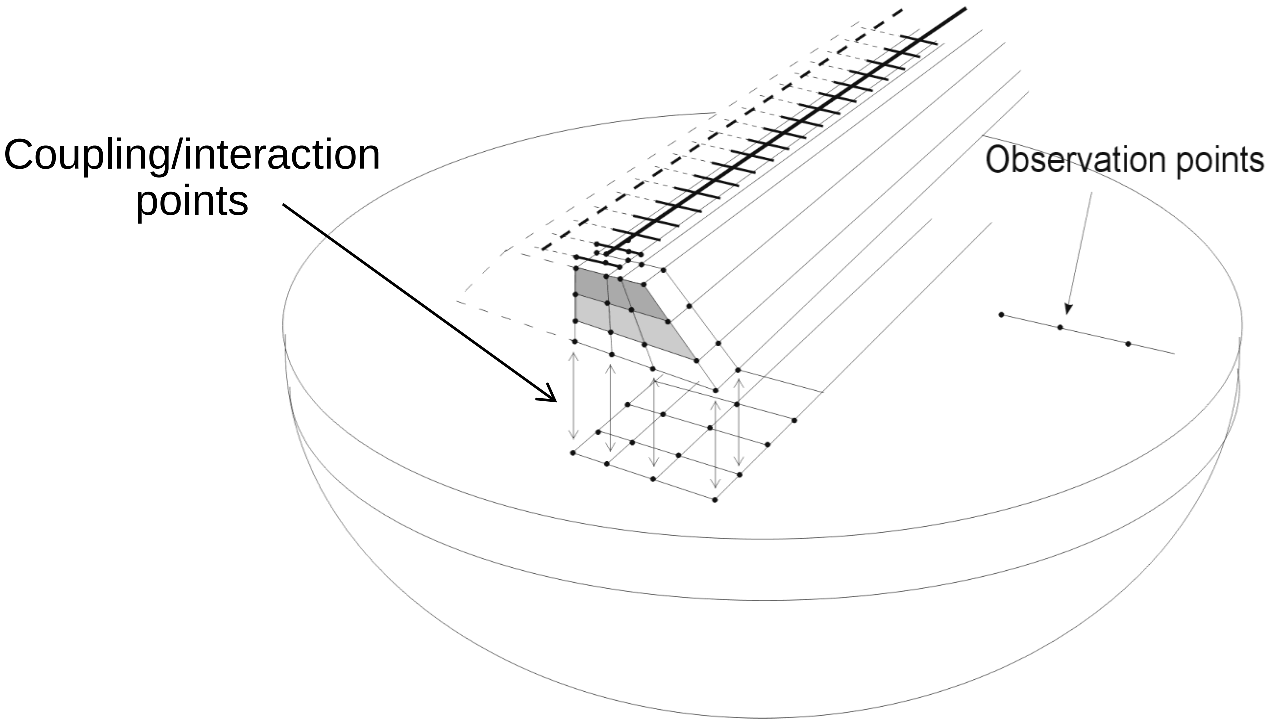


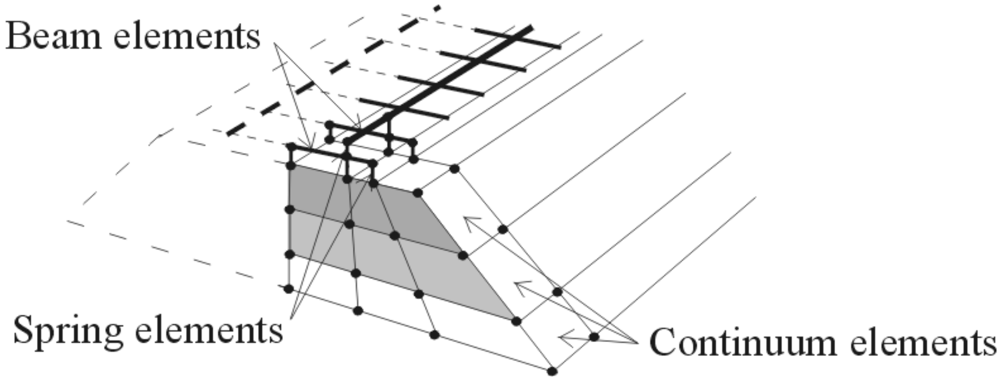
NB: Some standards/guidelines suggest V < Vcr/1,5 which likely come from our and similar studies. I personally believe this is rather an «academic» limit and does not have any design margin. Note that 235/1,5 = 155 km/h which is rather high!



Kaynia et al. (2000)

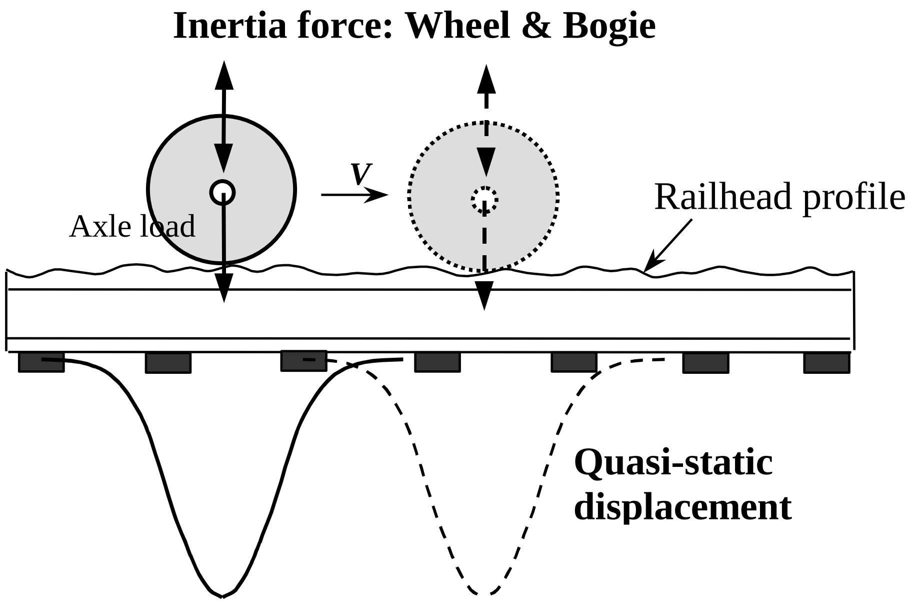
Further developments of *VibTrain(2)*: Detailed track

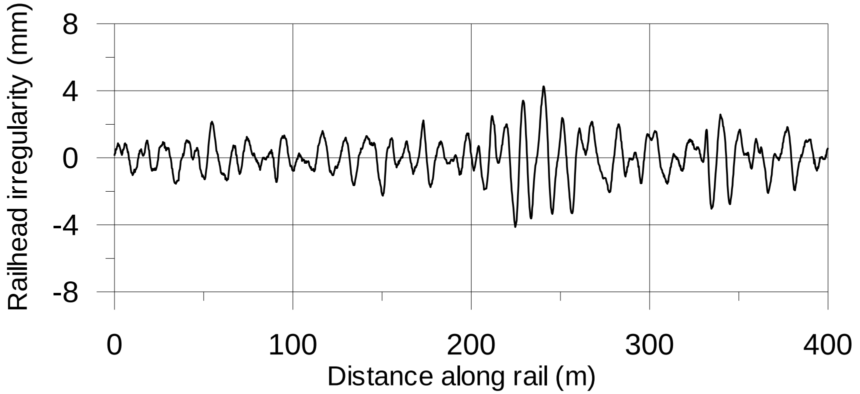




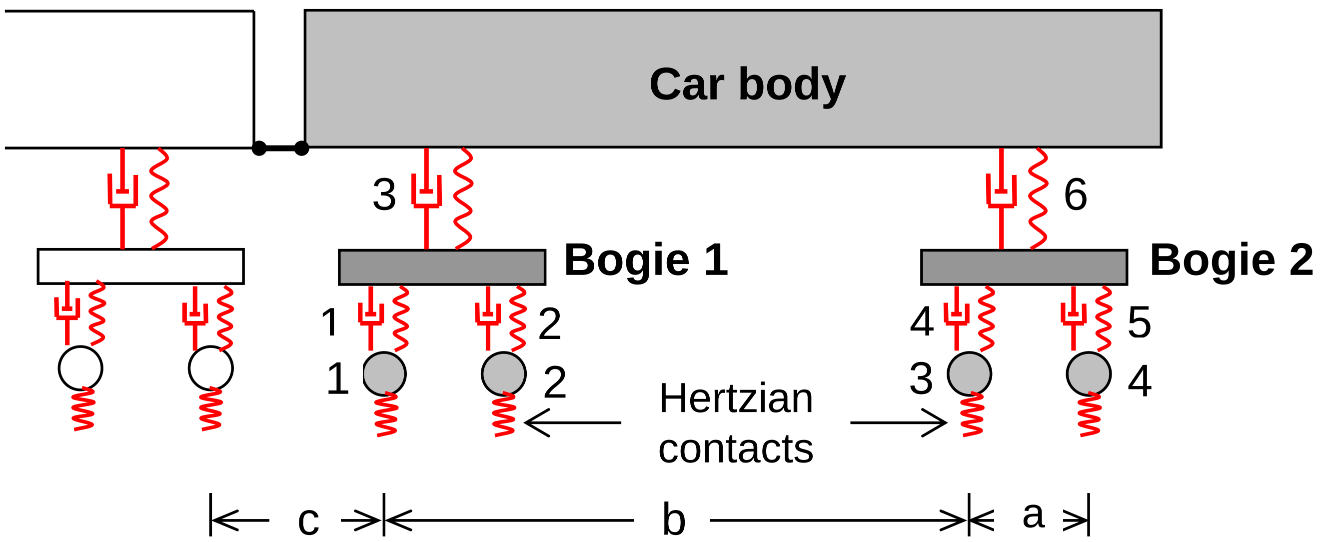
Detailed model of track and embankment in collaboration with CTH (facilitated by Trafikverket)

Further developments of *VibTrain*: Detailed vehicle



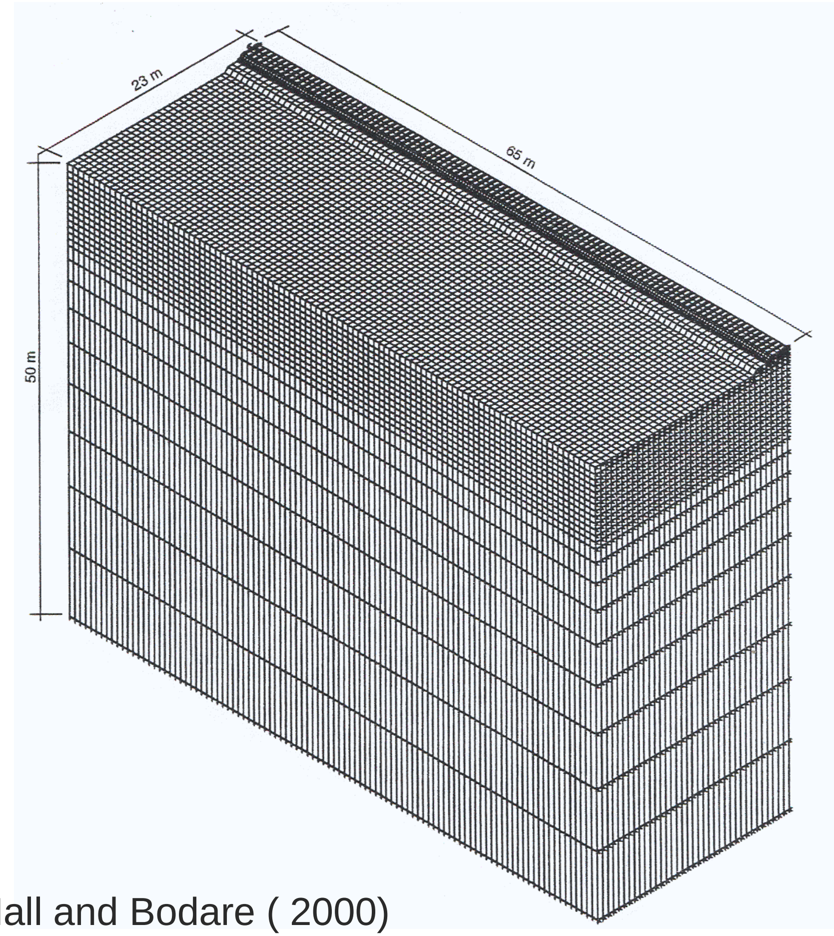


Rail vehicle model

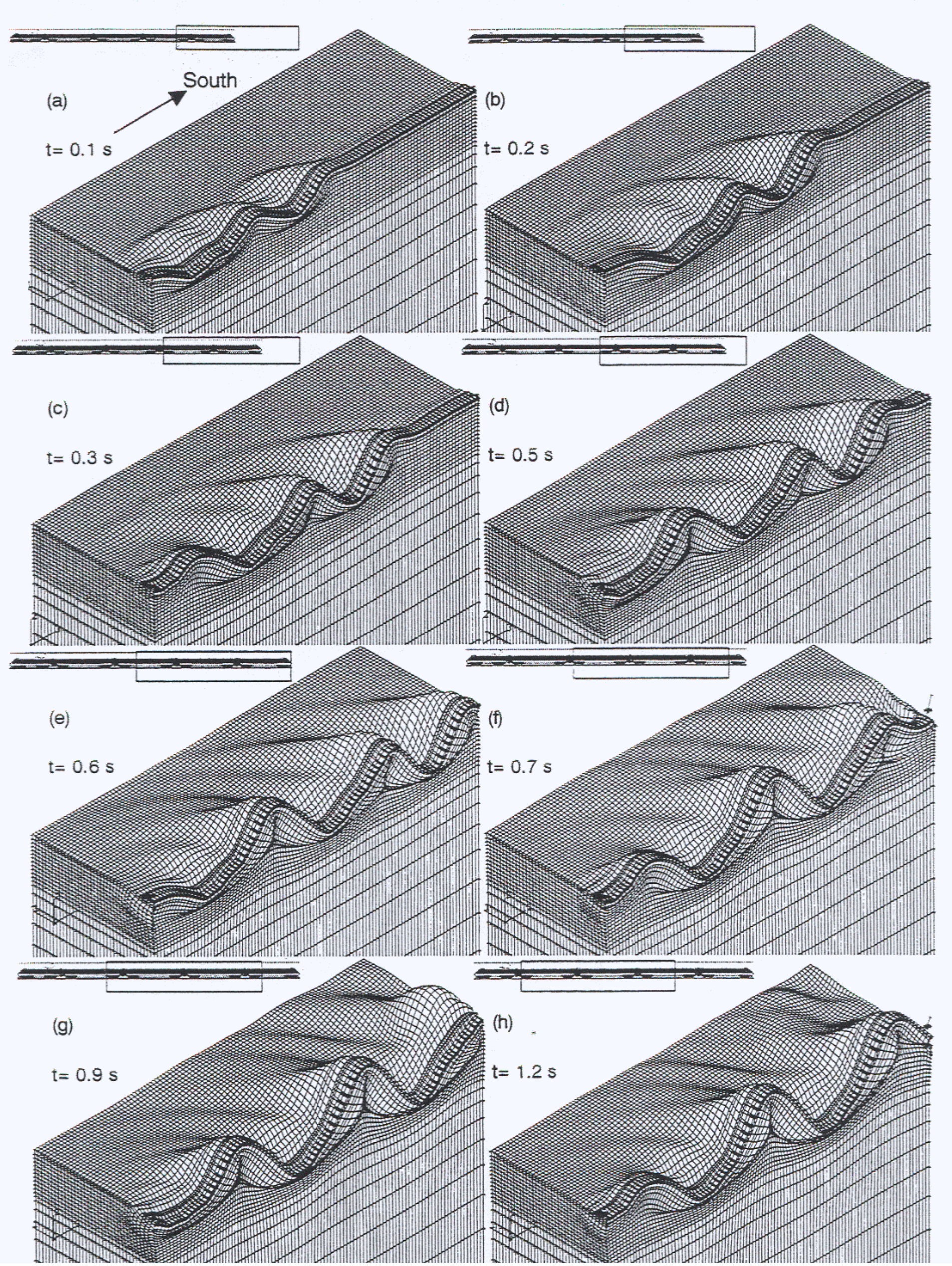


Kaynia (2001), *15th Int. Conf. Soil Mech. Geotech. Engng.*

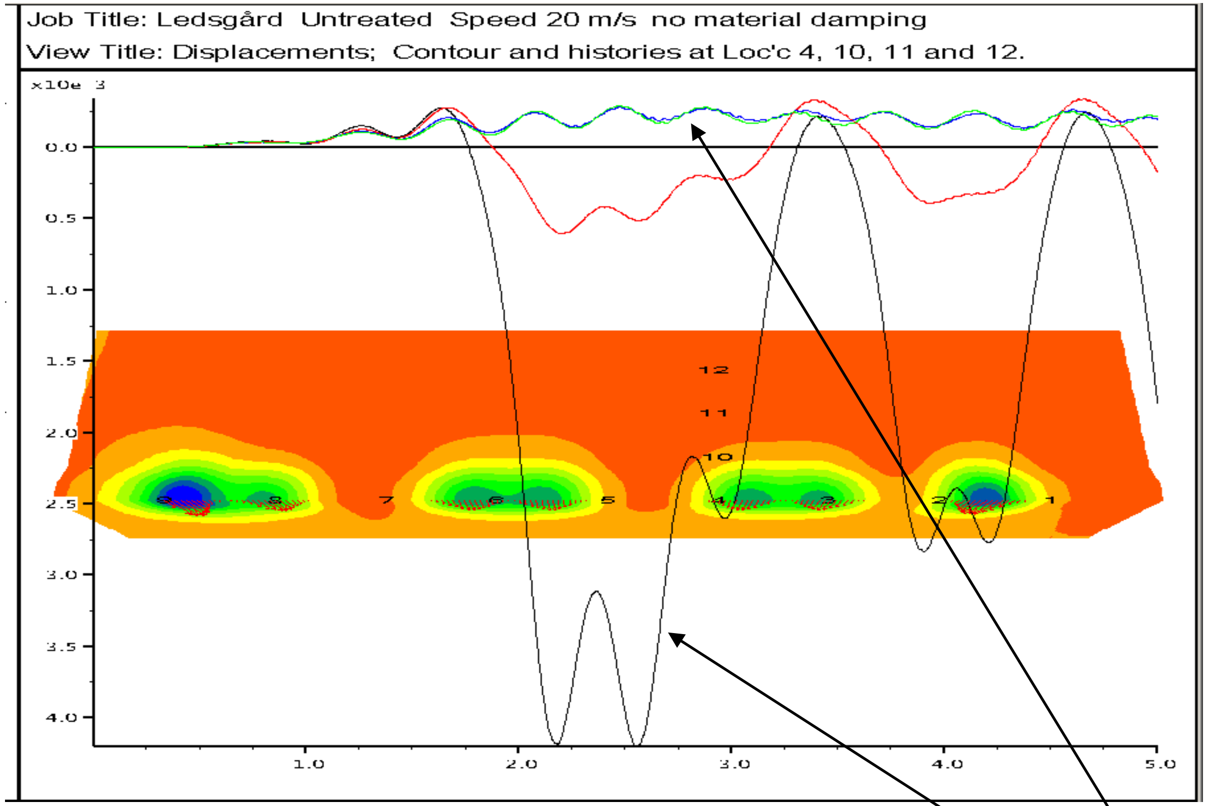
3D FE solutions

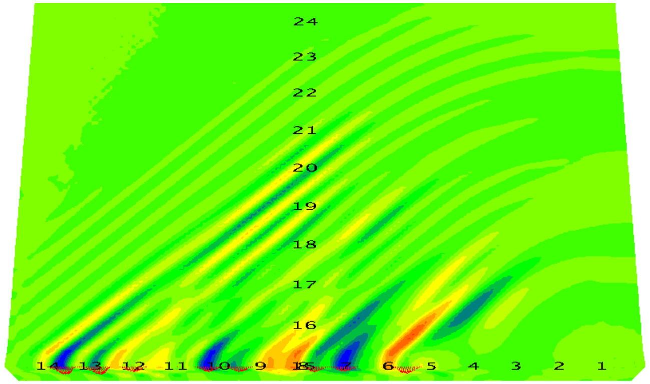


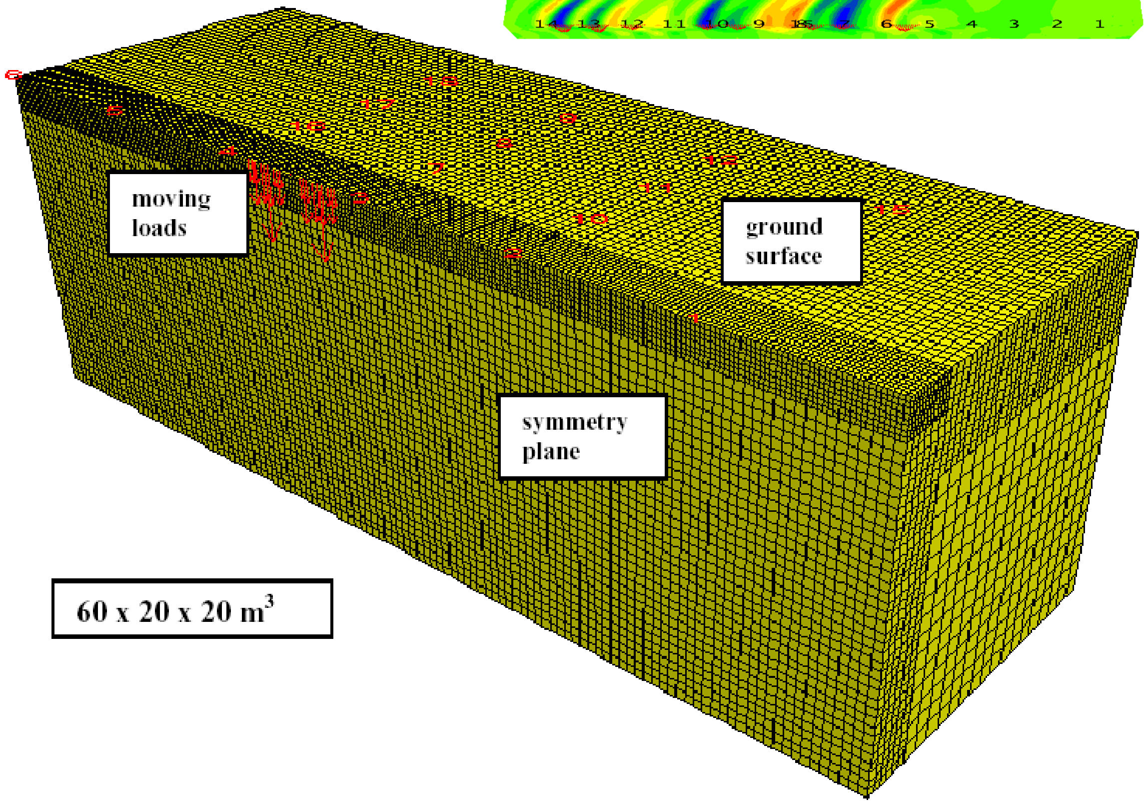
Hall and Bodare (2000)
Soil Dyn. & Earthquake Eng.



3D FD solutions







B. Andreasson (2000)
WSP group

Computed displacements at different distances from track

2.5D FE solutions

Because the size and material properties of track–subgrade structure are evenly distributed along the track, 2.5D FE method can be used. With a Fourier transform with respect to space dimension along the track, the 3D problem is transformed into a 2D problem in the wavenumber domain.

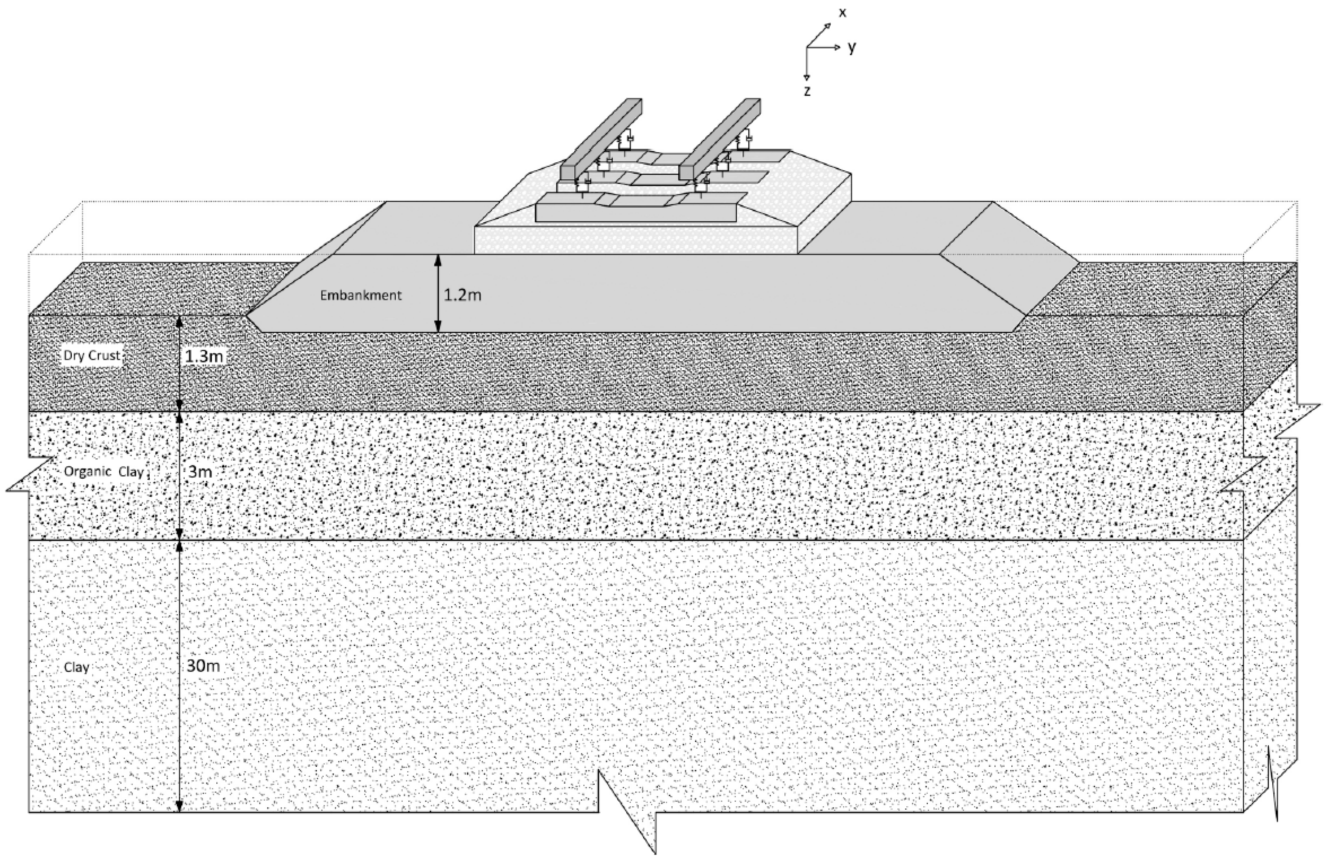
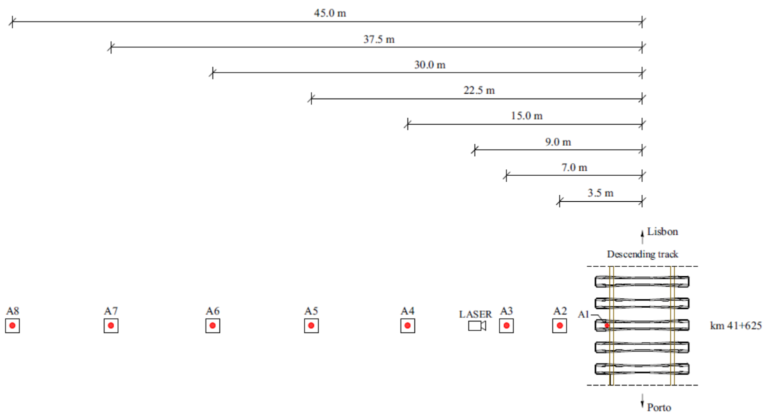


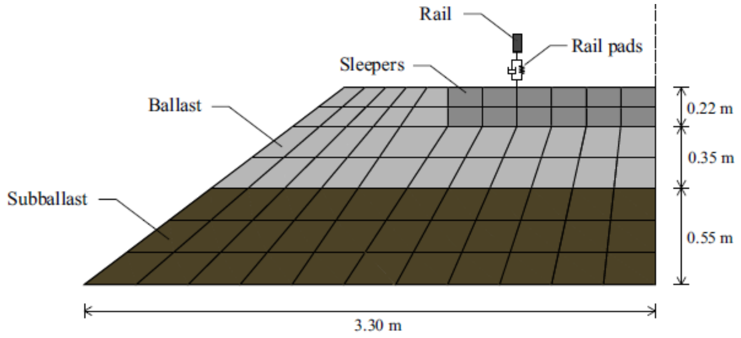
Fig. 8. Geometric dimensions at the Ledsgard site.

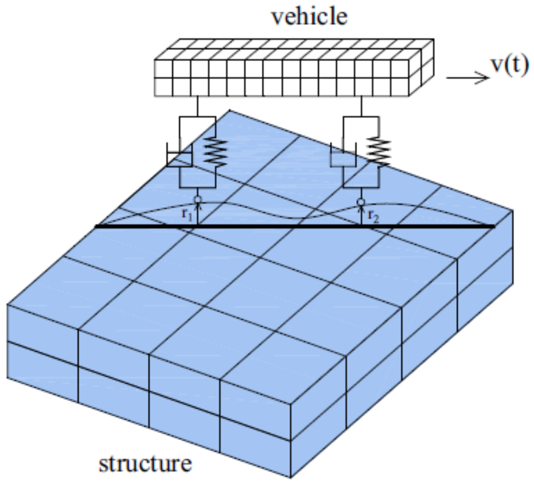
Dong et al. (2019)
Computers and Geotechnics

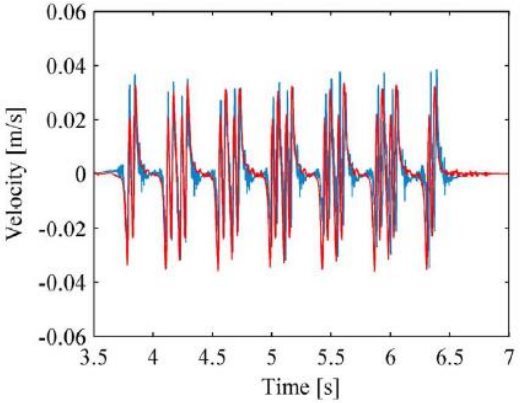
Hybrid 3D FE and semi-analytical

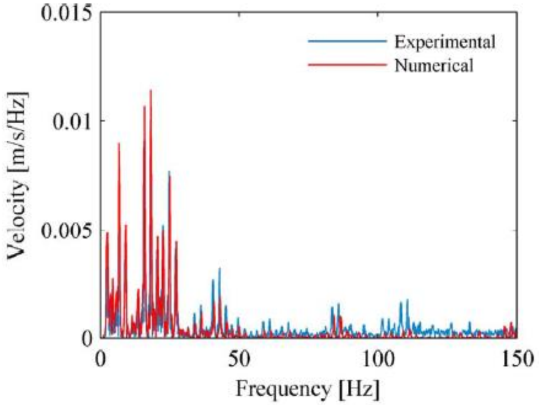
Track/embankment modelled by FE and ground by analytical Green's functions.

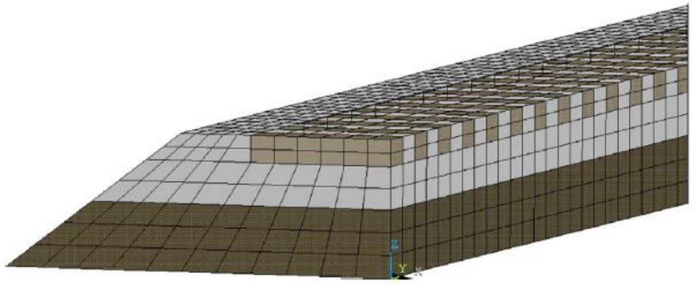


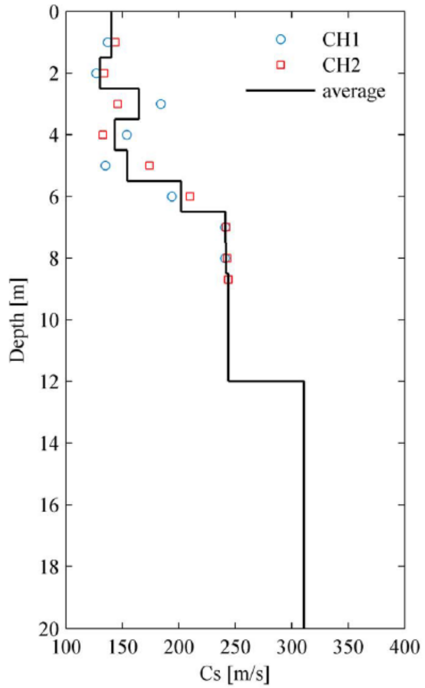








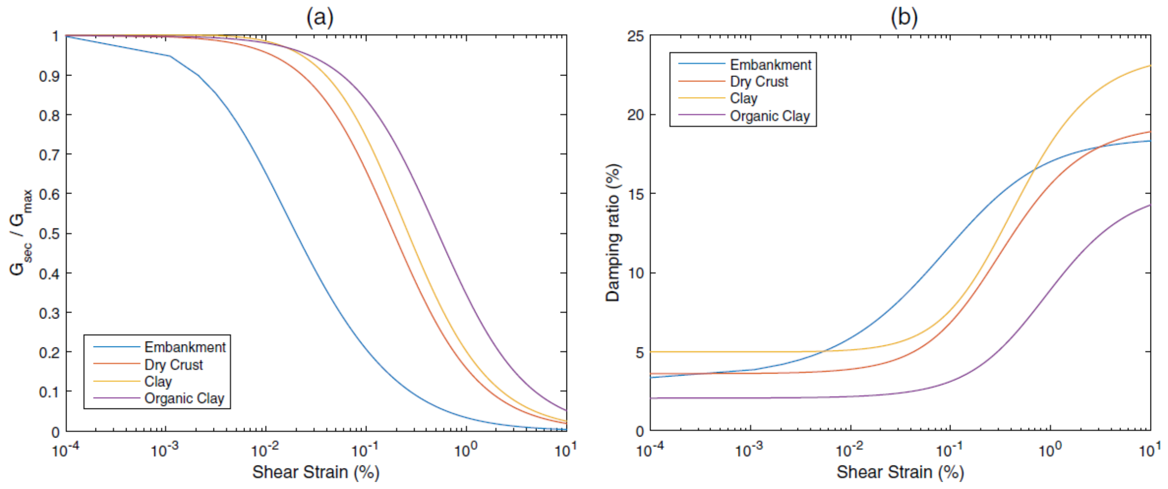




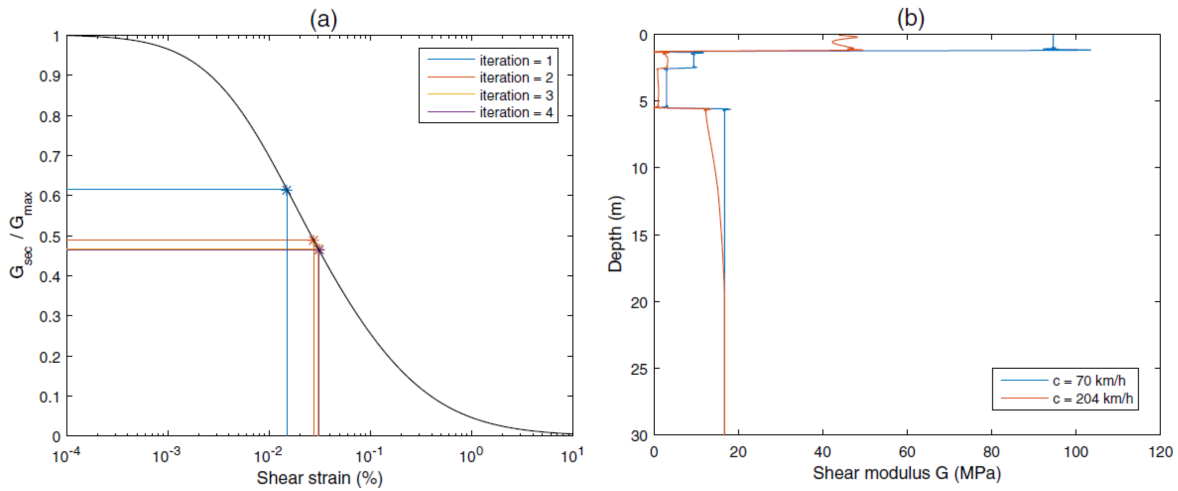
Correia dos Santos et al. (2017)
Soil Dyn. & Earthquake Eng.

3D FE – Equivalent linear method

Several studies have been performed to assess the degree of soil nonlinearity, especially as speeds approach Critical Speed. Some of the reported solutions have used the “equivalent linear method” Which iterates with the soil parameters to match the level of shear strain. Examples, Shih et al. (2017) and Dong et al. (2019).



Shear modulus and damping variations (Ledsgård site)



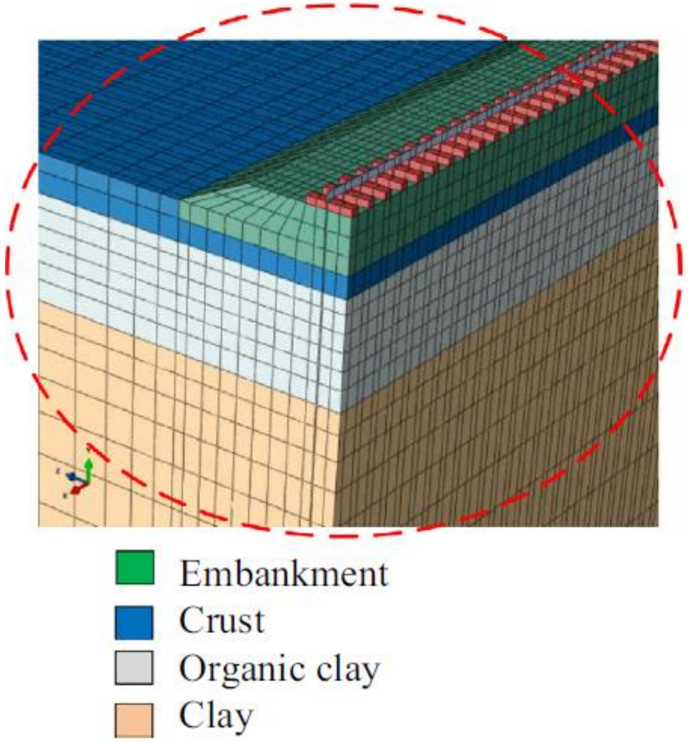
Iterations on shear strain

Final iterated shear moduli

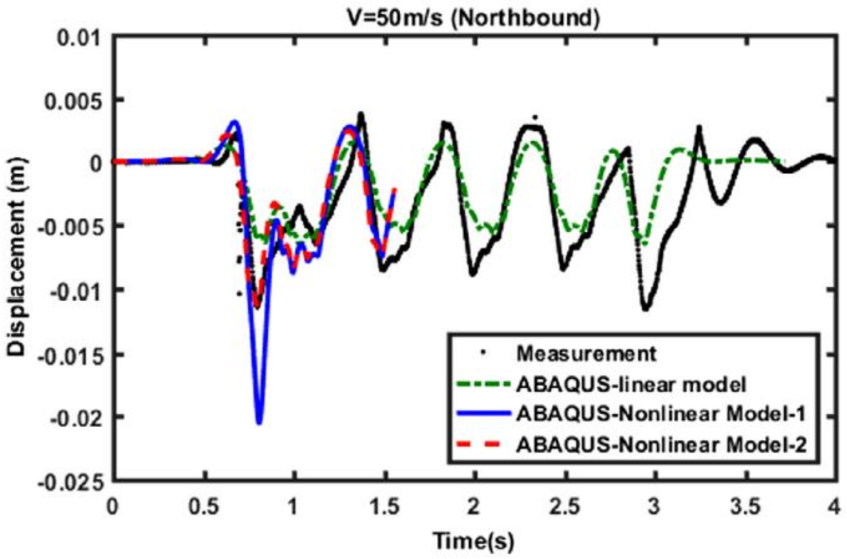
Dong et al. (2019) Computers and Geotechnics.

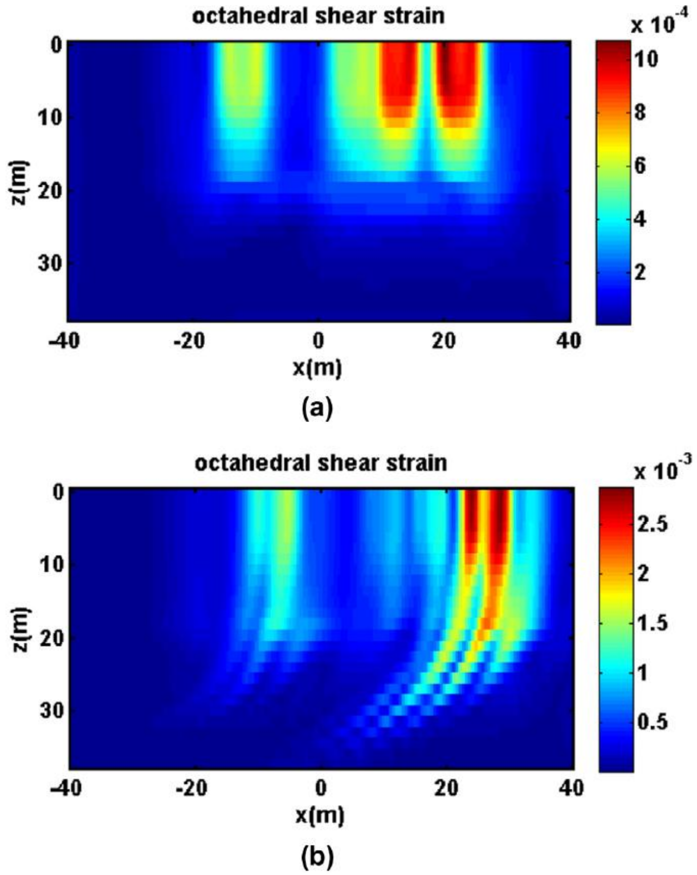
3D FE – Nonlinear solutions

Shih et al. (2017) performed 3D Abaqus analyses assuming both linear and Equivalent linear analyses for speed close to Critical Speed using Ledsgård data.



Shih et al. (2017) Transportation Geotechnics

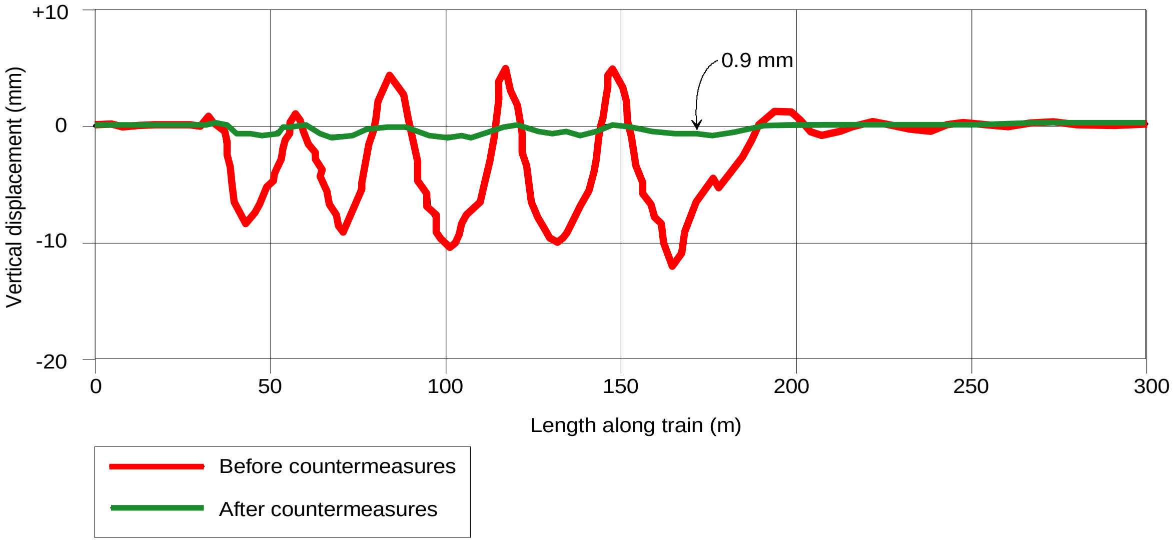


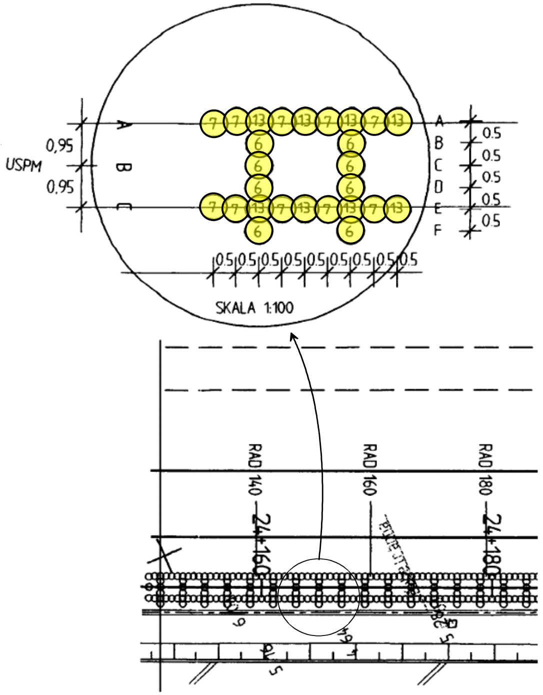


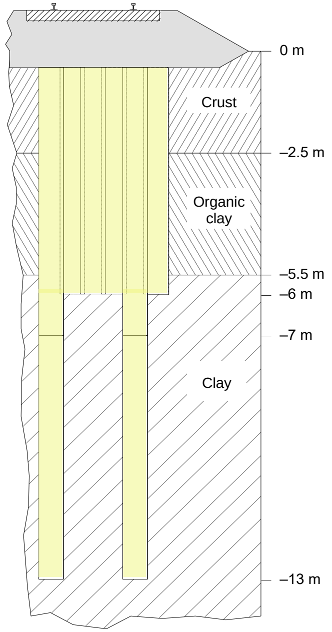
Results show nonlinear analyses yield larger (and more realistic) displacements and strains

3. Countermeasures

If countermeasure is against Critical Speed, one solution is to increase the stiffness of the soil, hence increasing Vcr, for example by lime cement columns (e.g. Ledsgård) or transfer the load to deeper soil.

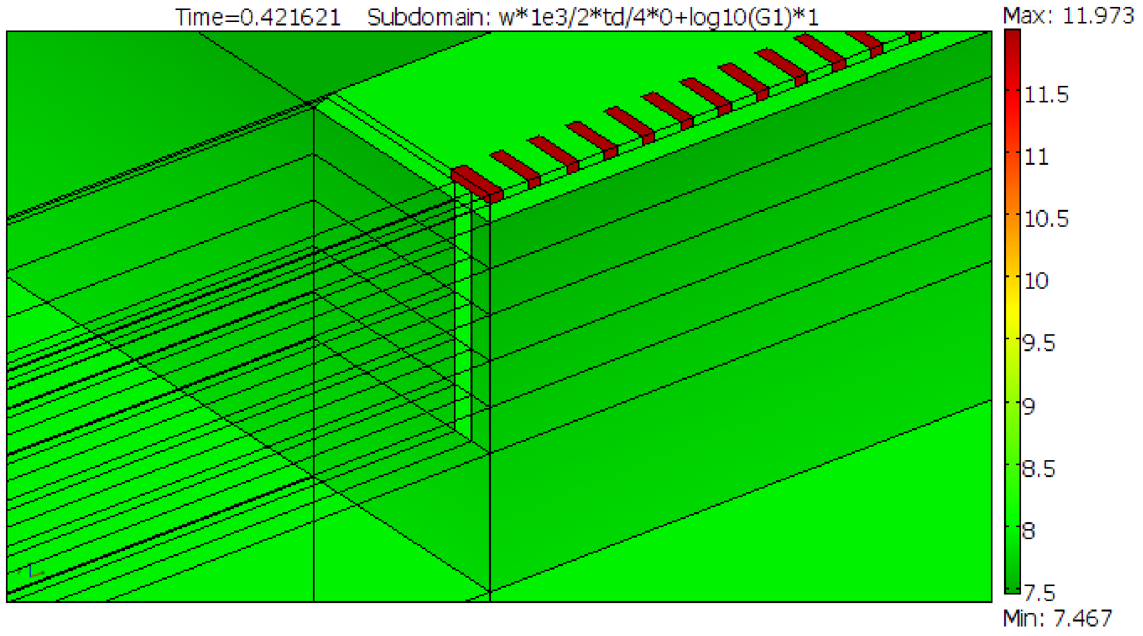




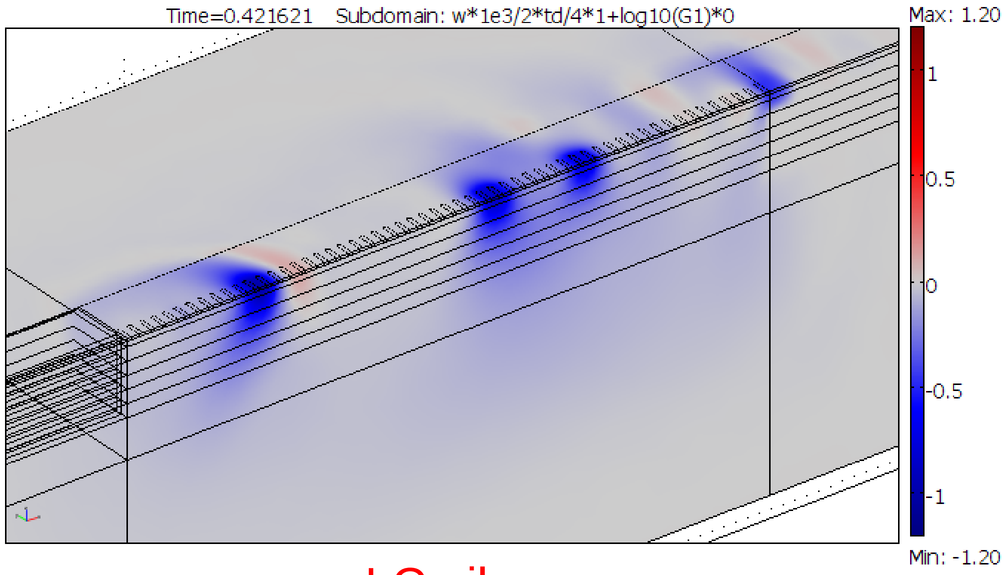


Countermeasure Design

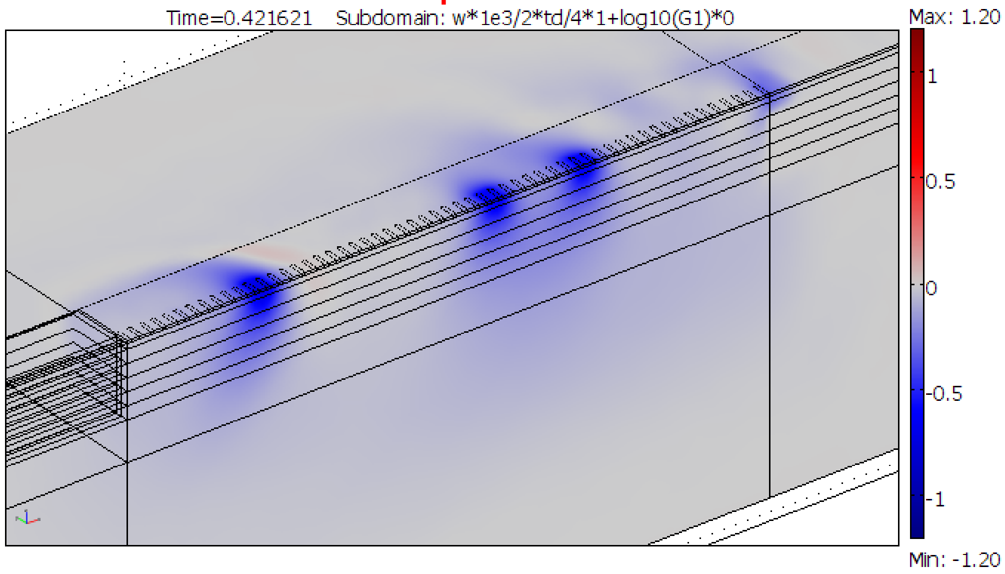
Countermeasures can be designed and optimized by numerical tools. Example: COMSOL (Ref. NGI)



No measures



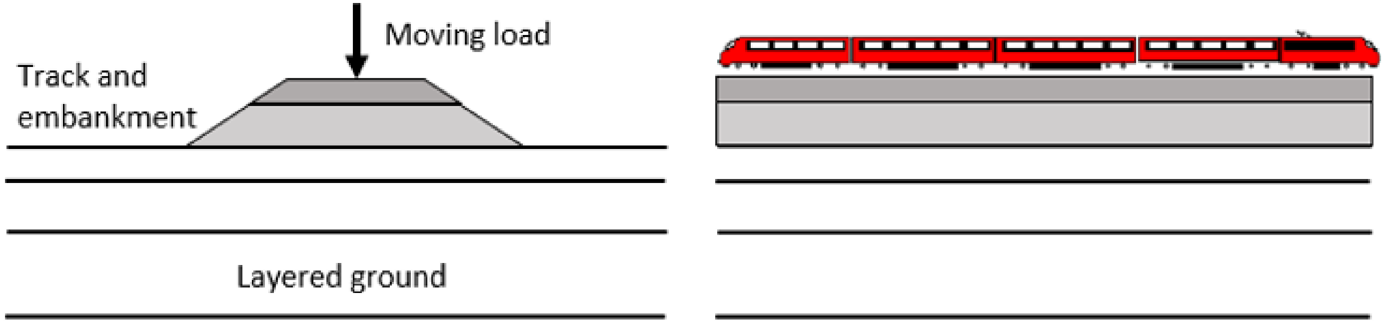
LC piles



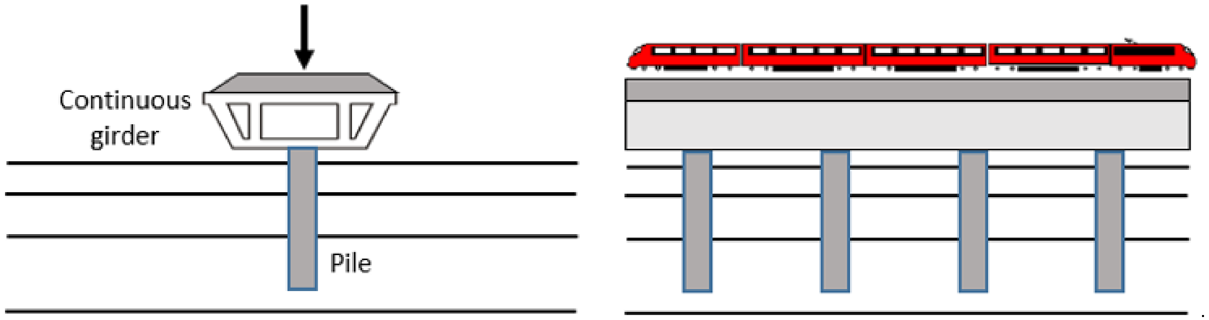
Critical Speed – How to increase it?

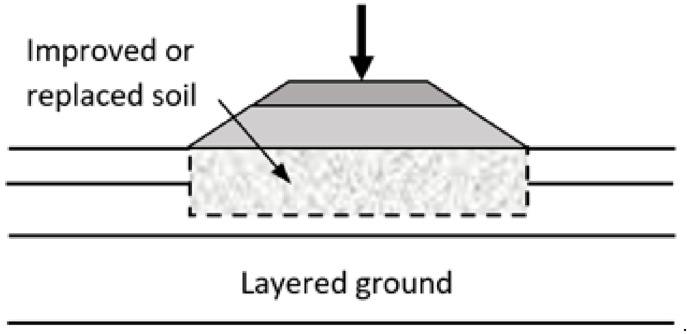
Three cases considered:

I. Stiffening the ground (ground improvement)
II. Stiffening the track or embankment
III. Use of piles



(a) Cross section (b) Longitudinal section



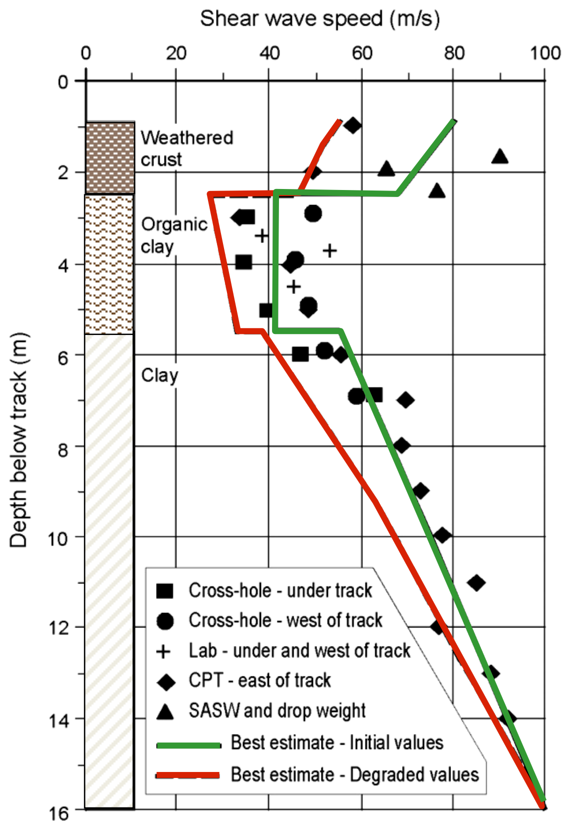


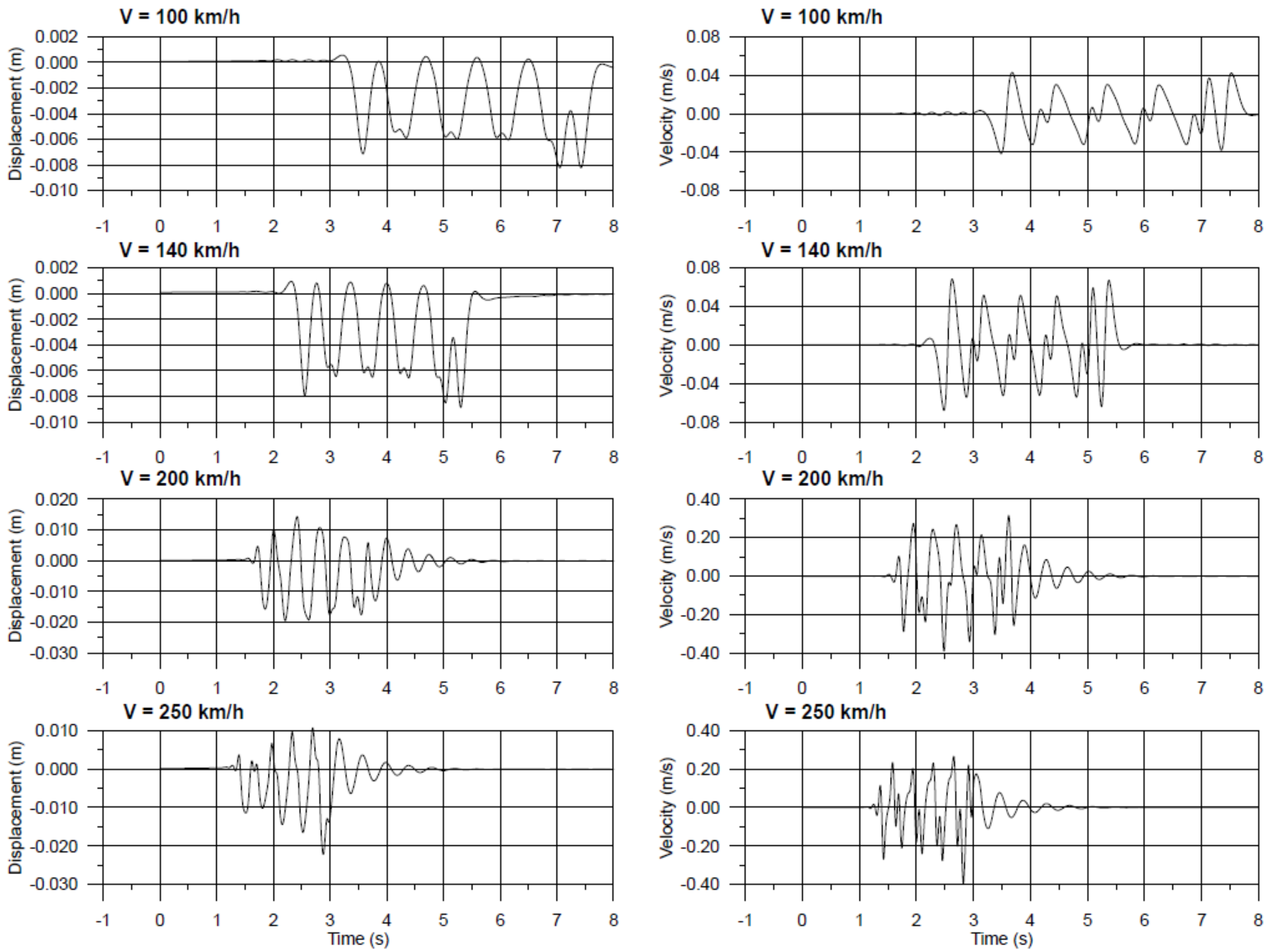
(c) Improved or replaced soil

Kaynia (2021), Springer

Base Case – no measures

Kaynia et al. (2000)



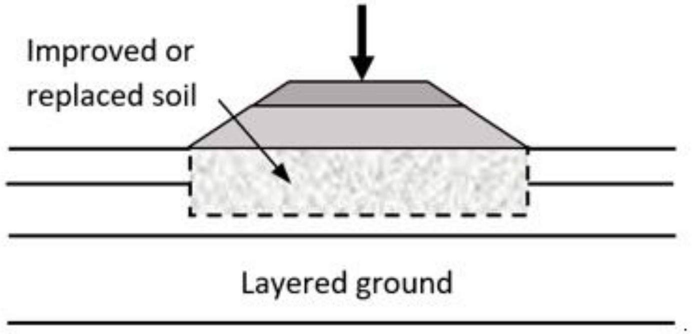


(a) Displacement

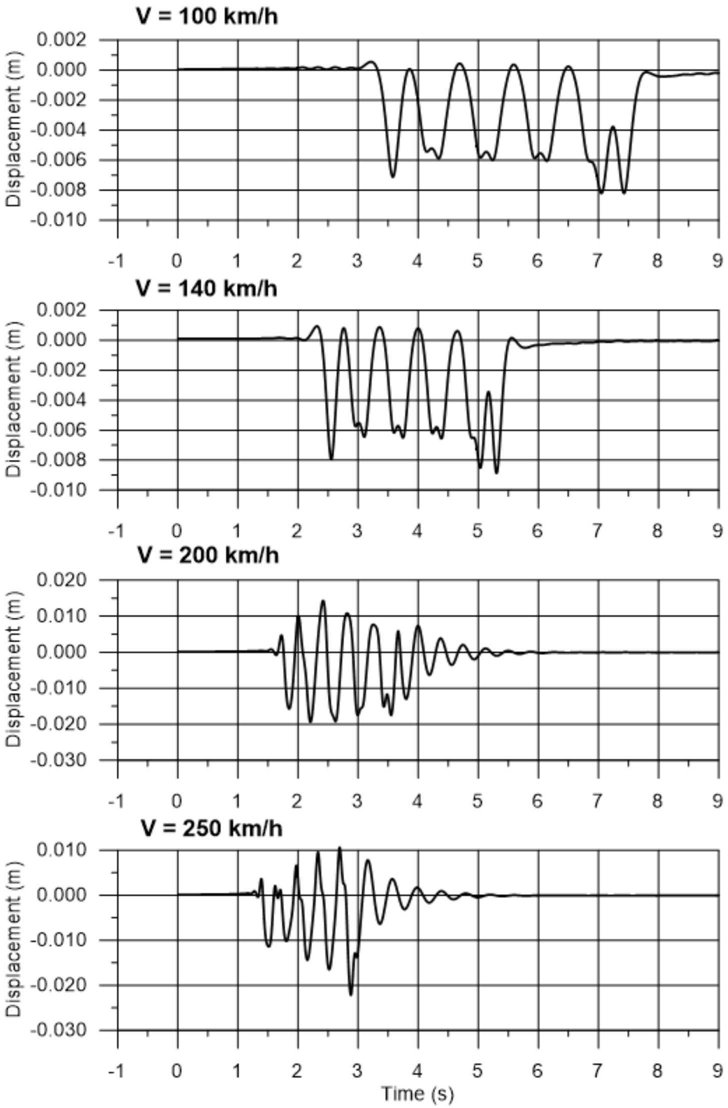
(b) Particle velocity

Case 1 – Ground Stiffening

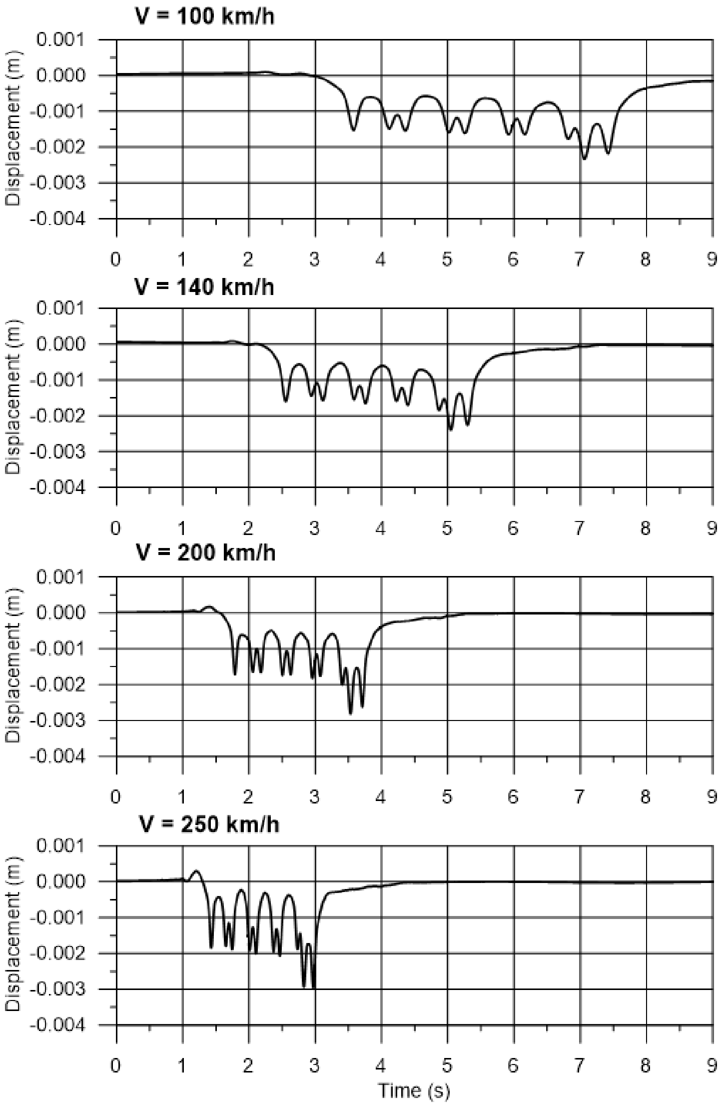
Soft layer (Ledsgård) is replaced by crushed rock.
NB: For LC columns, one could use the same model with “smeared” mechanical parameters.



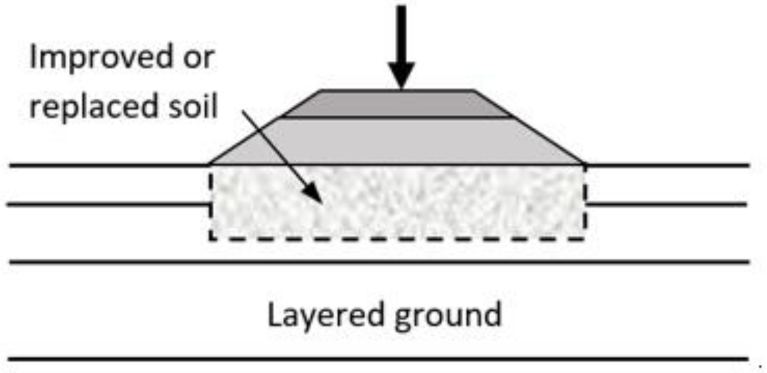
Base Case

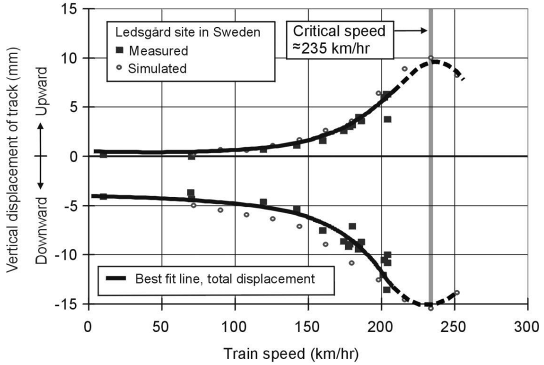


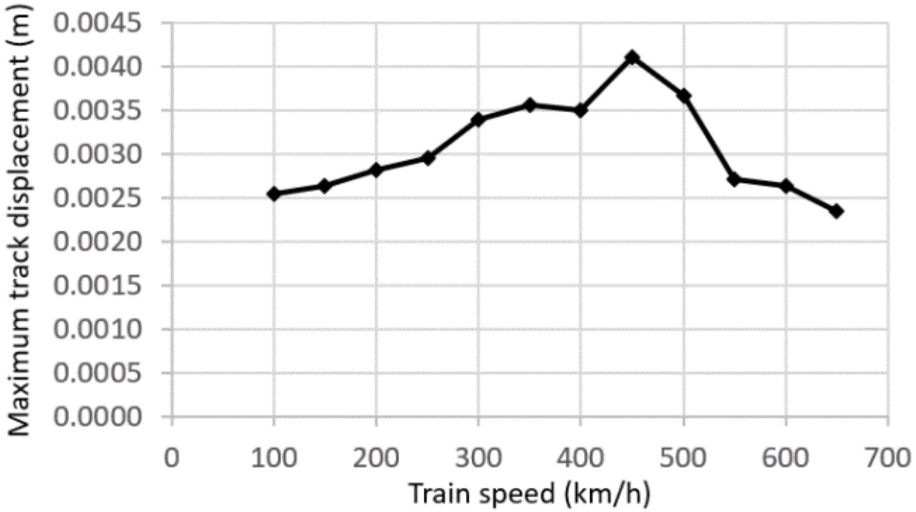
Stiffened ground



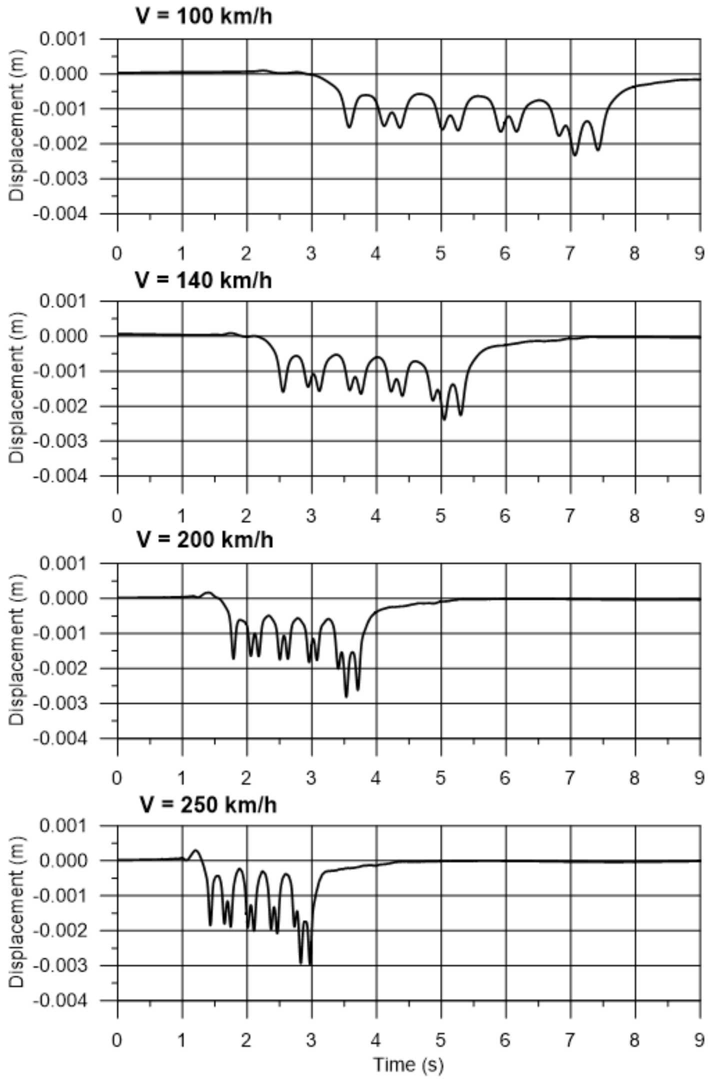
Case 1 – Ground Stiffening







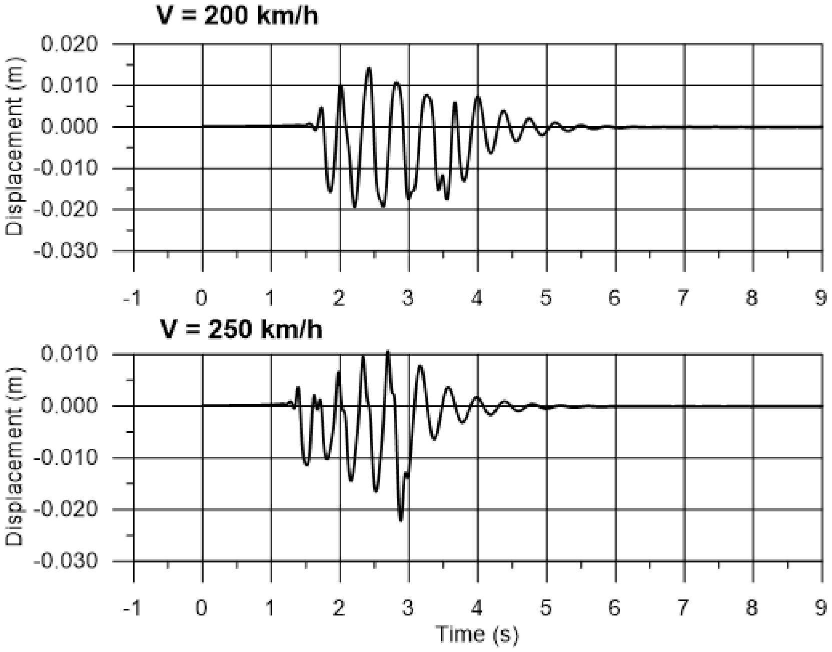
Stiffened ground



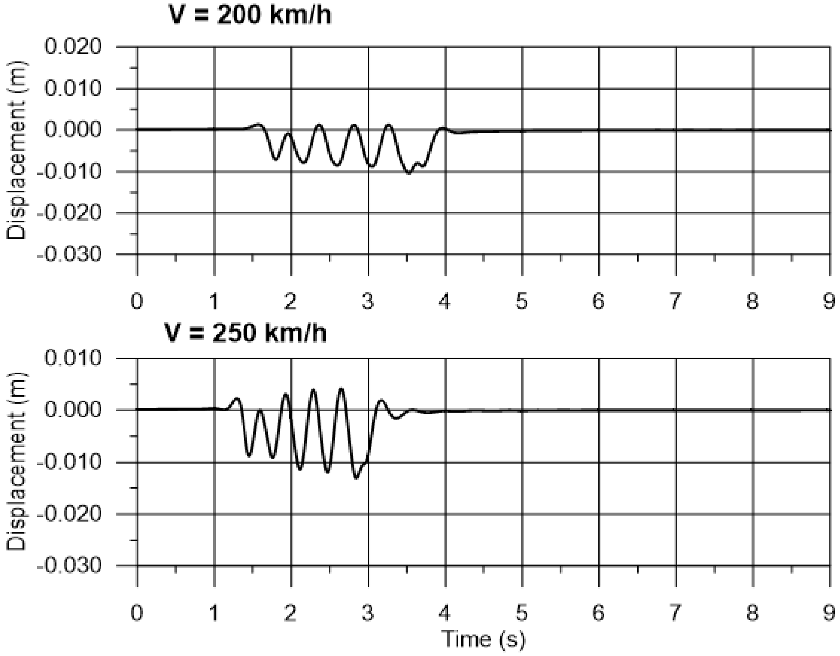
Case 2 – Track stiffening

For example, improvement by grouting or use of a stiff beam under the track

Base Case



Stiffened track

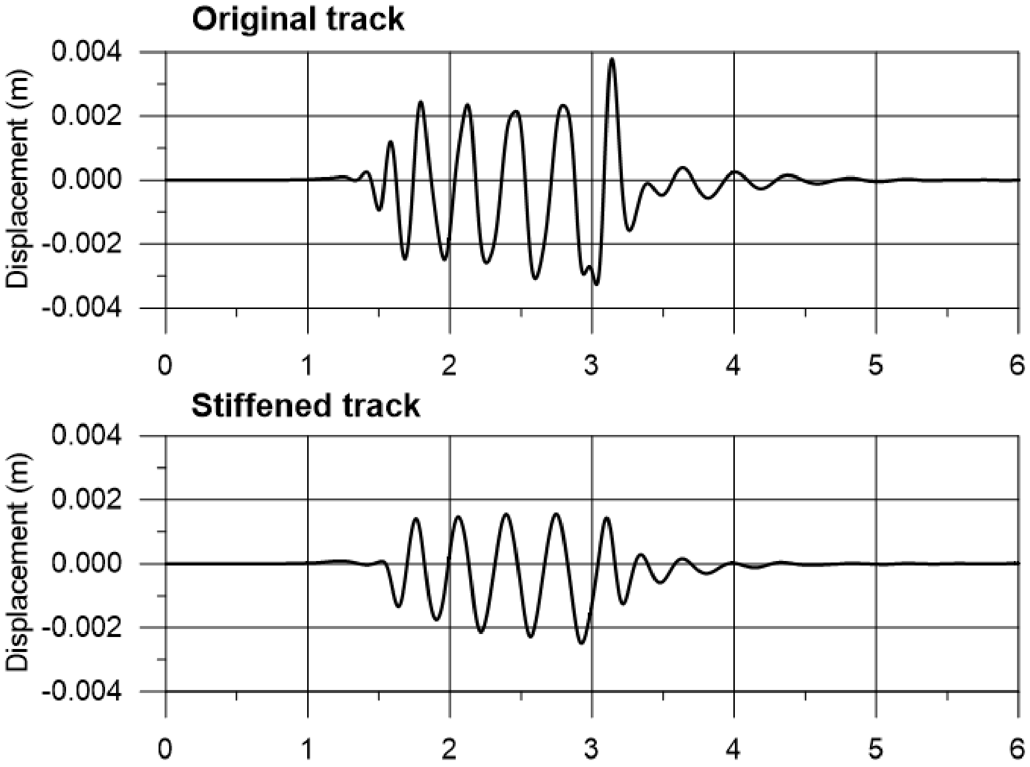


- The results for stiffened track are when the stiffness of the embankment in Base Case is quadrupled
- Stiffer tracks reduce displacements and vibrations
- But they do not noticeably change the Critical Speed (next slide)

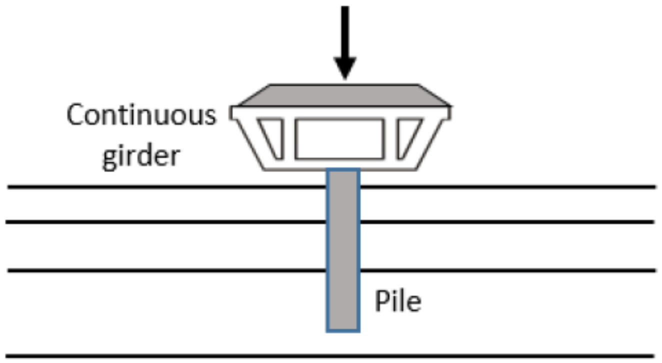
Case 2 – Track stiffening

There is no dramatic reduction of trackside ground response; we see the same vibration features. Therefore, track stiffness which otherwise is one of the solutions to reduce vibration, is not effective here.

Trackside Ground response 10 m from track

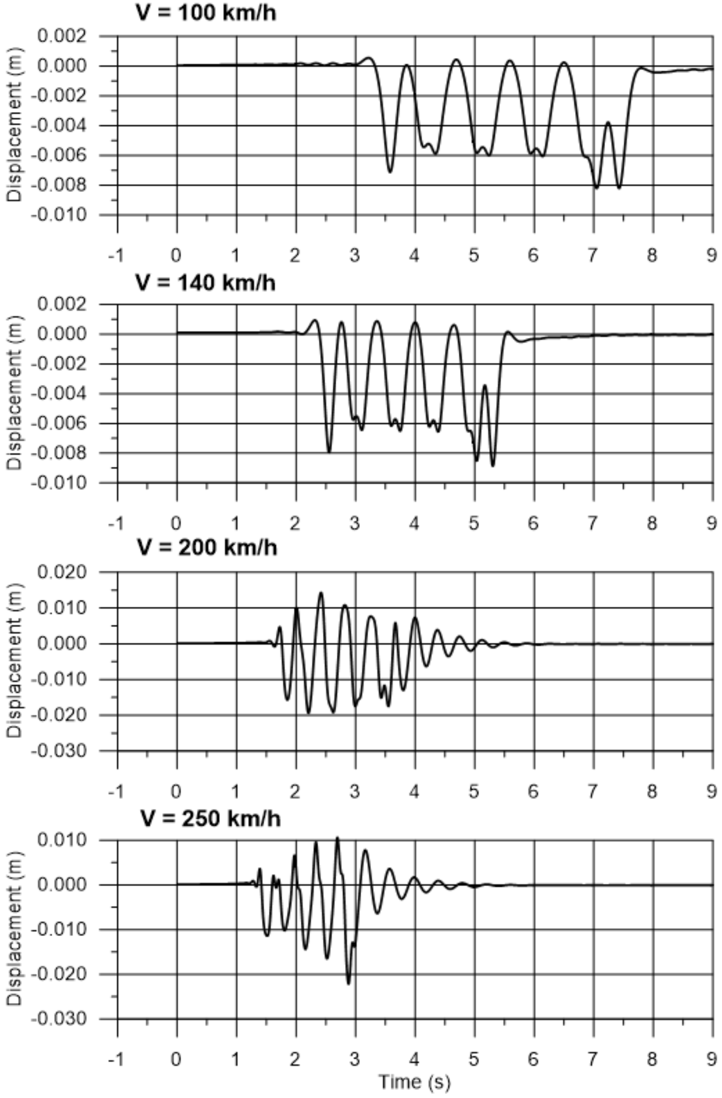


Case 3 – Piled track

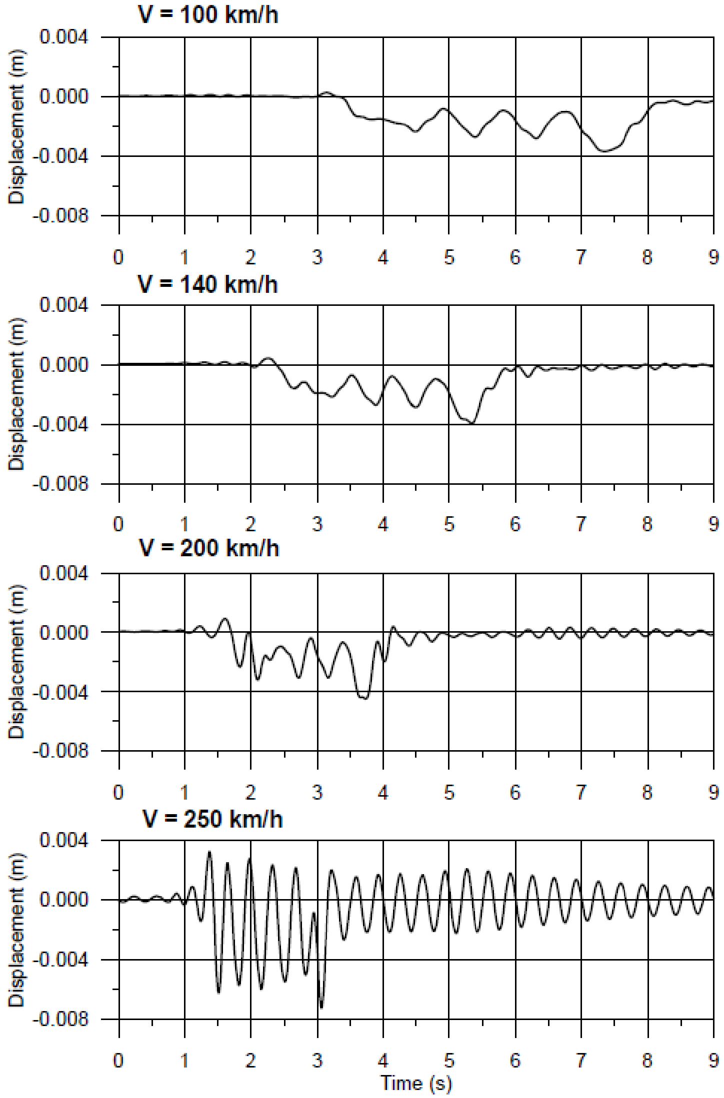


- 2 m diameter, 9 m long piles installed at every 12 m.
- Vibrations can be reduced dramatically at pile locations, but resonance of beam can cause large vibration at mid span. Design optimization is required.

Base Case



Piled track

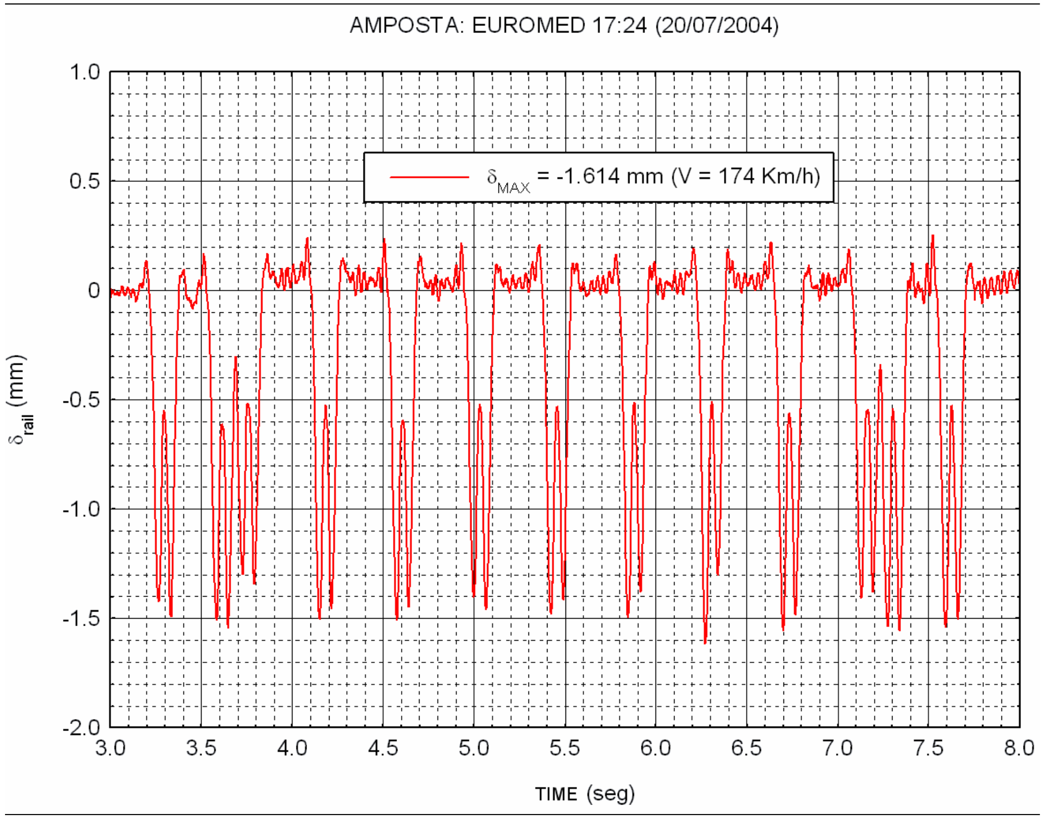


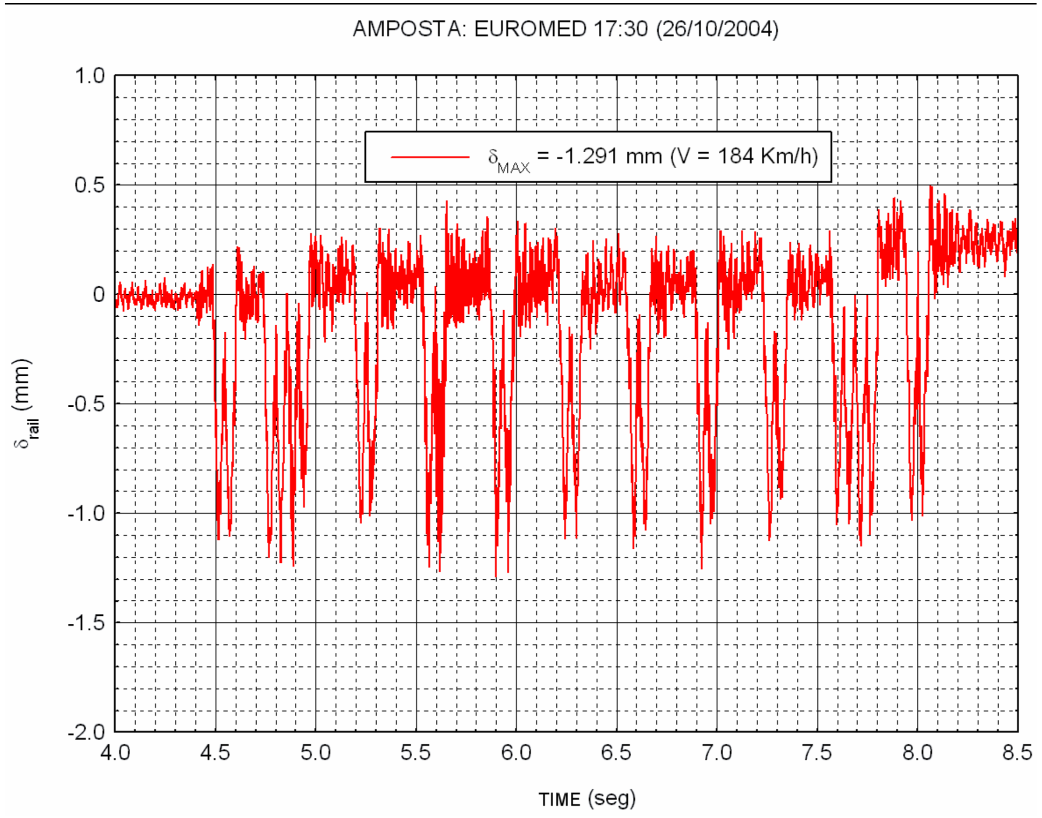
Track stiffening - Spain

Track stiffening/homogenization by hydraulic fracture grouting carried out during EU project SUPERTRACK (https://www.ngi.no/eng/Projects/Supertrack-improve-high-speed-railways) on the embankment of the viaduct over the Ebro River on the line Valencia-Barcelona. Grouting was performed in such a way to provide a smooth transition in the embankment while displacements were monitored (ref. V. Cuéllar, 2005).

Vibration countermeasure – Track stiffening

Measurements of track displacement before and after grouting (V. Cuéllar, 2005).



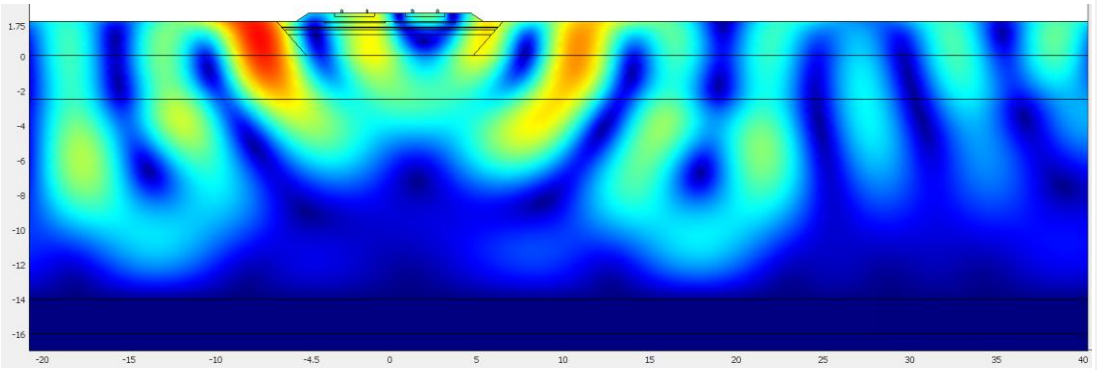


2D models: Vibration countermeasure – LC columns

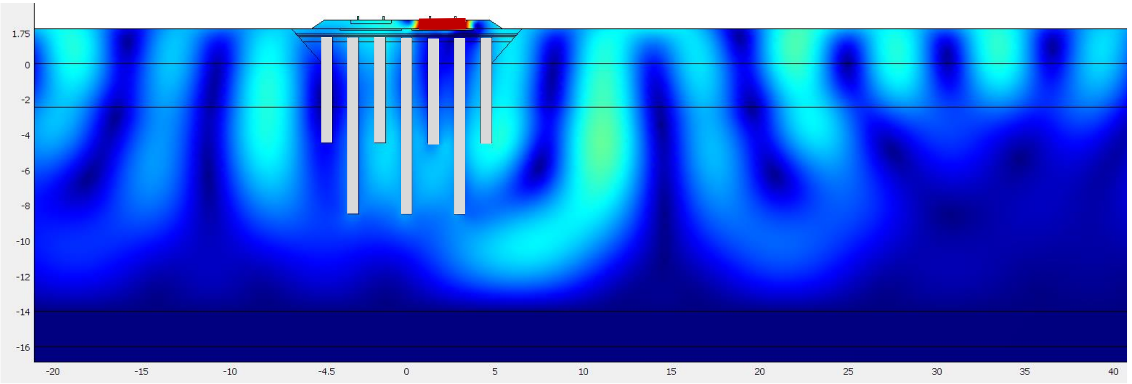
2D models can be used for **qualitative** assessment of countermeasures (e.g. Norén-Cosgriff et al. 2019)

Example of calculation results: Vibration velocity amplitude at 8 Hz

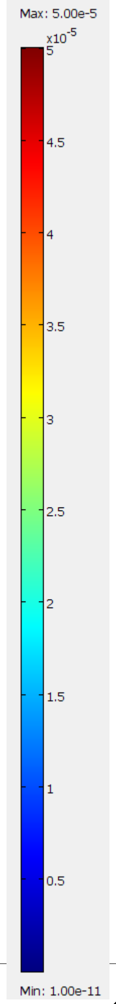
Reference model



Model with LC-piles with varying configuration



Norm vibration velocity amp

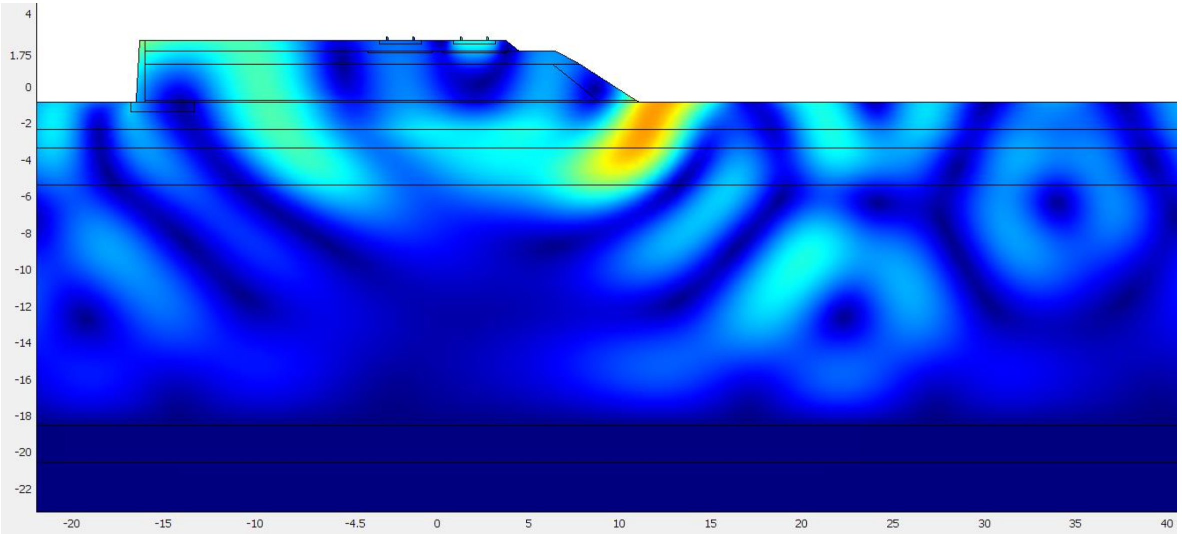


2D models: Vibration countermeasure – Sheet pile walls

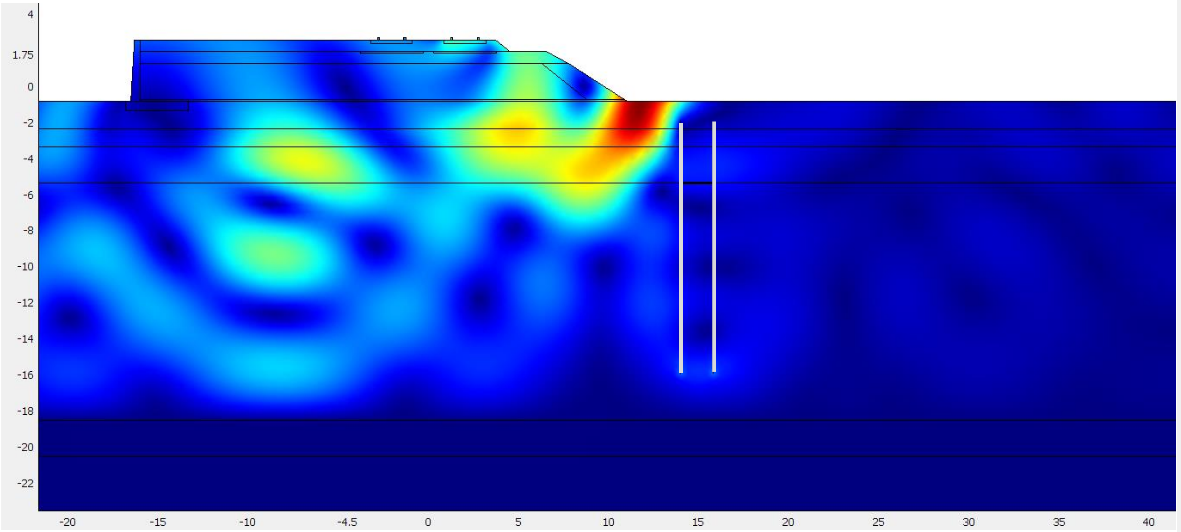
Norm vibration velocity amp

NB: 2D model only for qualitative assessment

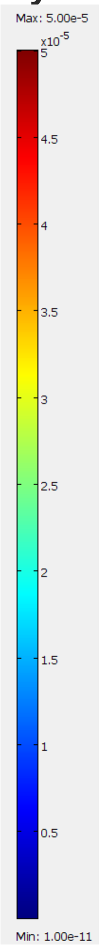
Example of calculation results – Vibration velocity amplitude at 8 Hz



Reference model



Model with double sheet pile wall



Summary

- Ground parameters are key to design of HS lines (field/lab tests and correlation with traditional soil parameters).
- There are many robust numerical tools with different levels of detail and sophistication. Use of simple tools in mapping and preliminary assessments is essential.
- There are two response regimes when considering reduction of ground vibration from high-speed train.
- Below Critical Speed, high frequency response can be reduced by countermeasures like ground or track stiffening.
- For train speed close to the Critical Speed, the only solution to reduce the response is to increase Vcr by ground improvement (soil stiffening) or use of piles - but not by track stiffening.
- Track stiffening will reduce track vibrations, but the vibrations away from the track are not noticeably affected – important for design of tracks on soft soil through urban areas.

Norconsult

Thank you for your kind attention