4th Int. Conf. on Transportation Geotechnics (ICTG), May 24-27, 2021

ICTG 2021 VIRTUAL

3rd Proctor Lecture

Railway track substructure: recent research and future directions

Presented by

William Powrie, University of Southampton, UK

Outline of lecture

- The decarbonisation challenge
- Key performance indicators for railway track: level and stiffness
- “If you can’t measure it, you can’t improve it”
- Relative effects of track level and stiffness
- Improving ballast performance
- Localised defects and voids
- Predicting track settlement
- The needs of speed
- Conclusions

The decarbonisation challenge

Averting climate catastrophe

The role of rail in transport

- Easily electrified, giving zero CO_2 emissions at point of use
- Efficiency of steel wheel on steel rail: effect on operational energy

  - Pendolino electric train average 23 Wh / seat.km @ $\leq$200 km/h

  - Electric car average 45 Wh / seat.km @ $\leq$112 km/h

- Low particulate emissions (tyre, road and brake dust)

Decarbonisation of rail transport

- Focus is often on reducing operational CO_2 emissions
- Infrastructure is also a cause of CO_2 emissions:

  - in building it

  - in maintaining it

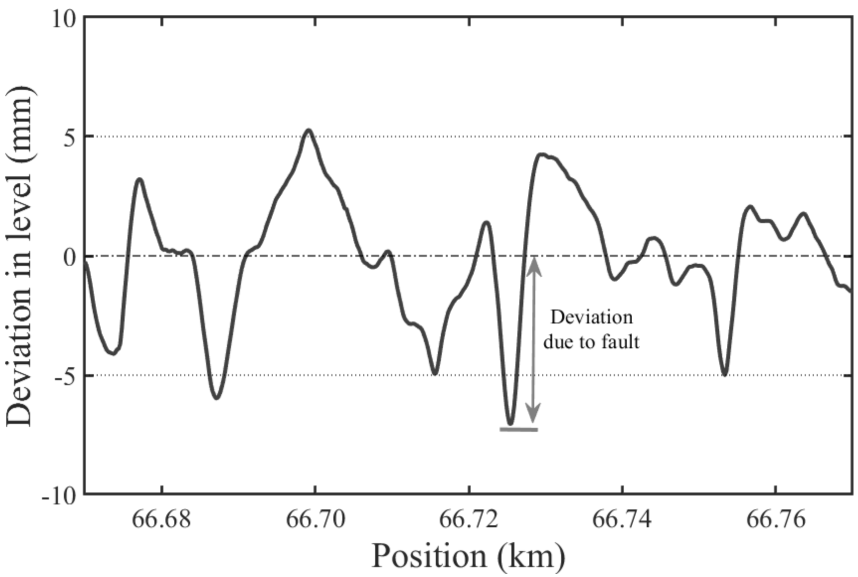
  - committed CO_2 as a result of operational constraints imposed


Ballasted track

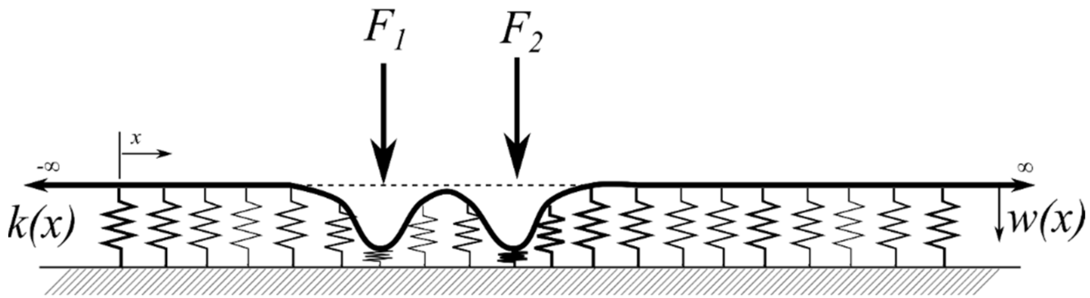
Key performance indicators for railway track: level and stiffness

Key track performance indicators

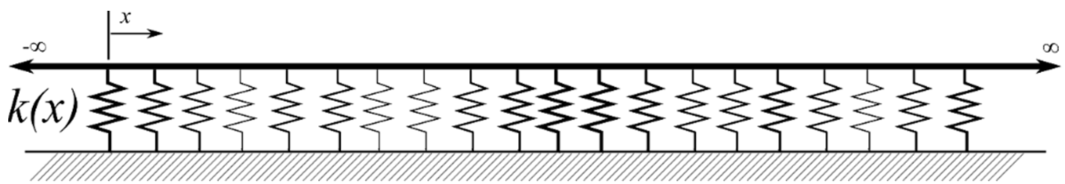
- Track vertical geometry: deviation from level over a length of track



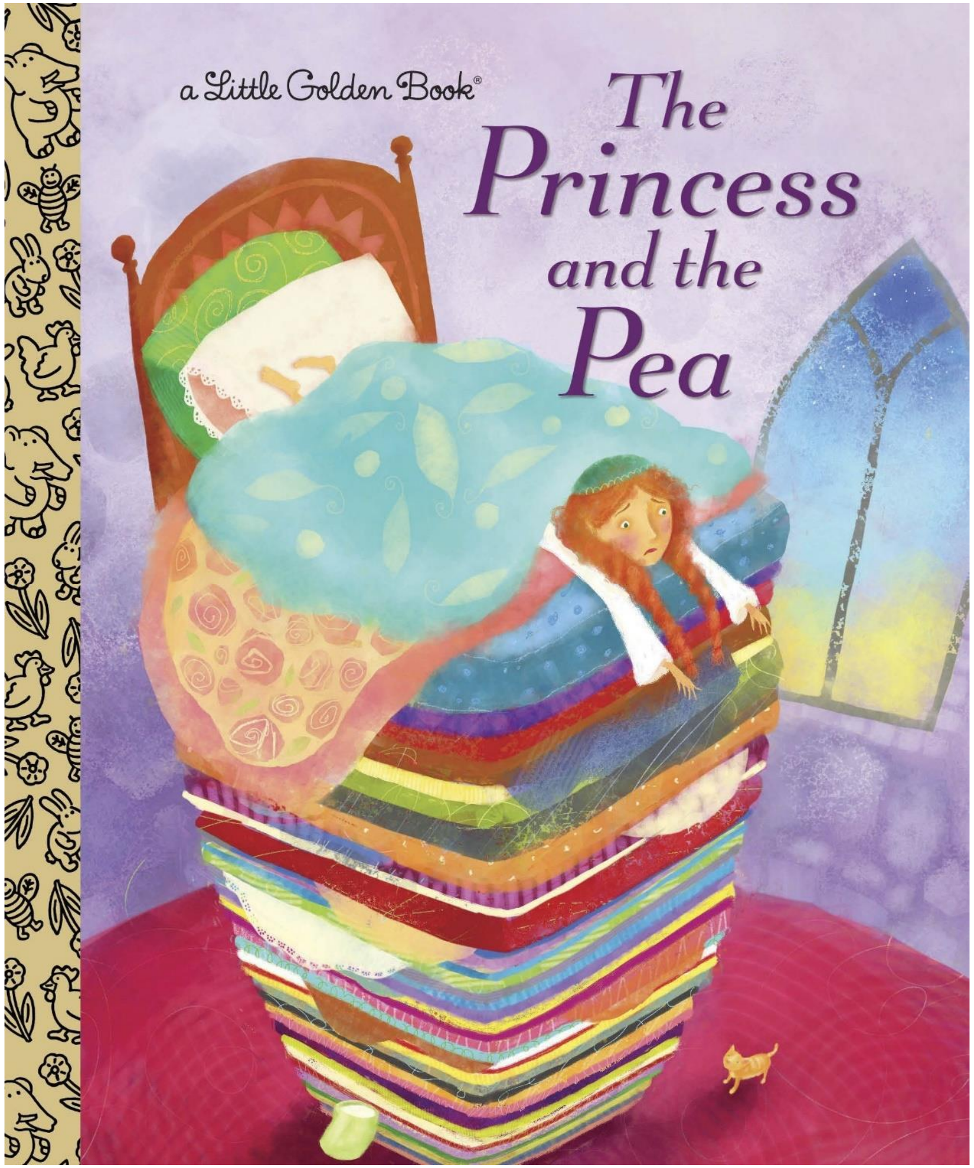
- Deflection under load



- Track support stiffness e.g. the load per sleeper end or per unit length along the track or that causes a unit deflection. Includes effects of subgrade, ballast, pads etc. (MN/m or MN/m^2)

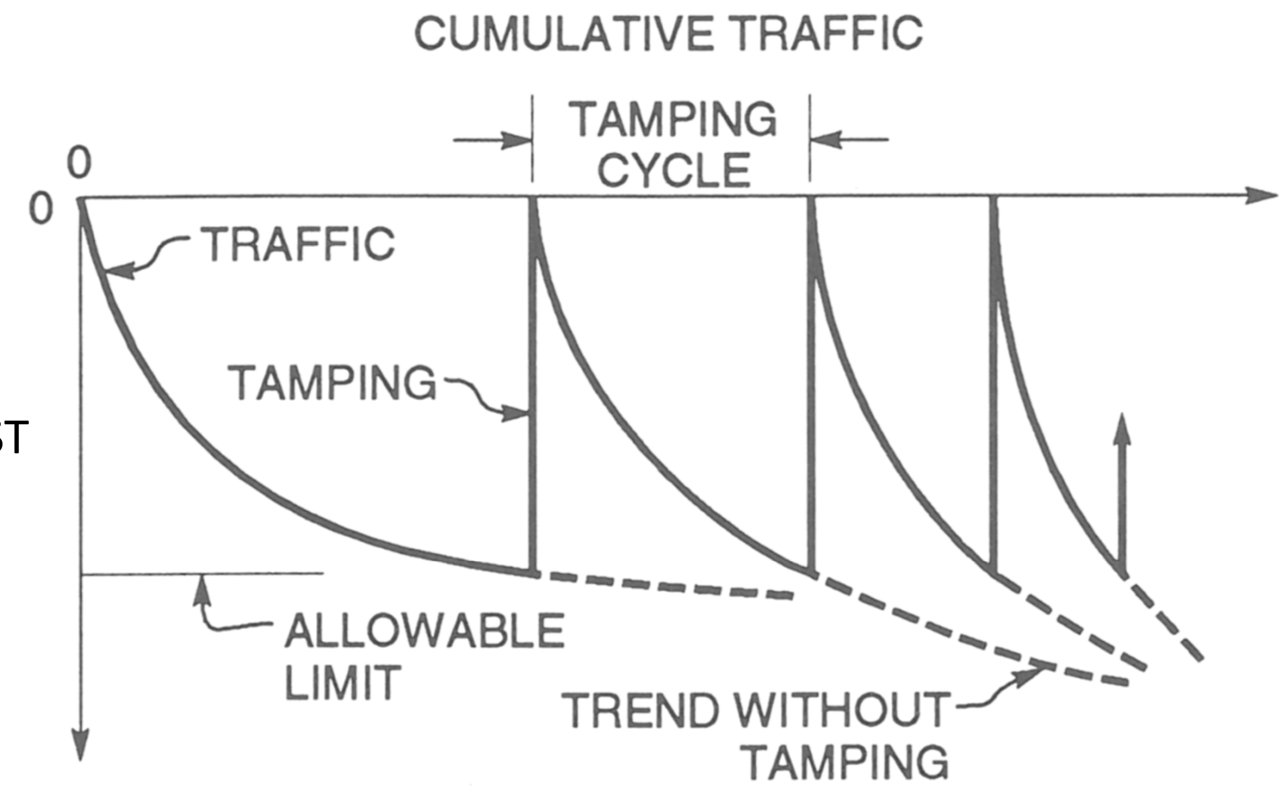


Vertical geometry (level): as smooth as possible (no lumps or dips)



Level: settlement of ballasted track and restoration of level by tamping

SETTLEMENT
CAUSED BY BALLAST
COMPACTION AND
SPREADING



Source: Selig & Waters, 1994

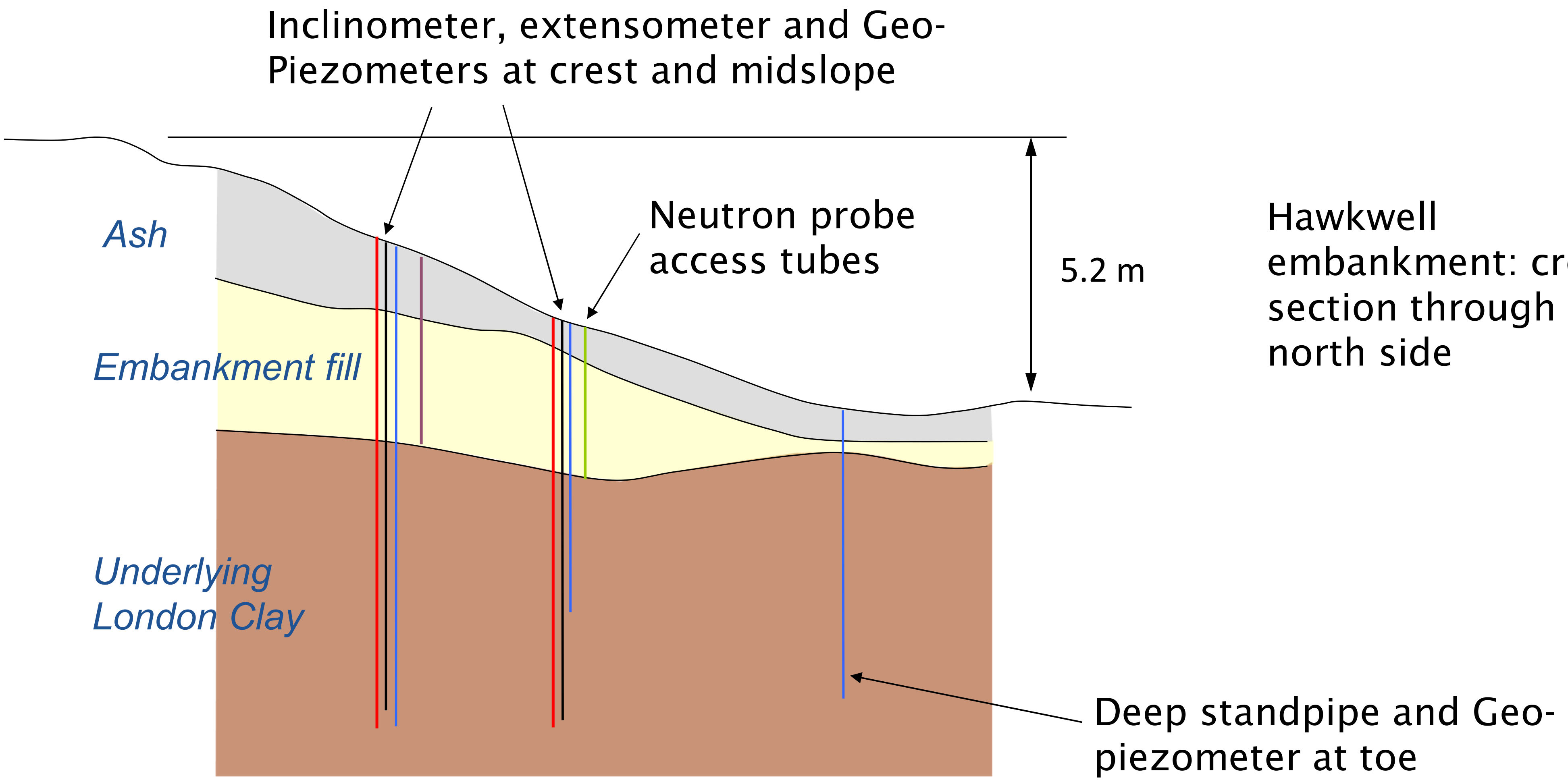
Settlement is not just due to the ballast:

Traditional embankment construction by end-tipping

Embankment construction by end tipping

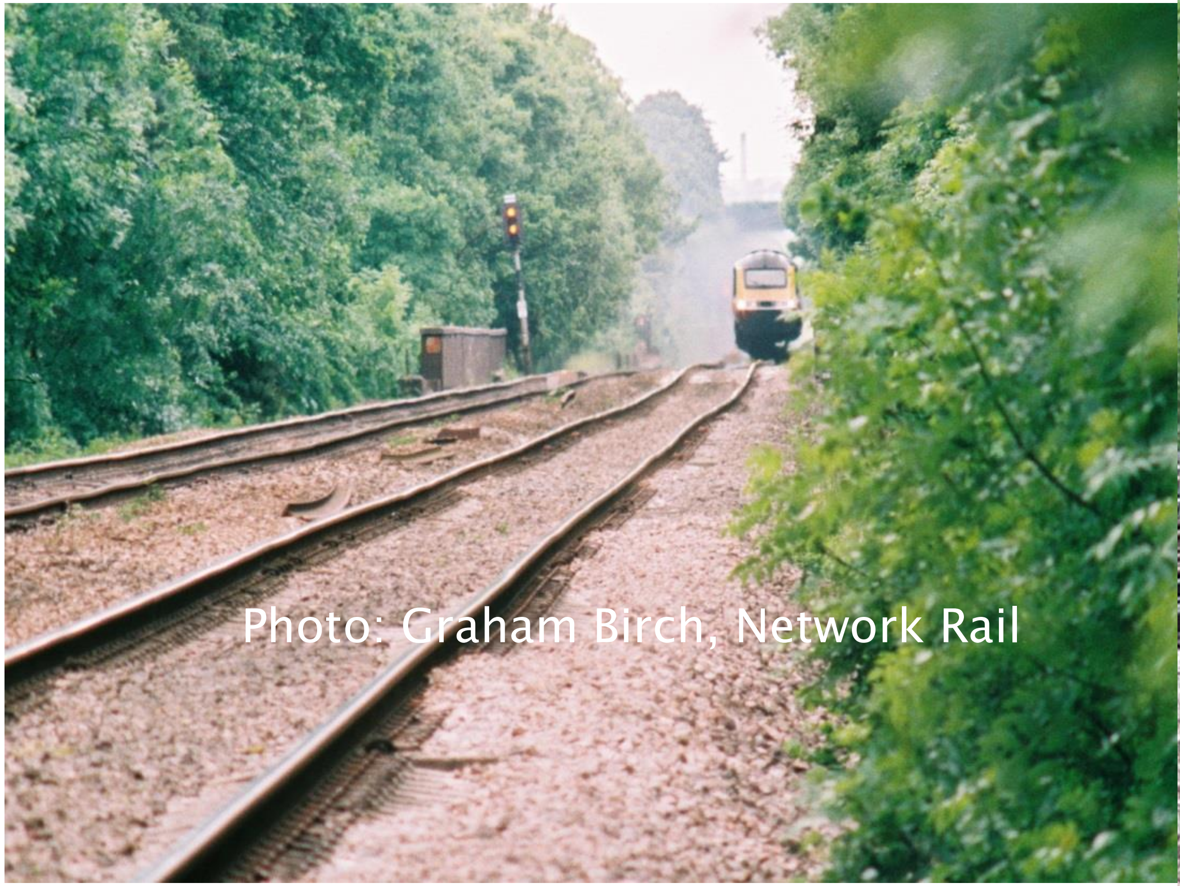
Image source: http://www.transportarchive.org.uk/

Earthwork settlement over time



Hawkwell embankment: cross section through north side

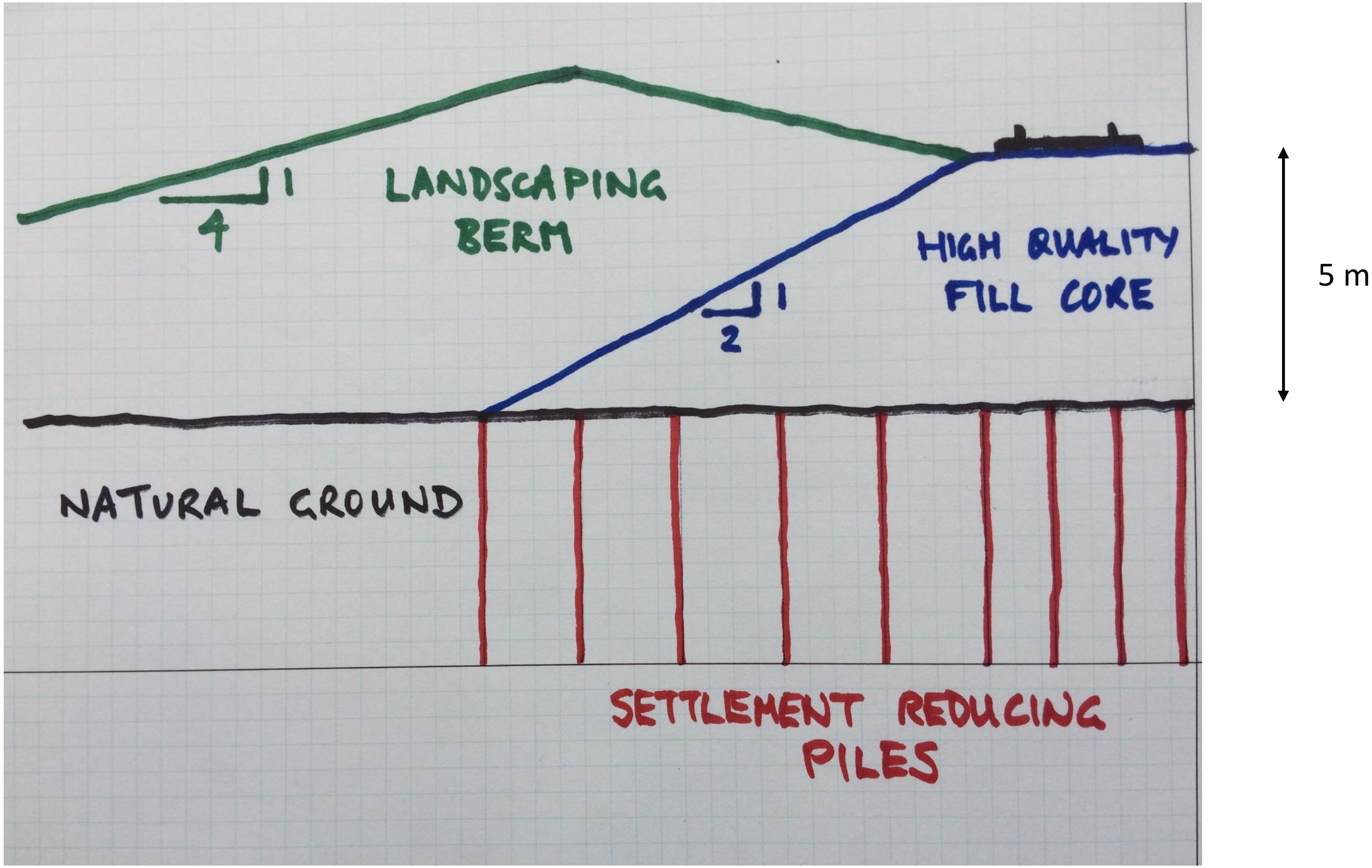
Seasonal cycles of shrinkage and swelling



Godstone, 2019

Photos: Network Rail

Modern highly engineered embankment



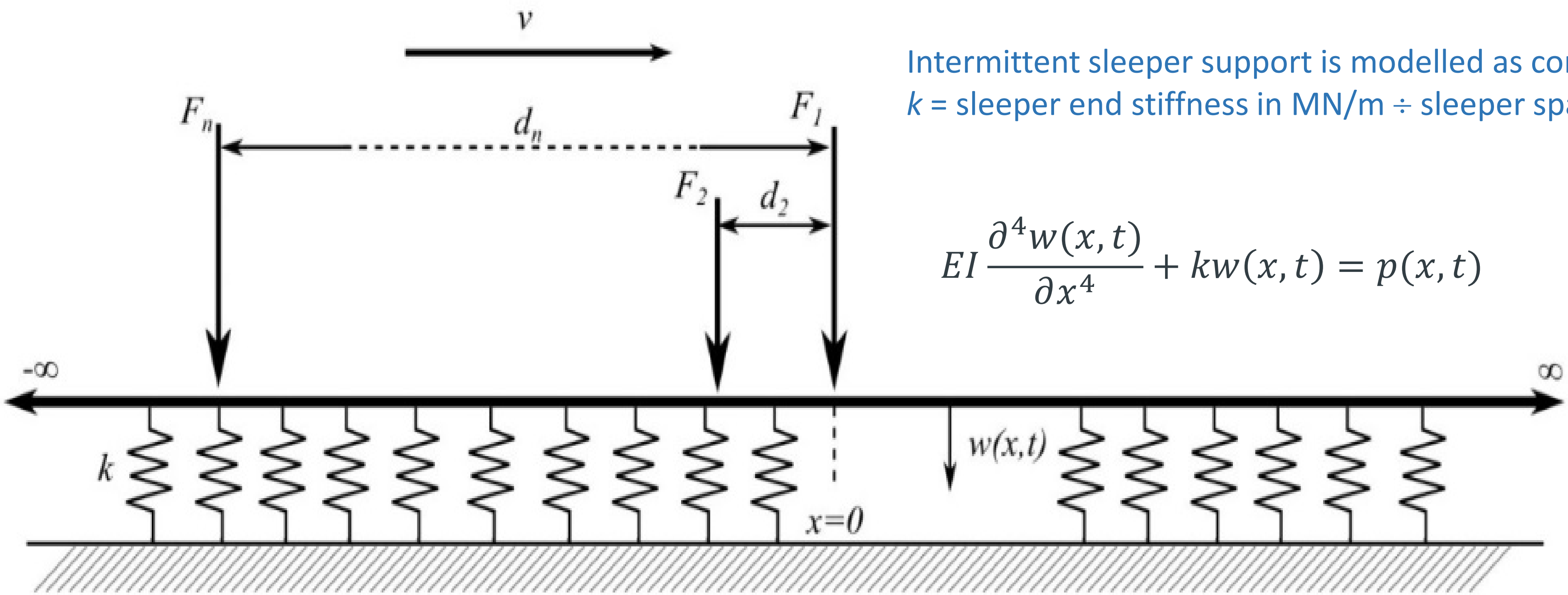
Carbon costs (payback periods based on operations only)

- Traditional earthwork
  - 1.1 tonnes CO_2 equivalent per linear metre (including 2 × major maintenance interventions)
  - payback period based on 72 × 400 seat trains / day in each direction; ~2 years if journeys displaced from petrol /diesel car

- Modern earthwork
  - 44.5 tonnes CO_2 equivalent per linear metre (no maintenance)
  - payback period based on 144 × 600 seat trains / day in each direction;
    ~90 years if journeys displaced from electric car
    ~6 years if journeys displaced from domestic air

Tracey Najafpour Navaei / RSSB Carbon calculator

Stiffness: conceptual track model - rail as a beam on an elastic foundation (BOEF)



Intermittent sleeper support is modelled as continuous:
k = sleeper end stiffness in MN/m ÷ sleeper spacing in m

$$EI\frac{\partial^4 w(x,t)}{\partial x^4} + kw(x,t) = p(x,t)$$

$$w(t) = \sum_{n=1}^{N} \frac{F_n}{2kL} e^{-\frac{|vt-d_n|}{L}} \left(\cos\left(\frac{|vt-d_n|}{L}\right) + \sin\left(\frac{|vt-d_n|}{L}\right) \right)$$

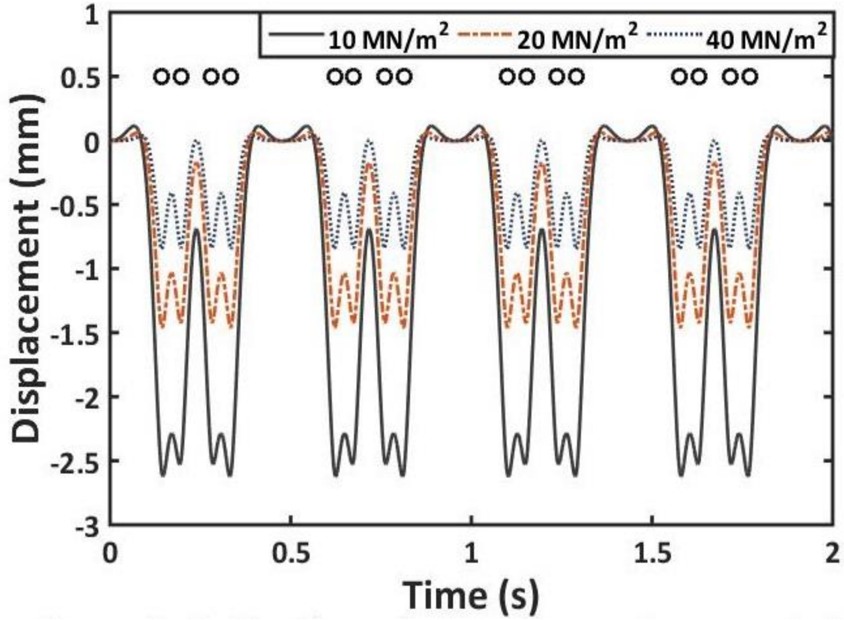
$$L = \sqrt[4]{\frac{4EI}{k}}$$

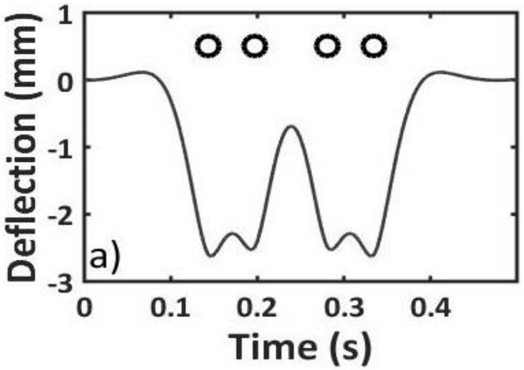
Rail support system modulus ***k***, MN/m^2 load per unit length along the track that causes a unit deflection; includes effects of subgrade, ballast, pads etc.

Bending stiffness of the rail *EI,* MN.m^2

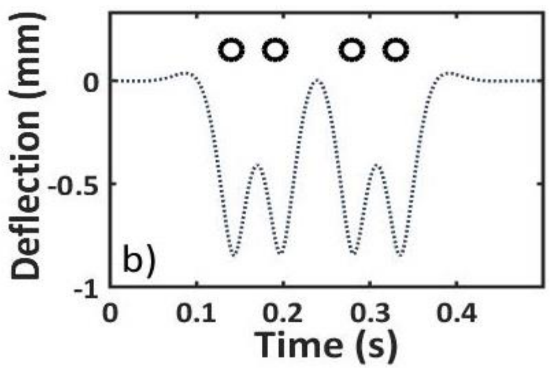
Position and number of wheels at speed ***v*** and time ***t***

Effect of track support stiffness: BOEF model deflections





k = 10 MN/m^2



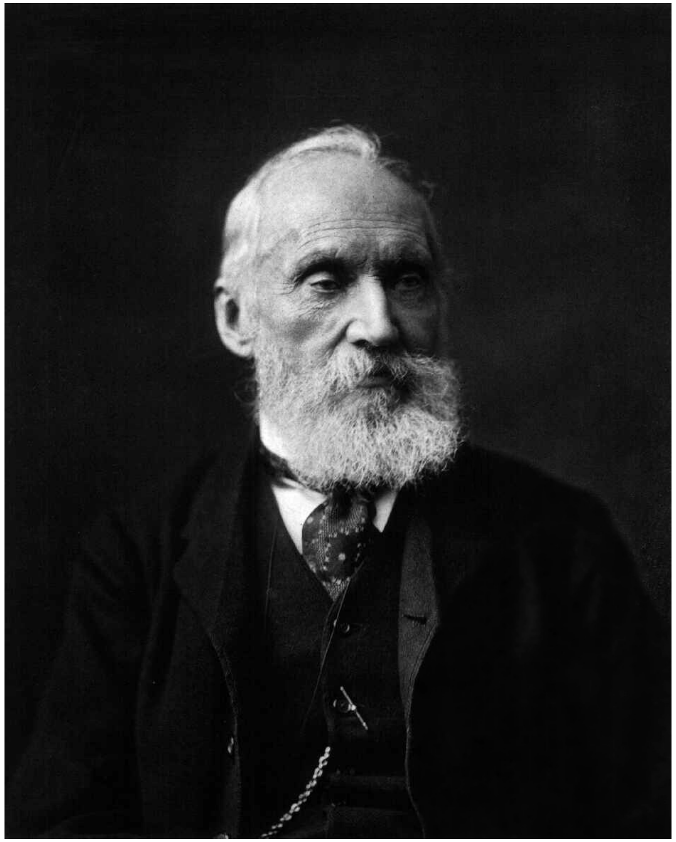
k = 40 MN/m^2

With increasing rail support system stiffness k,

- the maximum deflection reduces
- the deflection bowl narrows
- recovery between axles becomes more pronounced
- local stresses increase

Support stiffness: not too hard, not too soft, but “just right”, and reasonably uniform

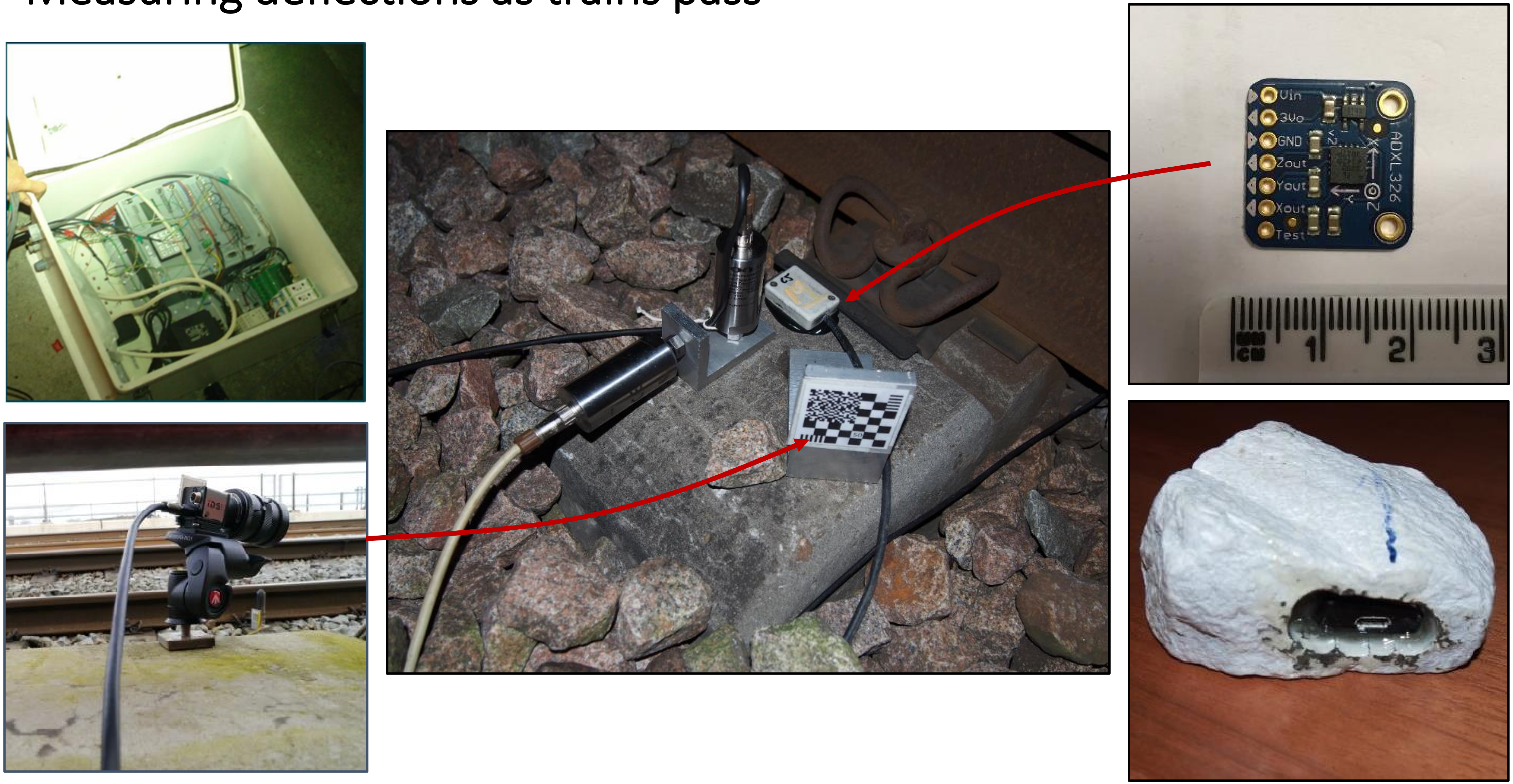
If you can’t measure it,
you can’t improve it



Track geometry measurement train

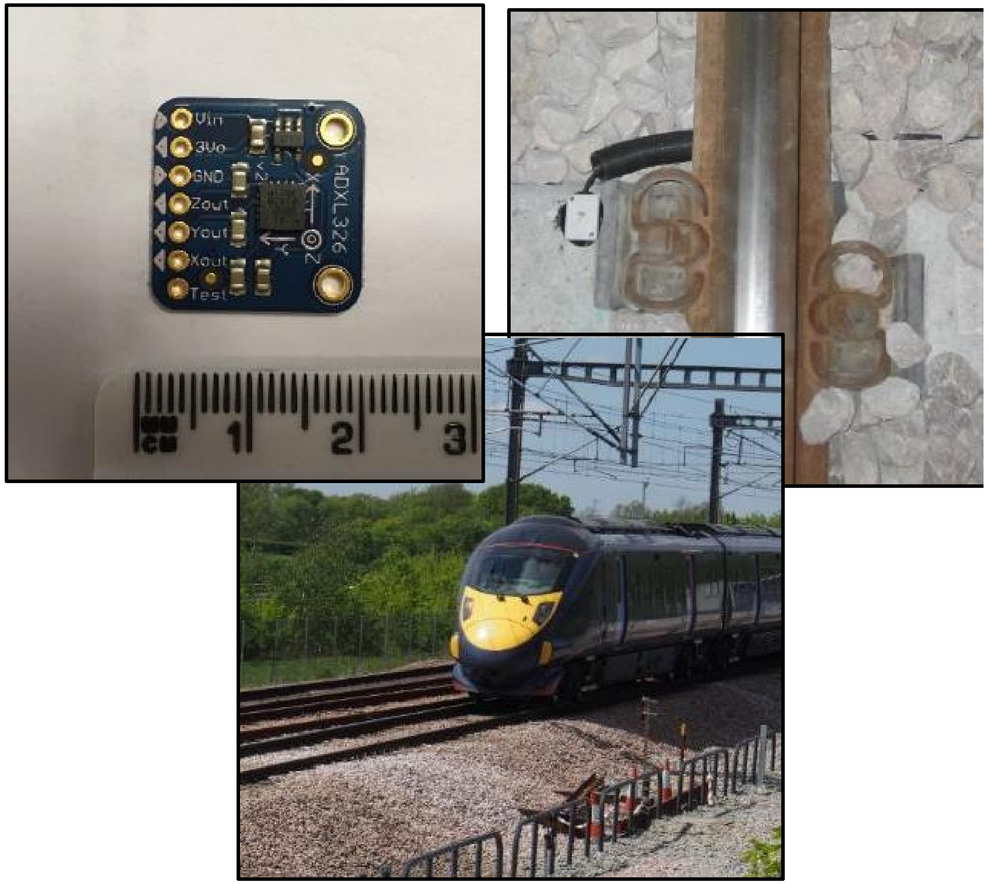
Photo: 125 Group

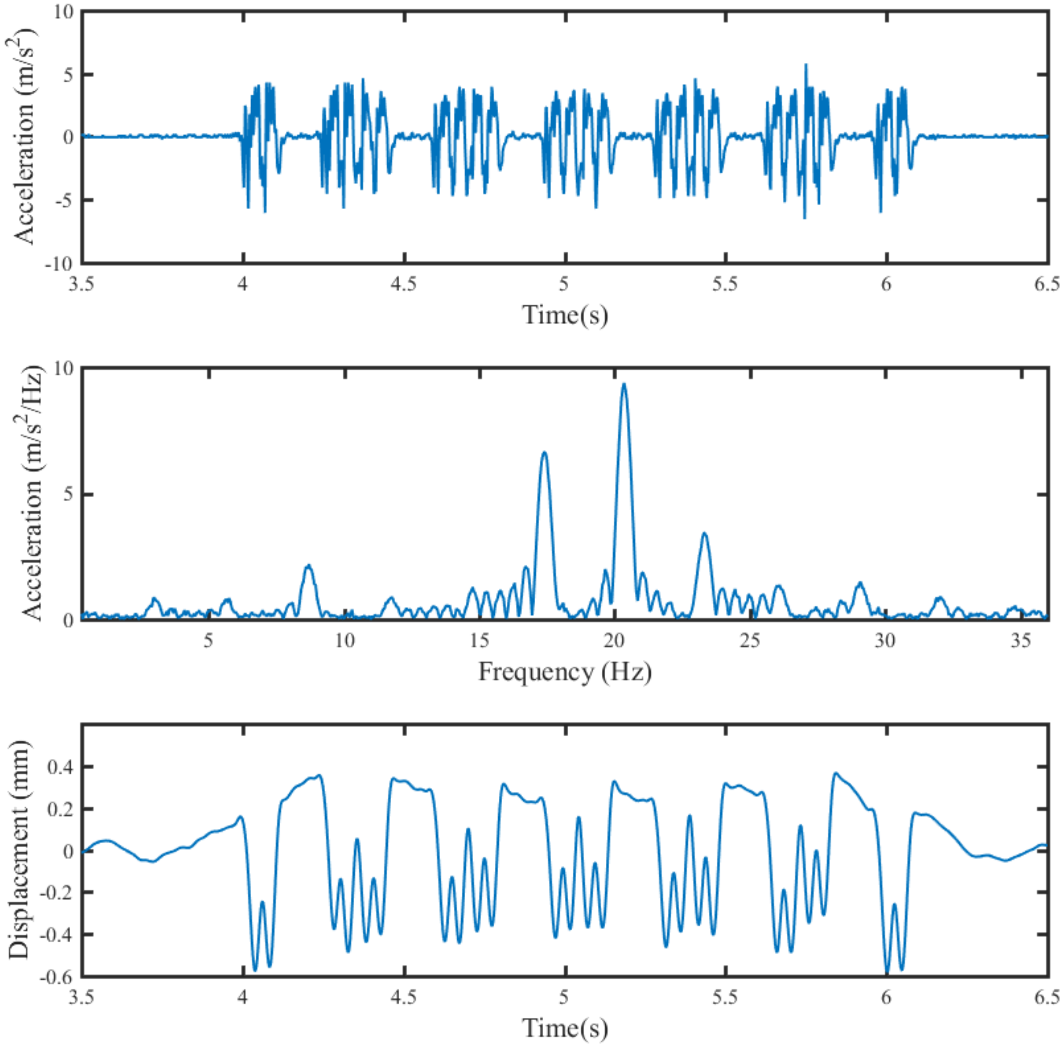
Measuring deflections as trains pass



MEMS Accelerometers

- Low cost and robust, suitable for long term monitoring (leave in place)



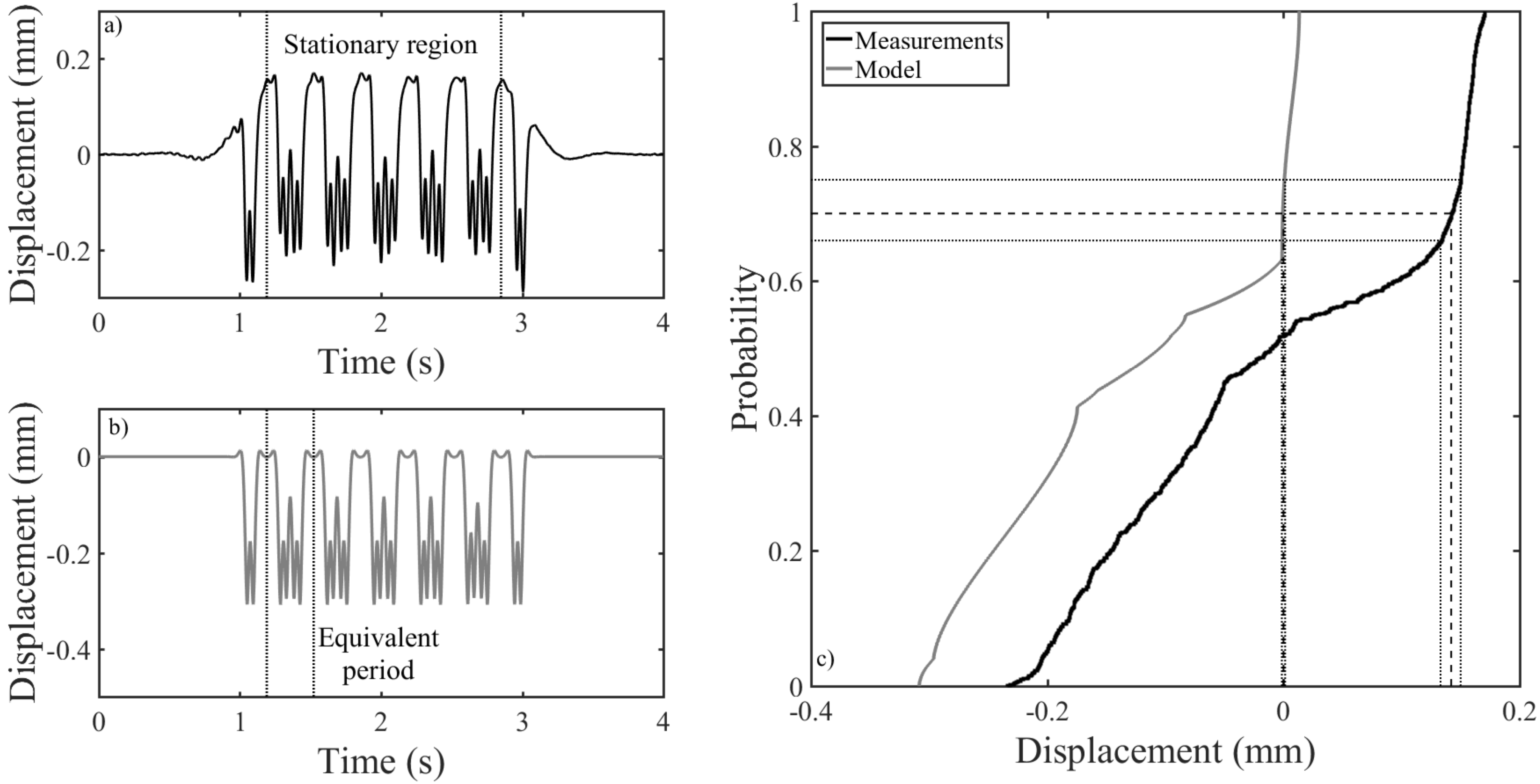


Automated estimation of track zero position (datum finding) by considering the cumulative distribution function (CDF)

Automated processing of railway track deflection signals obtained from velocity and acceleration measurements. D R Milne, L M Le Pen, W Powrie and D J Thompson. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* (2018). doi 10.1177/0954409718762172

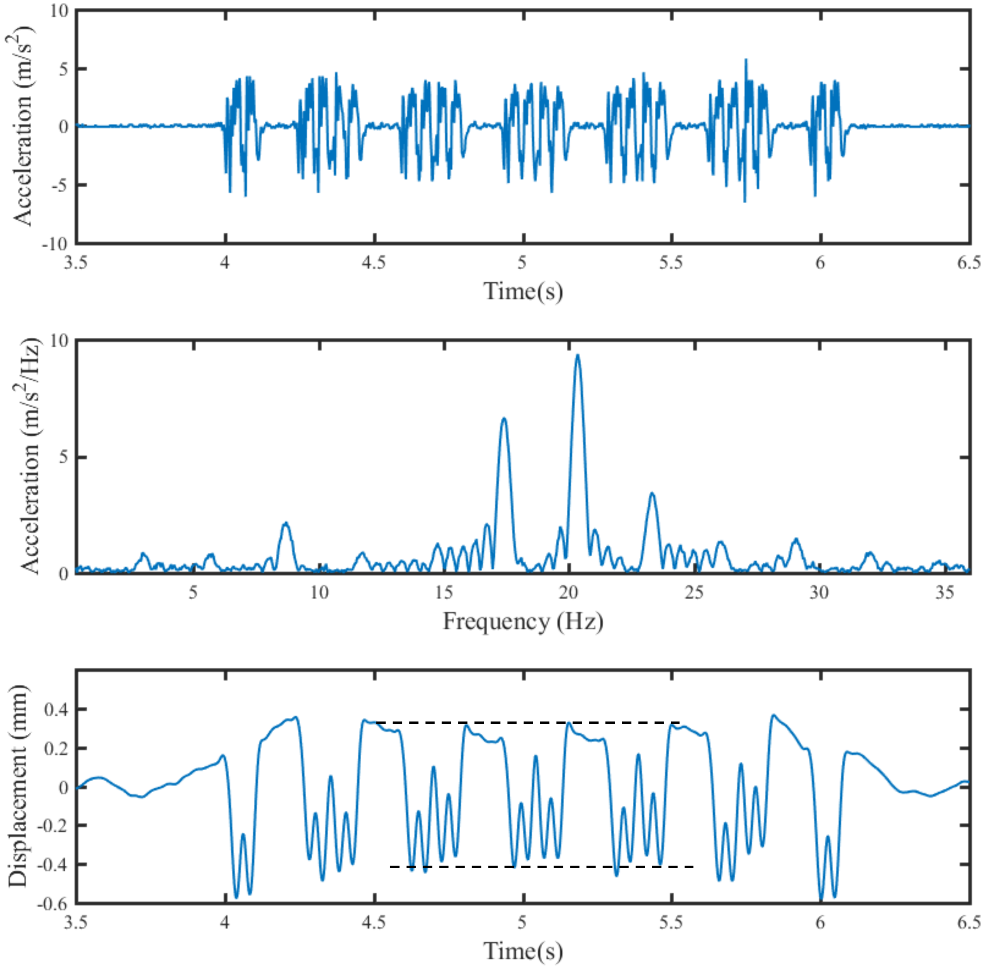
Measured and theoretical displacements and distribution functions for a Javelin train

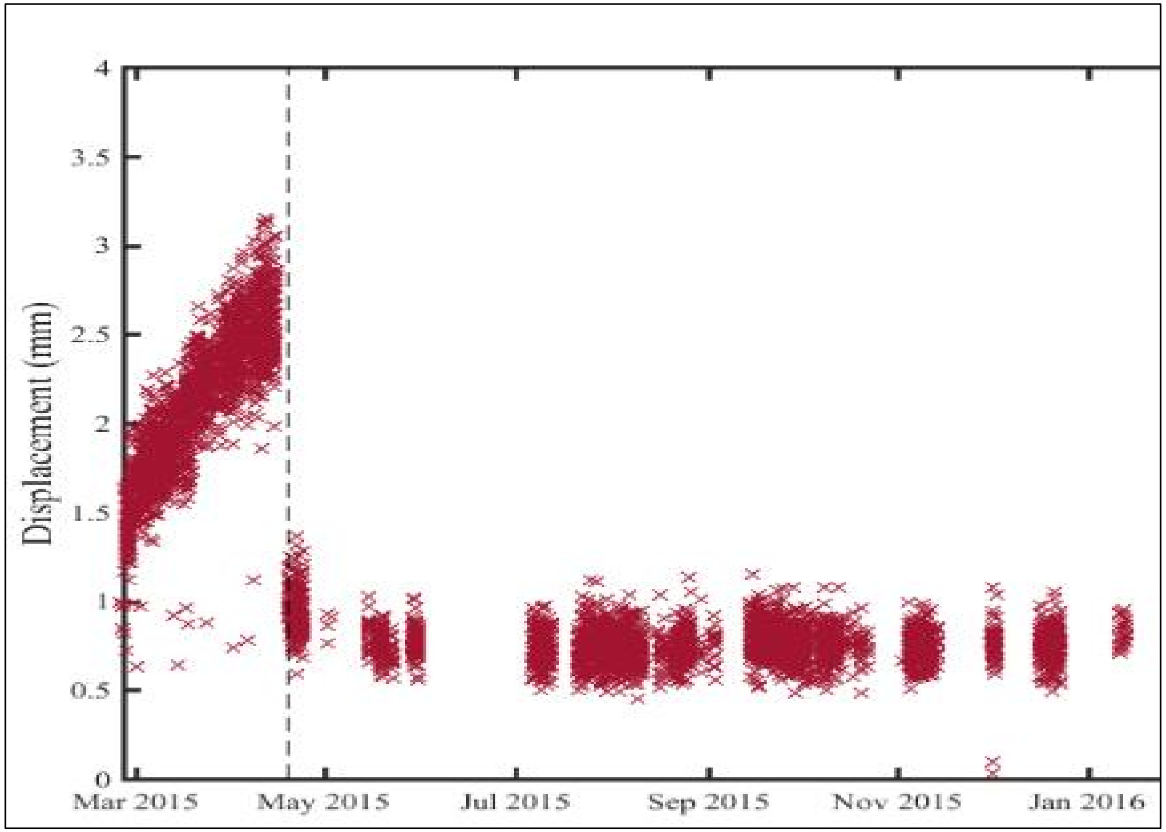
Source: Milne et al, JRRT (2018)



Probability that displacement is greater (more negative) than the selected value

Application to MEMS accelerometer data

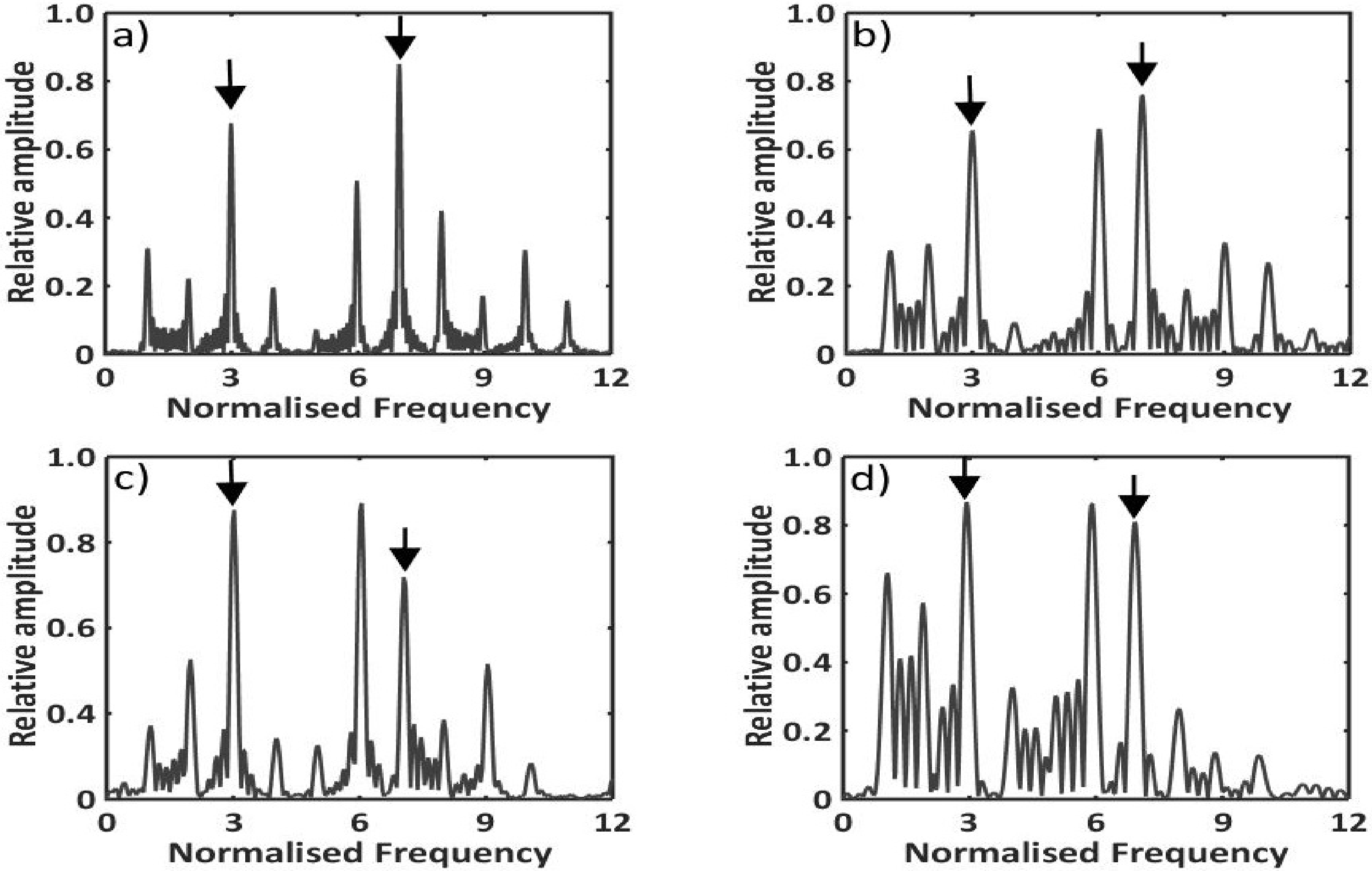




Estimating the support system stiffness from the ratio of harmonic peaks, without knowledge of the train load

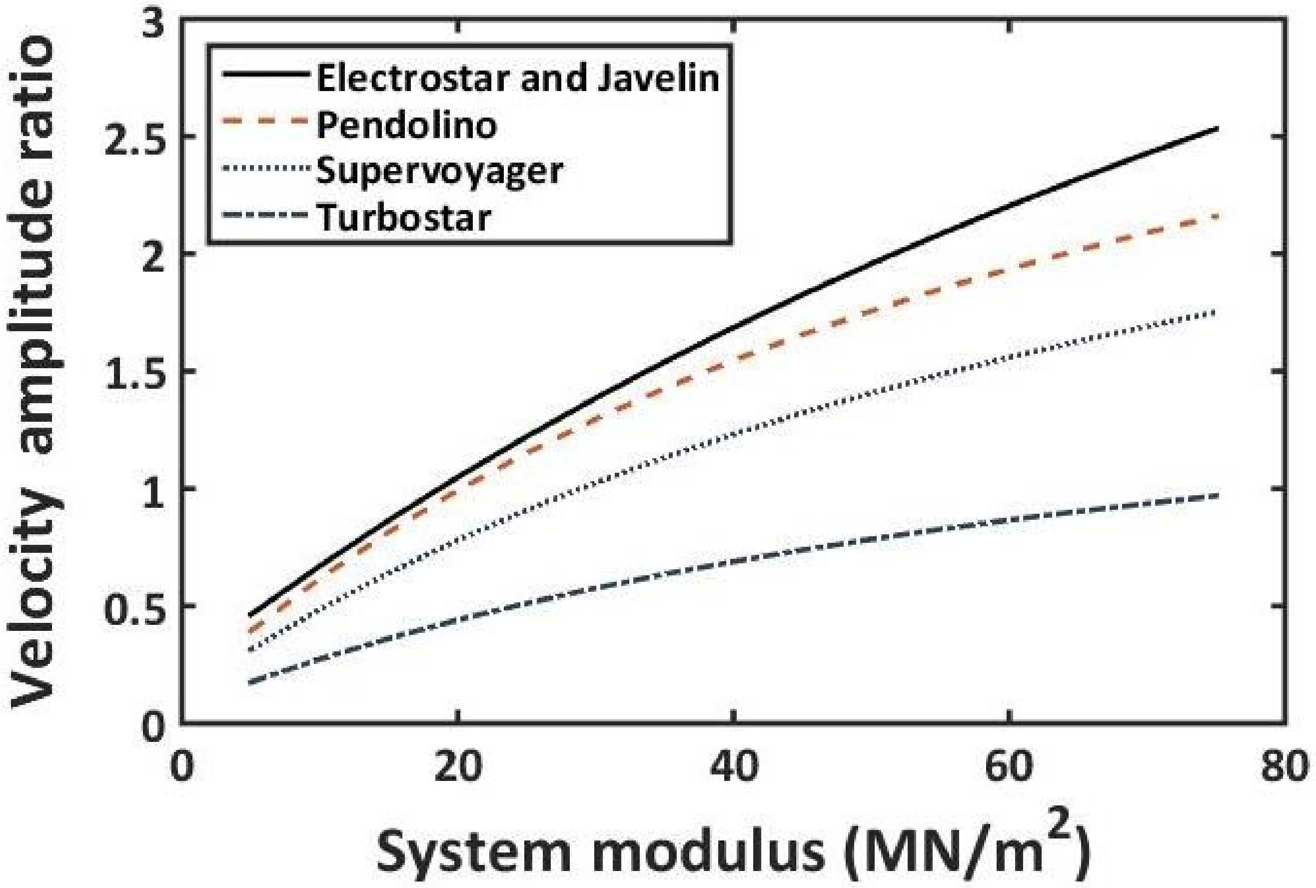
Evaluating railway track support stiffness from trackside measurements in the absence of wheel of wheel load data. L Le Pen, D Milne, D Thompson and W Powrie. *Canadian Geotechnical Journal* **53**(7), 1156-1166, 2016. https://doi.org/10.1139/cgj-2015-0268

Numerical frequency spectra for measured velocity data from 4 different trains: (a) 11 car Pendolino; (b) 5 car Supervoyager; (c) 6 car Turbostar; (d) 4 car Electrostar



Frequency normalised by car passing frequency

Velocity amplitude ratio (7th to 3rd peaks) *vs* rail support system modulus for different train types



Measuring absolute level

Relative effects of track level and stiffness

Insights based on:

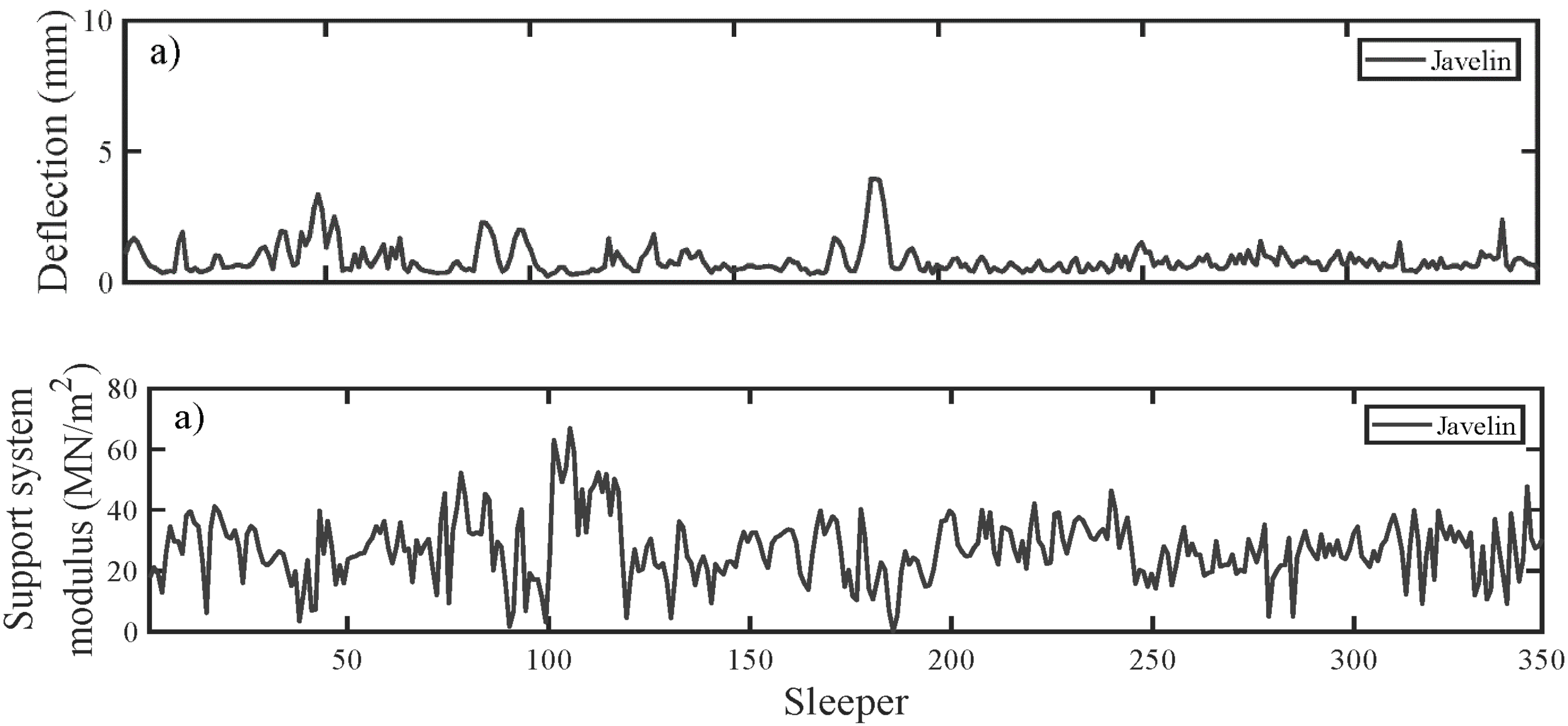
- Level, deflection and stiffness survey over a 350 sleeper length of track
- Vehicle-track interaction modelling

A model for stochastic prediction of track support stiffness. L M Le Pen, D R Milne, G V R Watson, J Harkness & W Powrie (2019). *Proc I Mech E Part F: Journal of Rail and Rapid Transit*

The influence of variation in track level and support system stiffness over longer lengths of track on track performance and vehicle track interaction. D R Milne, J Harkness, L Le Pen & W Powrie (2019). *Vehicle System Dynamics*

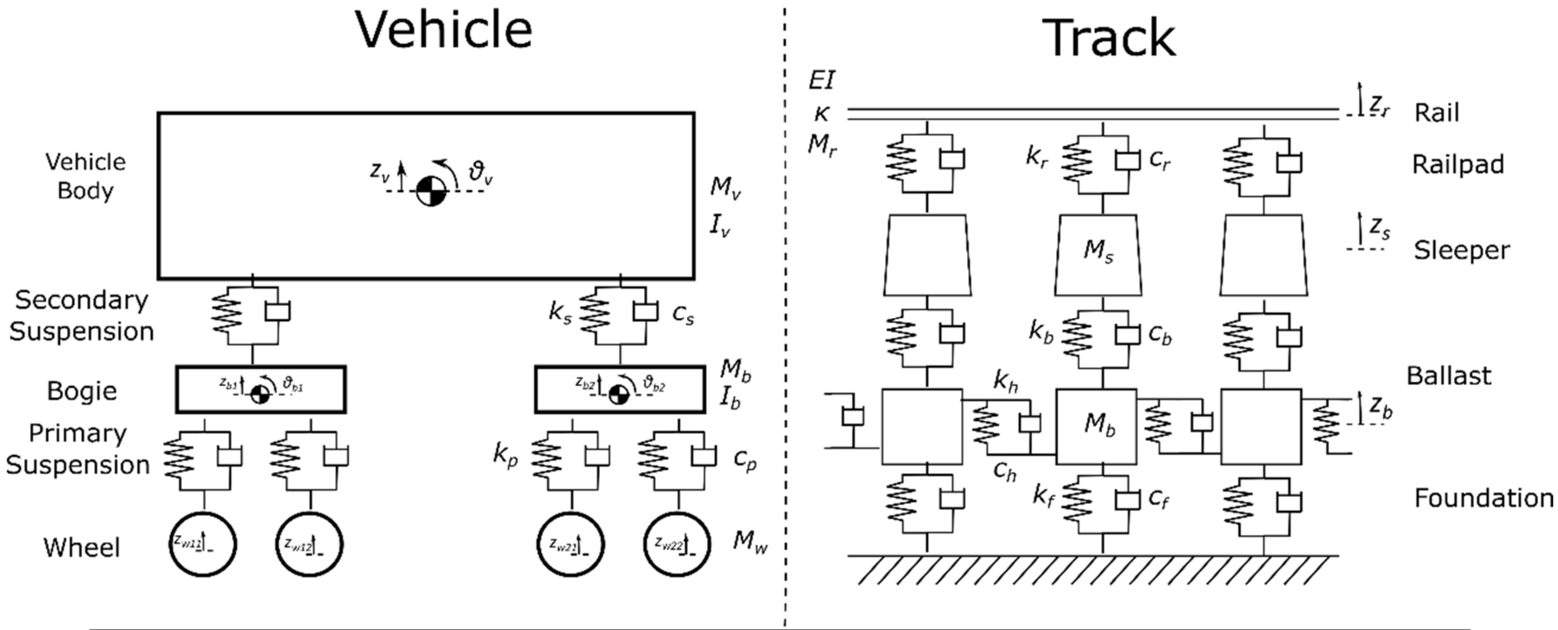
Deflection and stiffness measured using MEMS accelerometers

Field data: deflections and system support modulus



Vehicle track interaction: simulations

Track stiffness and level from measurements

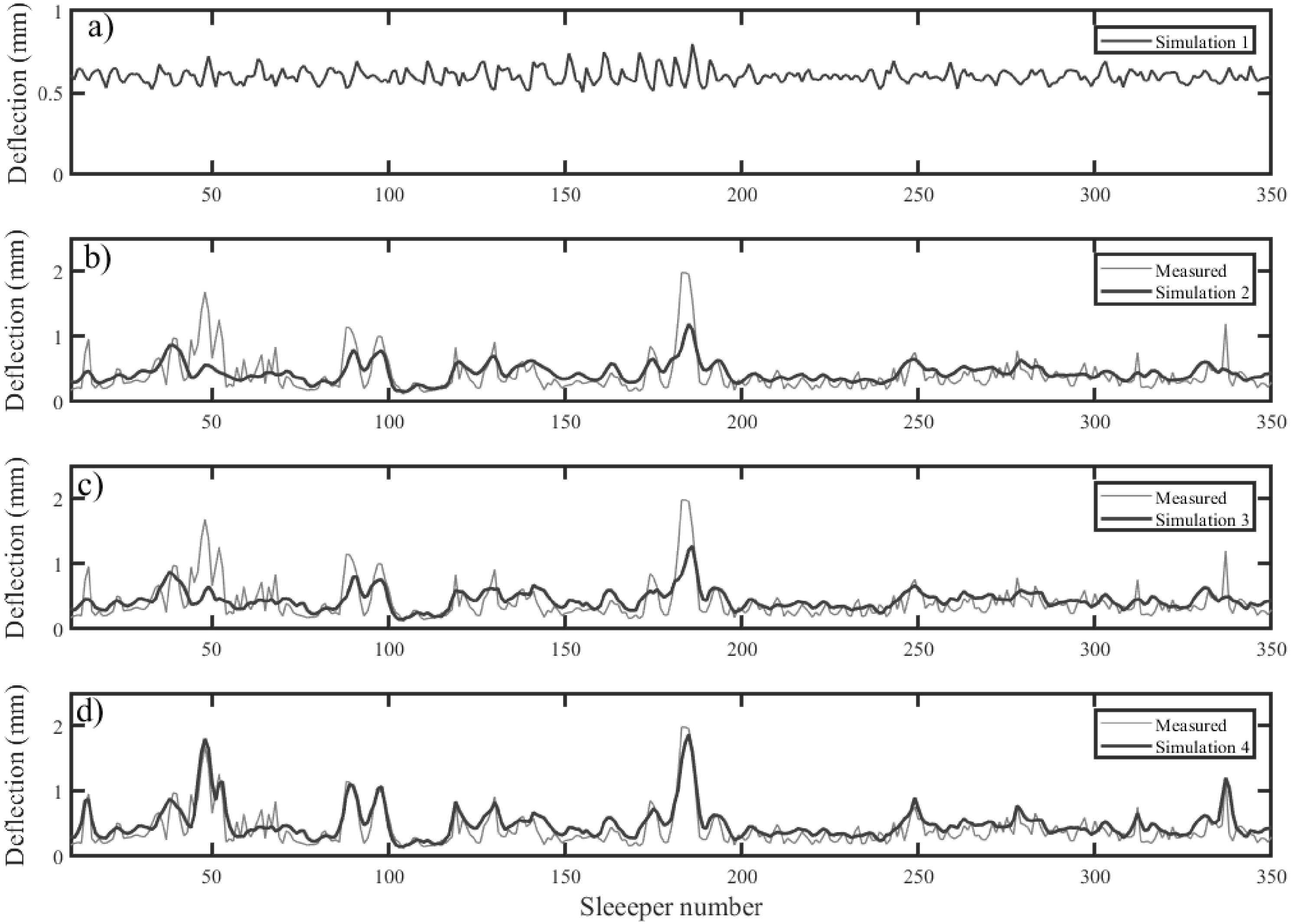


Simulation	Level	Track Modulus	Voiding
1	Measured*	Uniform 30MPa	None
2	Smooth	Measured†	None
3	Measured*	Measured†	None
4	Measured*	Measured†	Included

* From total station

† From accelerometers

Simulated sleeper deflections



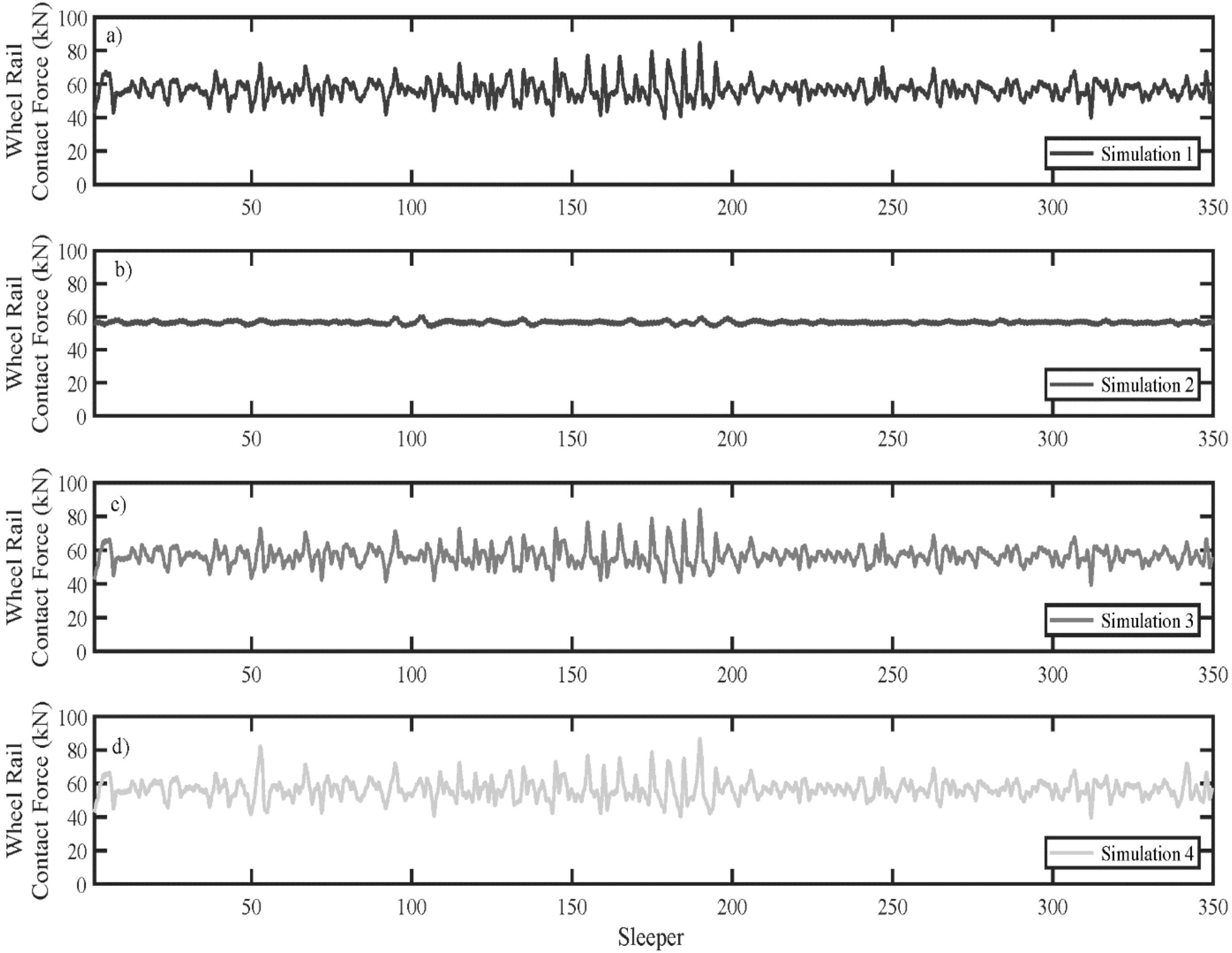
Measured initial track level, modulus 30 MN/m^2

Smooth initial track level, measured modulus

Measured initial track level, measured modulus

Measured initial track level / modulus + imposed voids

Simulated wheel/rail contact forces



Measured initial track level, modulus 30 MN/m^2

Smooth initial track level, measured modulus

Measured initial track level, measured modulus

Measured initial track level / modulus + imposed voids

Comments

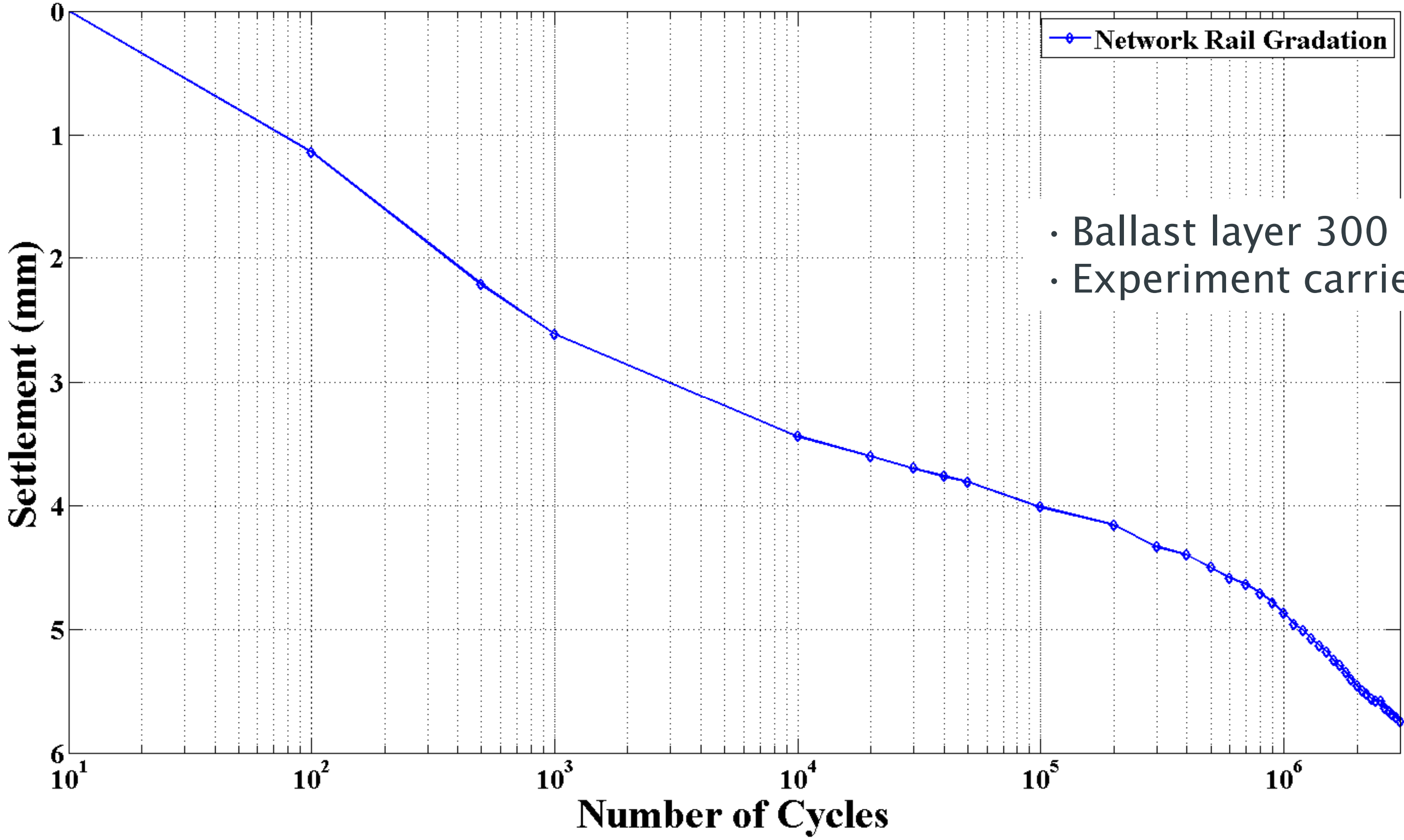
- Sleeper deflections depend more on the support stiffness than on the track level: modelling voids is locally important
- Wheel / rail contact forces depend more on the track level than on the support stiffness, although voiding is locally important

Improving ballast performance

Measuring settlement under controlled conditions

The Southampton Railway Testing Facility (SRTF)

Gradual settlement



- Ballast layer 300 mm thick
- Experiment carried out at 3 Hz

Equivalent 20 tonne axle load

Plastic settlement of ballast layer

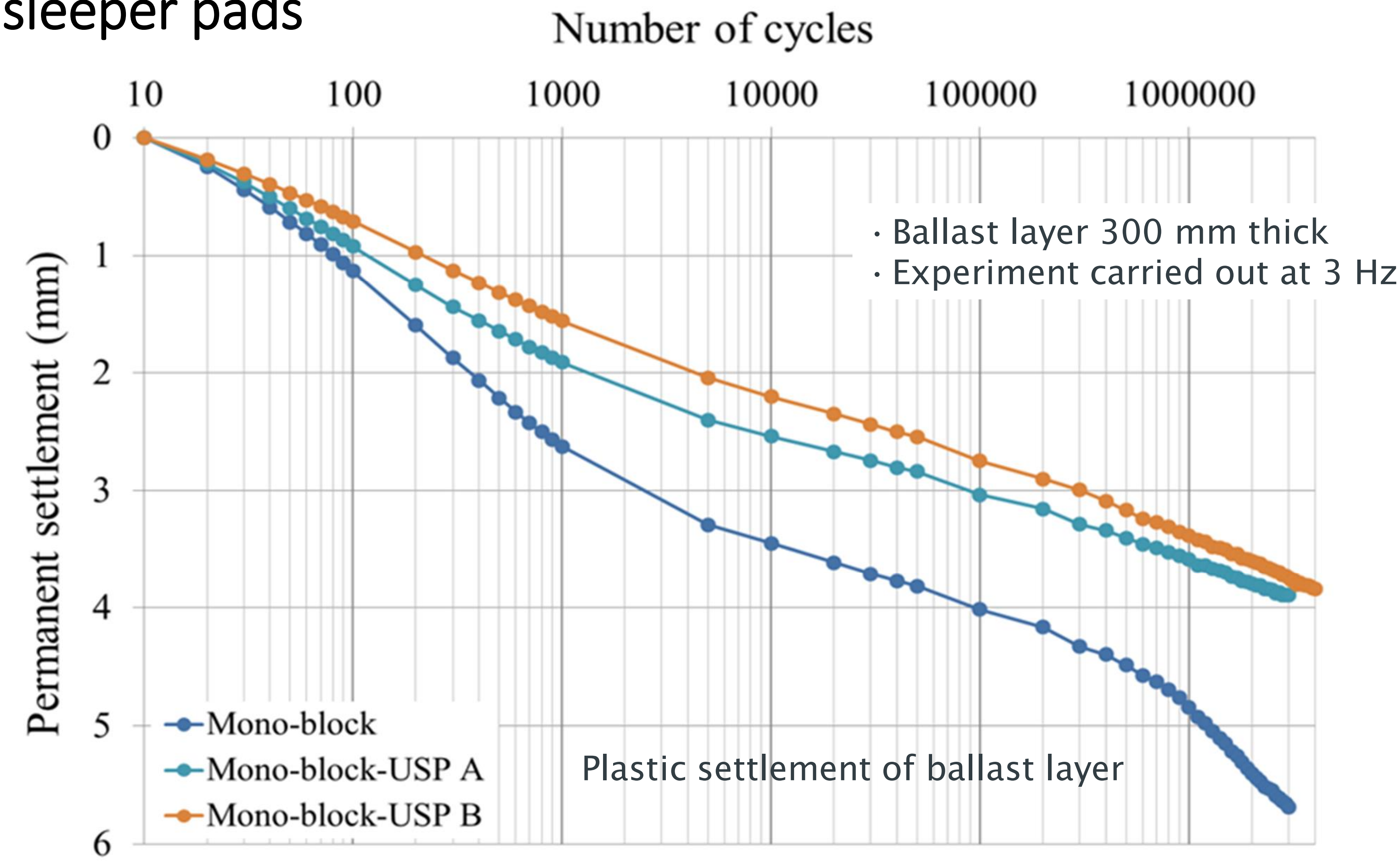
Improving ballasted track: methods

- Under sleeper pads (to reduce ballast attrition and improve contact area)
- Changing the ballast grading (increasing the proportion of smaller grains to improve interlock)
- Random fibre reinforcement (to improve ballast ductility)
- Reduce shoulder slope (to reduce lateral spread)

Improving the performance of railway track through ballast interventions. T C Abadi, L Le Pen, A Zervos and W Powrie. *Proceedings of the Institution of Mechanical Engineers Part F, Journal of Rail and Rapid Transit* **232**(2), 337-355.

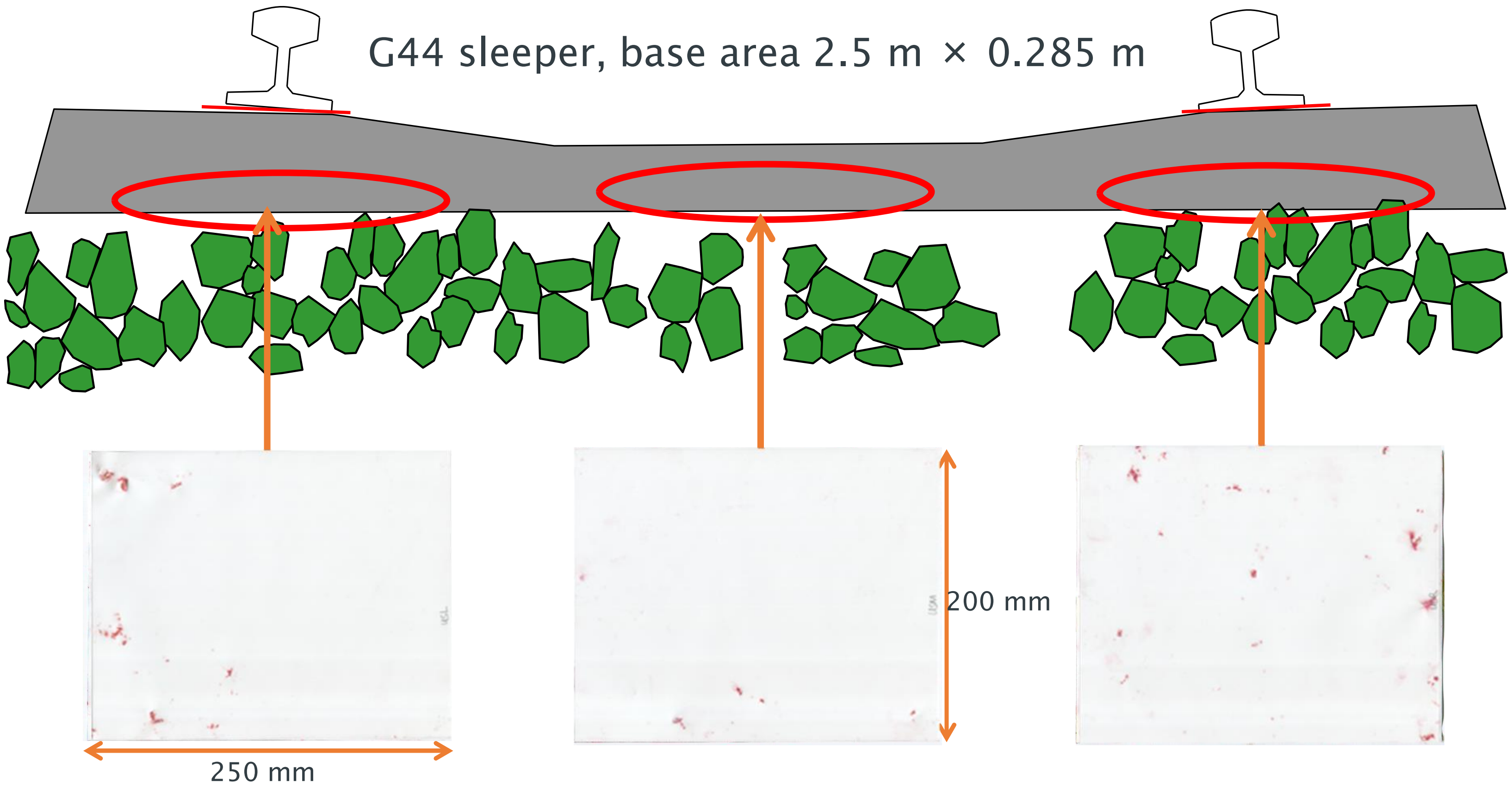
The effect of sleeper interventions on railway track performance. T C Abadi, L M Le Pen, A Zervos and W Powrie (2019). *ASCE Journal of Geotechnical and Geoenvironmental Engineering* **145**(4), 1-14.

Under sleeper pads



Sleepers rest on relatively few ballast grains

Measuring the area and number of ballast particle contacts at sleeper/ballast and ballast/subgrade interfaces. T C Abadi, L Le Pen, A Zervos and W Powrie. *International Journal of Railway Technology* **4**(2)



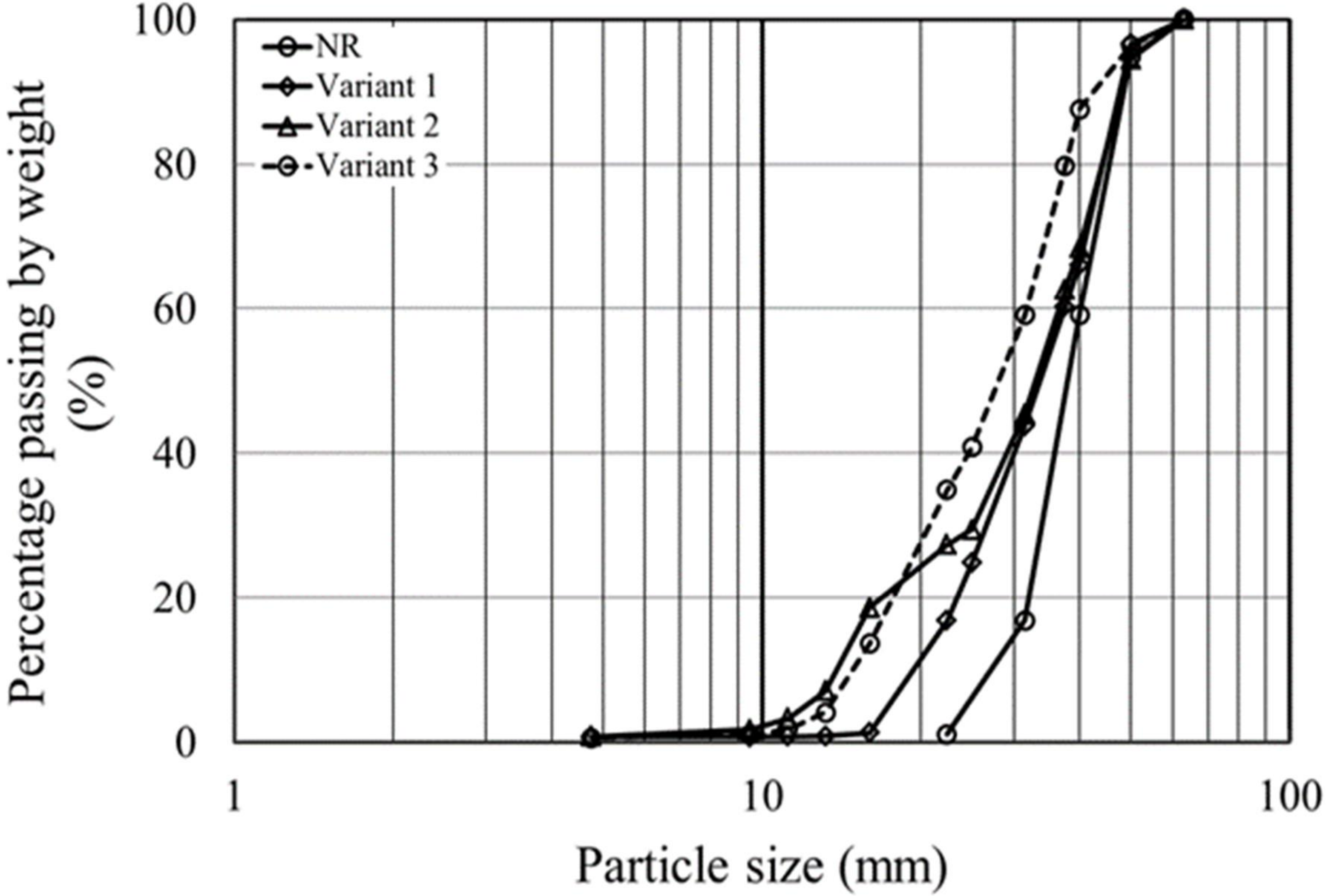
Pressure sensitive paper shows contact history after 2.5M load cycles

Under sleeper contacts

G44 sleeper (no USP): 147 “contacts”

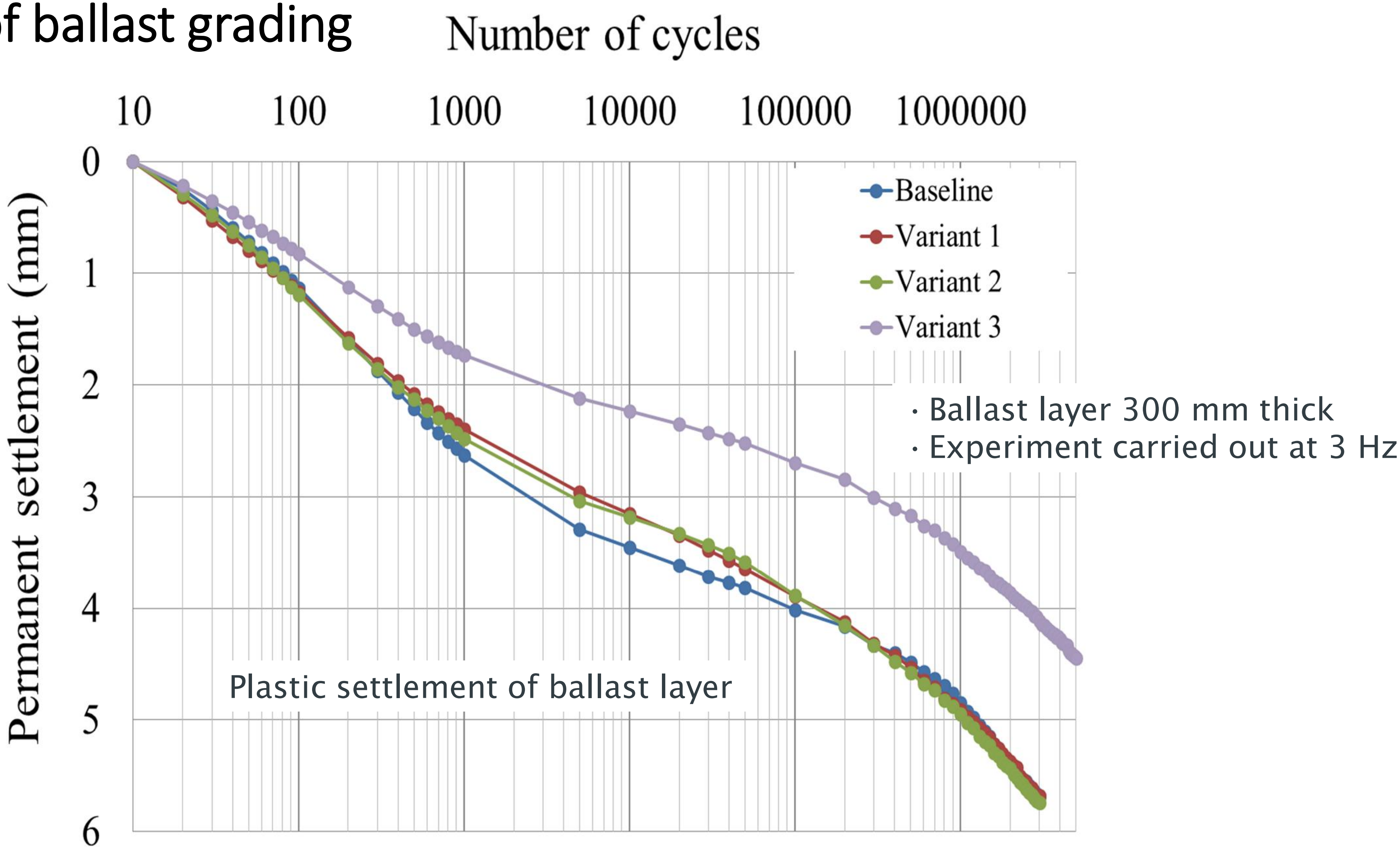
G44 sleeper with USP: 314 “contacts” covering a greater area

Different ballast grading



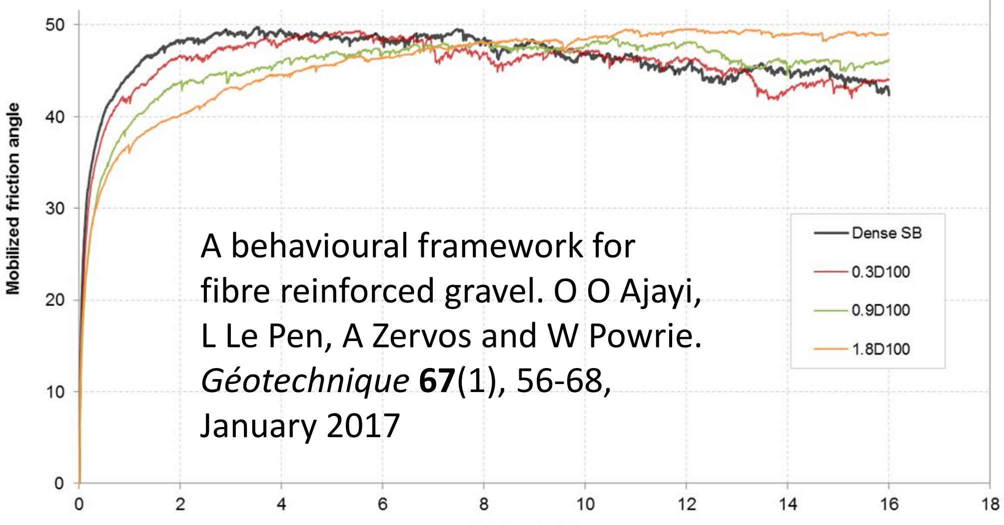
Particle size distribution curves

Effect of ballast grading



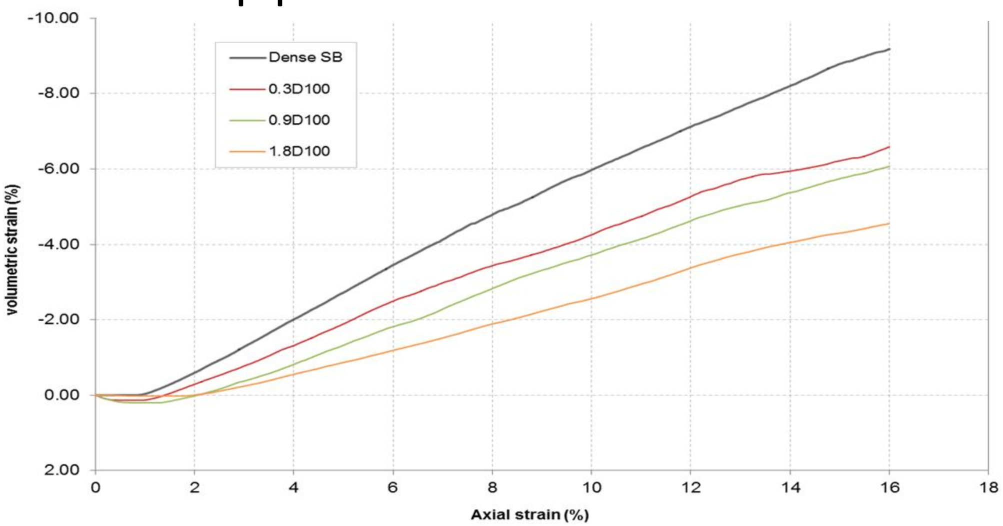

Random fibre
reinforcement

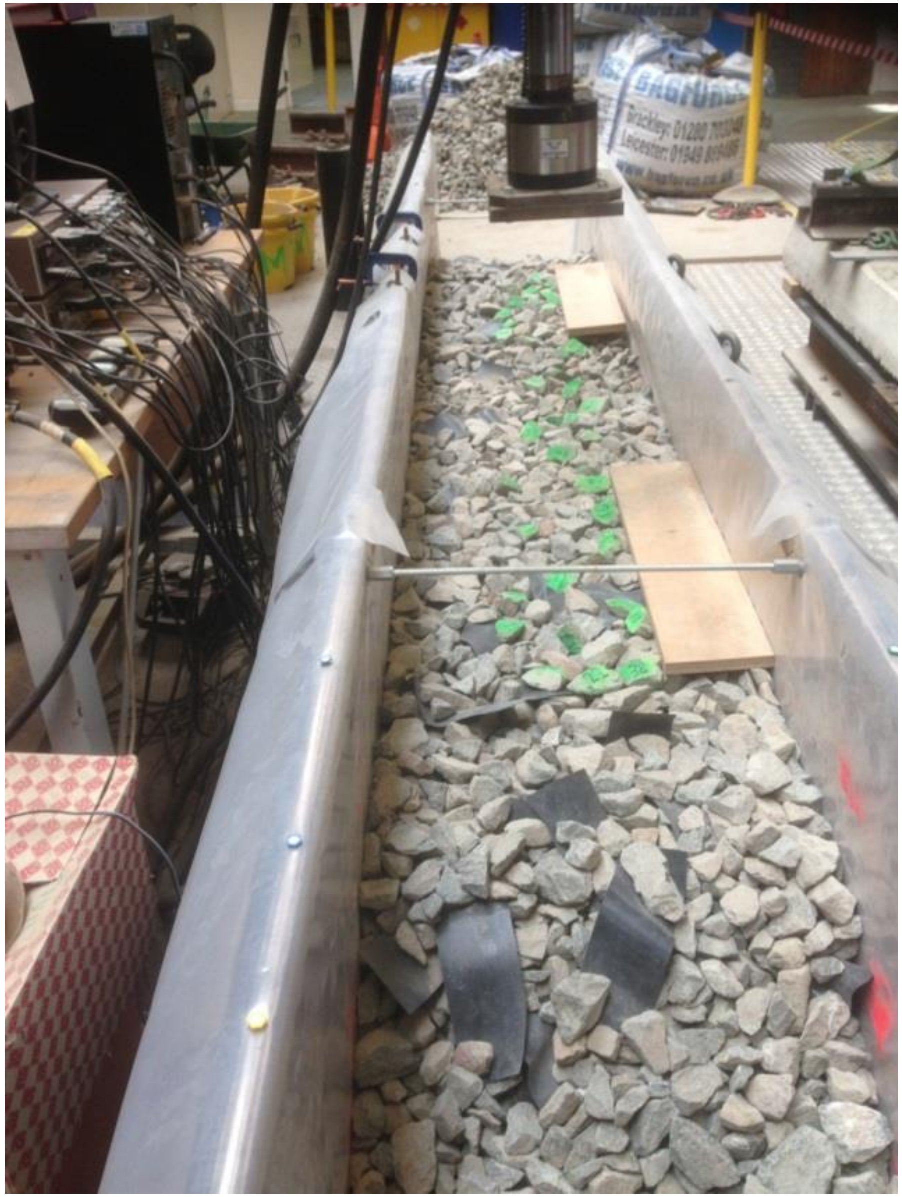
increases ballast ductility

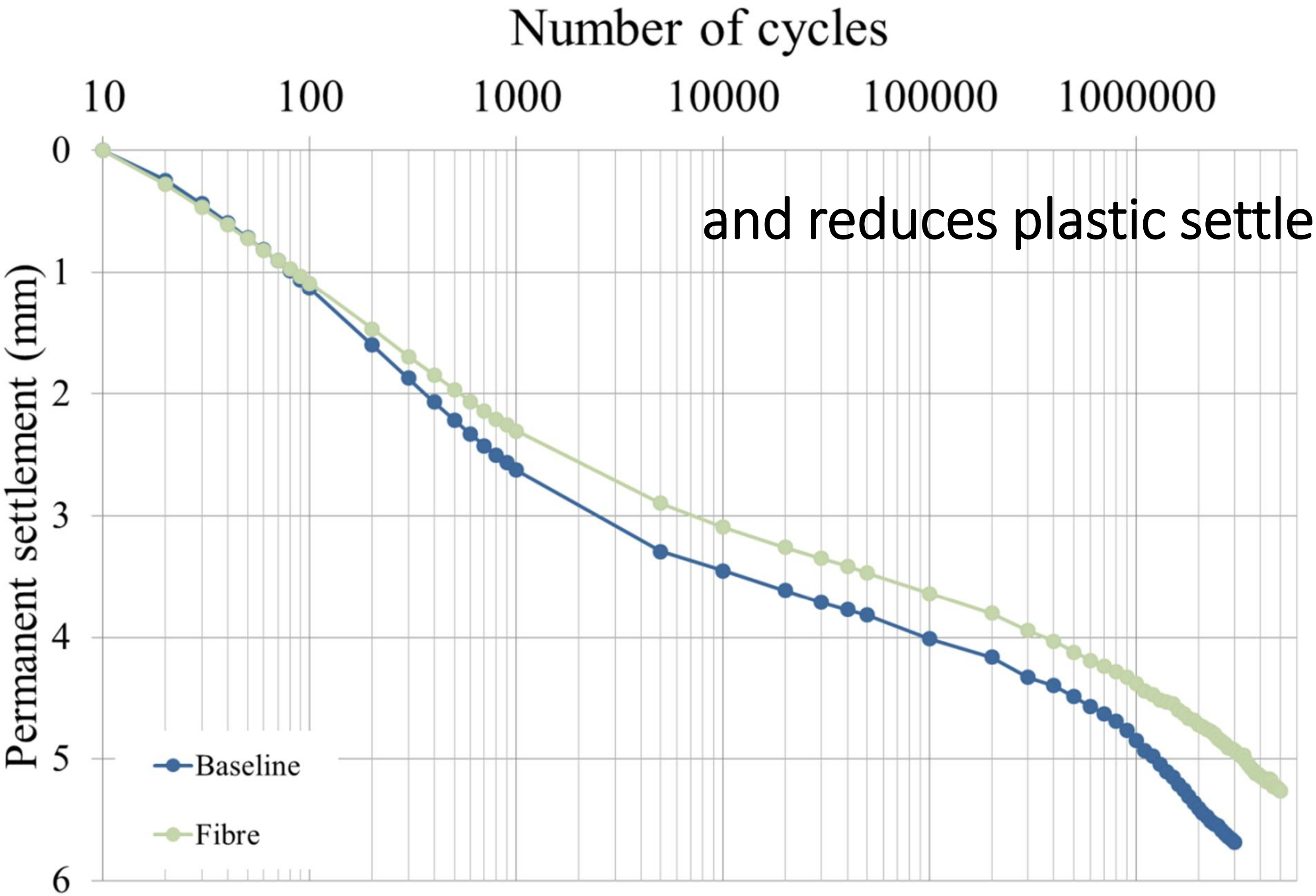


A behavioural framework for fibre reinforced gravel. O O Ajayi, L Le Pen, A Zervos and W Powrie. *Géotechnique* **67**(1), 56-68, January 2017

suppresses dilation



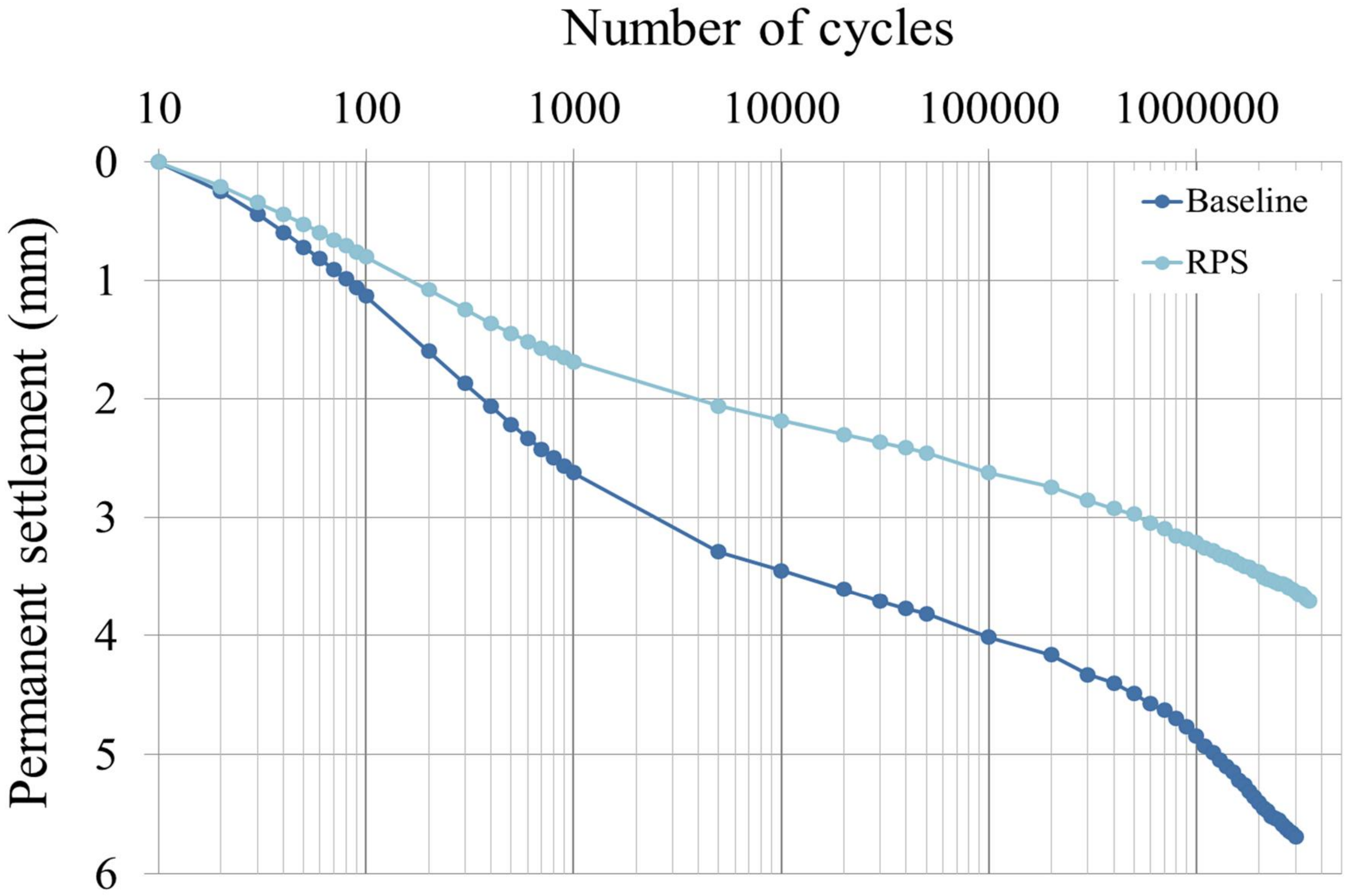




and reduces plastic settlement

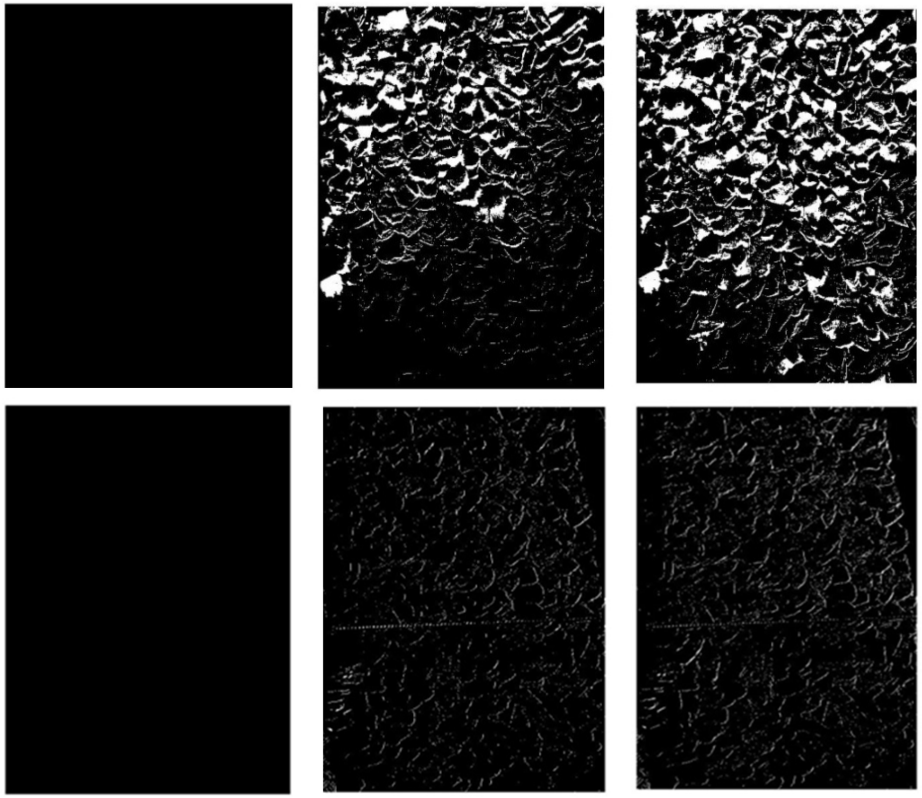

Steep ballast shoulder

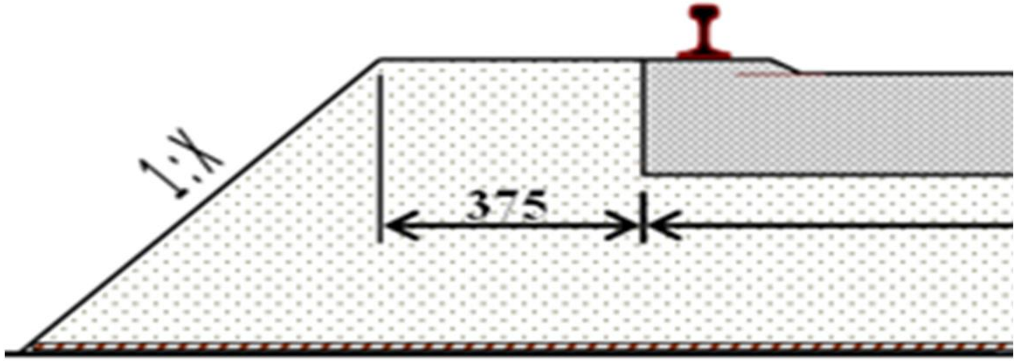
Reducing the shoulder slope



Reducing the shoulder slope

Ballast grain movements
(a) start, (b) 0.25 million cycles (c) end



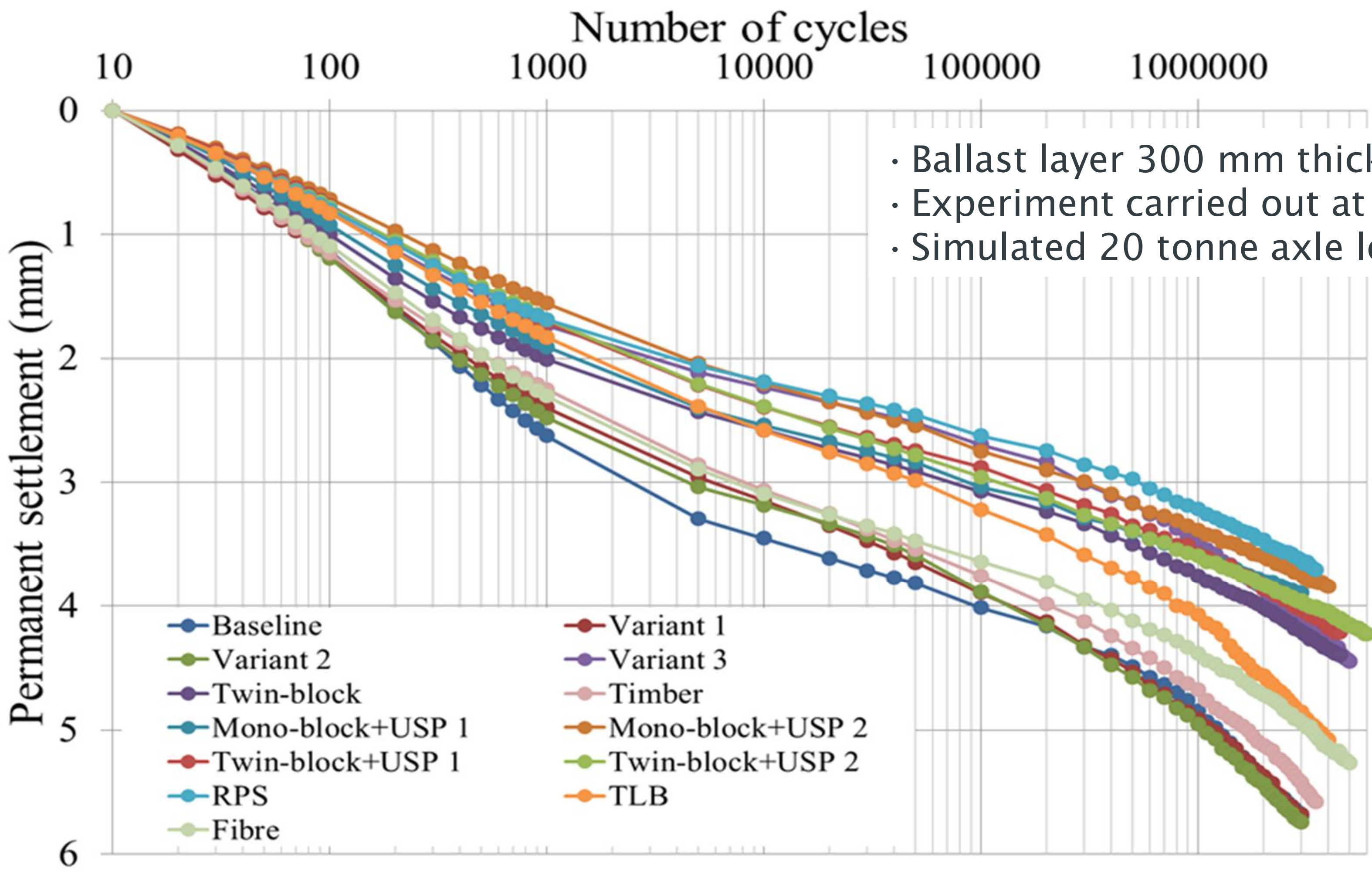


twin-block sleeper test
Shoulder slope 1V:1H

RPS slope test
Shoulder slope 1V:2H

Subtraction of contrast: identical gives a black image. Where particles have moved about, the subtraction is not zero and shows as a shade of grey/white

Reducing the plastic settlement of ballasted track



- Ballast layer 300 mm thick
- Experiment carried out at 3 Hz
- Simulated 20 tonne axle load

Implementation in practice?

- Under sleeper pads now standard in Austria (University of Graz) and have been specified at certain locations on UK Network Rail
- Ballast grading has been changed in Australia following work by Professor Buddhima Indraratna’s group at Wollongong / UTS
- Field trial of fibre reinforced ballast on London Underground at Burnt Oak, UK (right)
- The most effective remedy, reducing the shoulder slope or confining the ballast laterally, has not really found traction

..but
maybe it is
just too
difficult!

Localised defects and voids

Monitoring and repair of isolated trackbed defects on a ballasted railway. D R Milne, L M Le Pen, G V R Watson, D J Thompson, W Powrie, M Hayward and S Morley. *Transportation Geotechnics* **17**(Part A), 61-68 (2018). doi 10.1016/j.trgeo.2018.09.002

Localised defects associated with poor support conditions

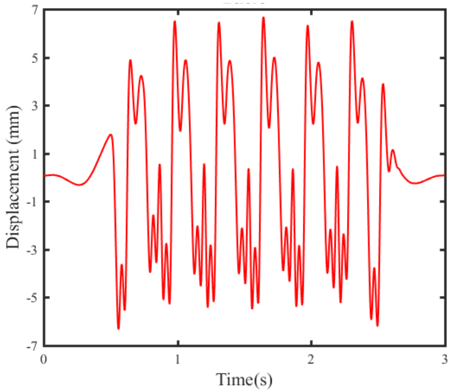
Sleeper transition and UTX defect site

- Transition from mono-block to duo-block sleepers
- Shallow concrete UTX in the vicinity of the defect
- Site was unsuccessfully tamped

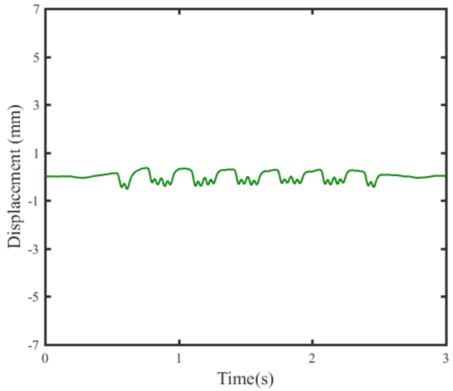
- Repaired using under sleeper pads and targeted hand packing
- Monitored using MEMS accelerometers

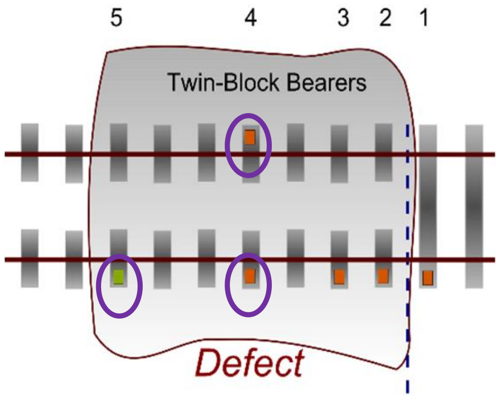
Sleeper transition and concrete UTX site

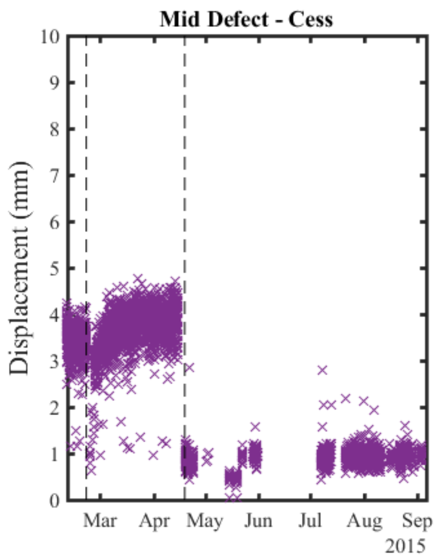
After tamping

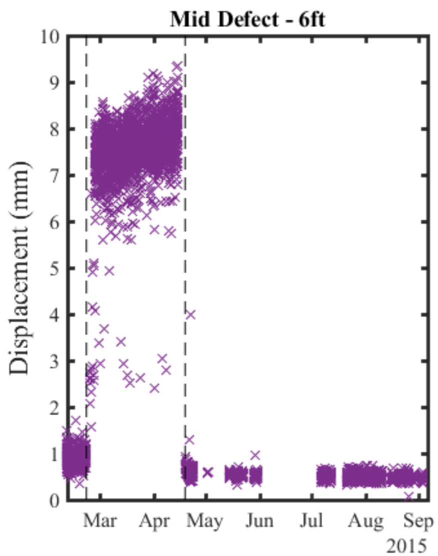


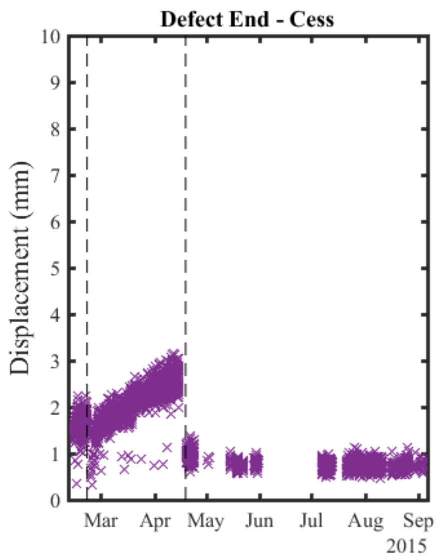
After repair









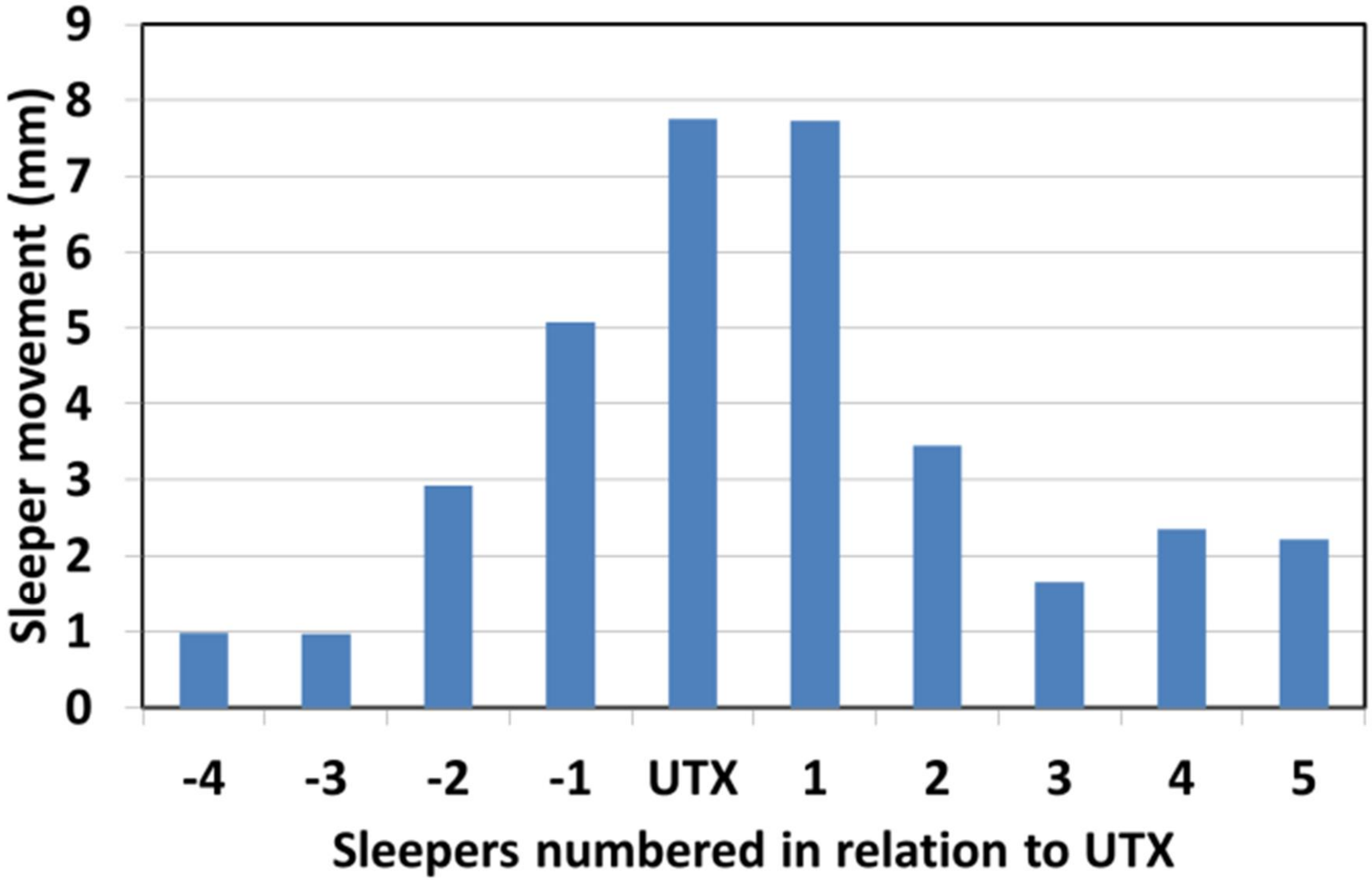


Flexible UTX

Behaviour of under-track crossings on ballasted railways. W Powrie, L M Le Pen, D R Milne, G V R Watson and J Harkness (2019). *Transportation Geotechnics* **21**. doi 10.1016/j.trgeo.2019.100258

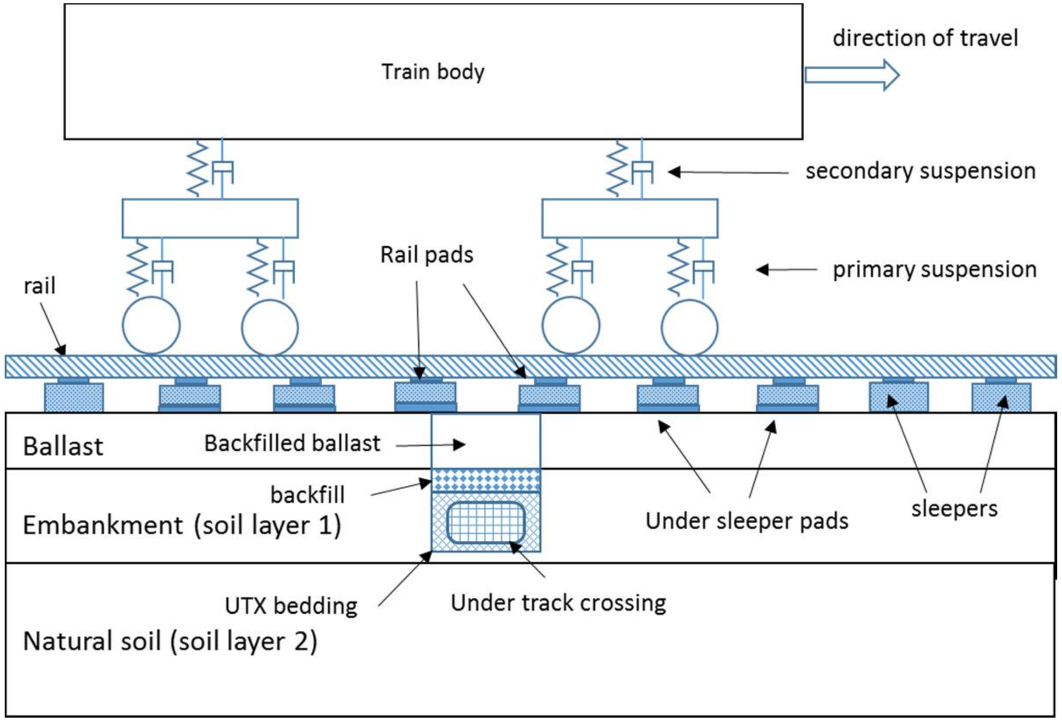

Flexible UTX
Installed at
study site


Track over flexible UTX



Flexible UTX site: sleeper movements measured using geophones

Finite element model



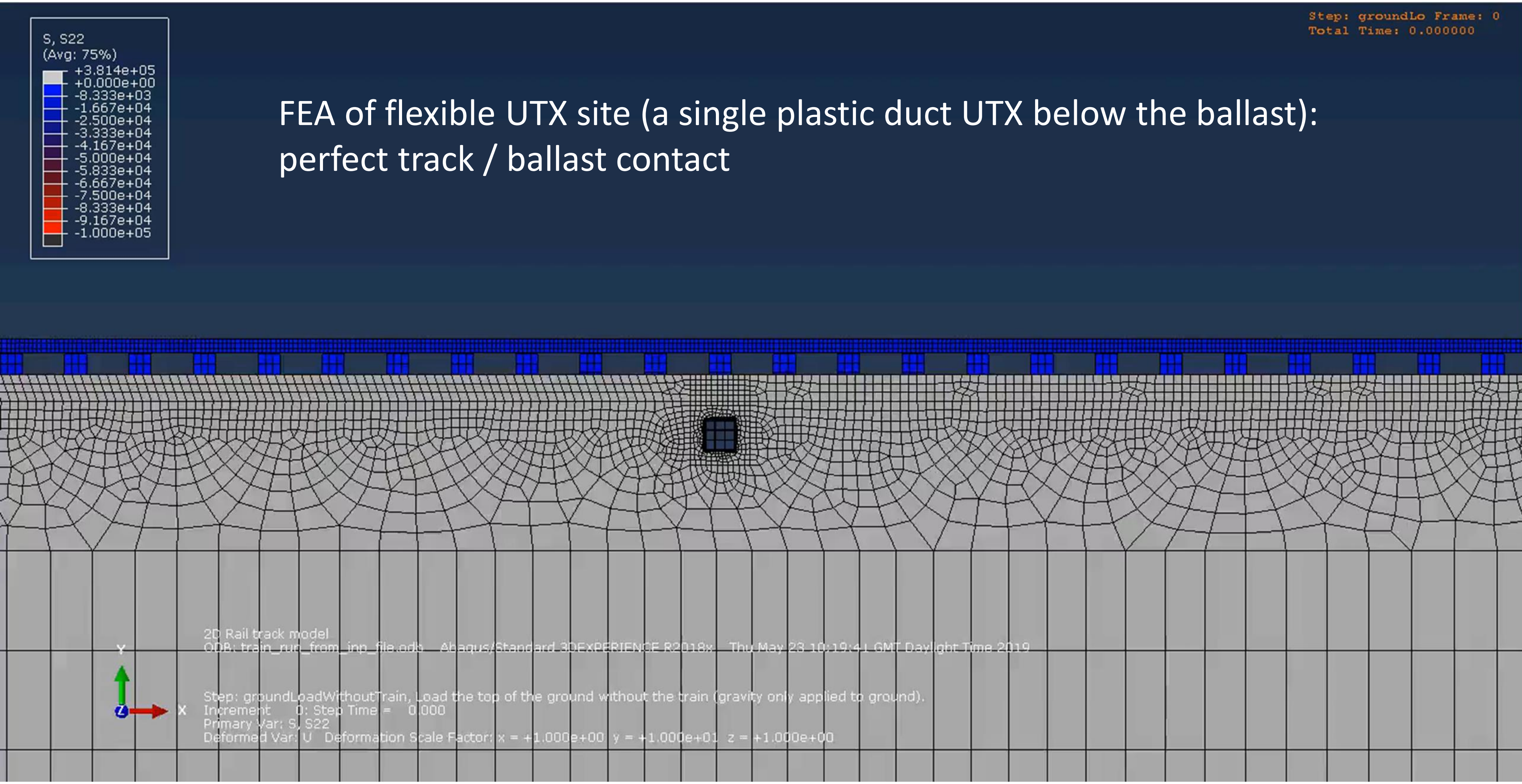
- 2D, representing conditions on track centreline
- Generic two carriage vehicle model with primary and secondary suspension
- Model length: 165 sleepers (~107 m)
- 3 layer linear elastic ground model
- Plastic duct UTX
- Train speed 40 m/s

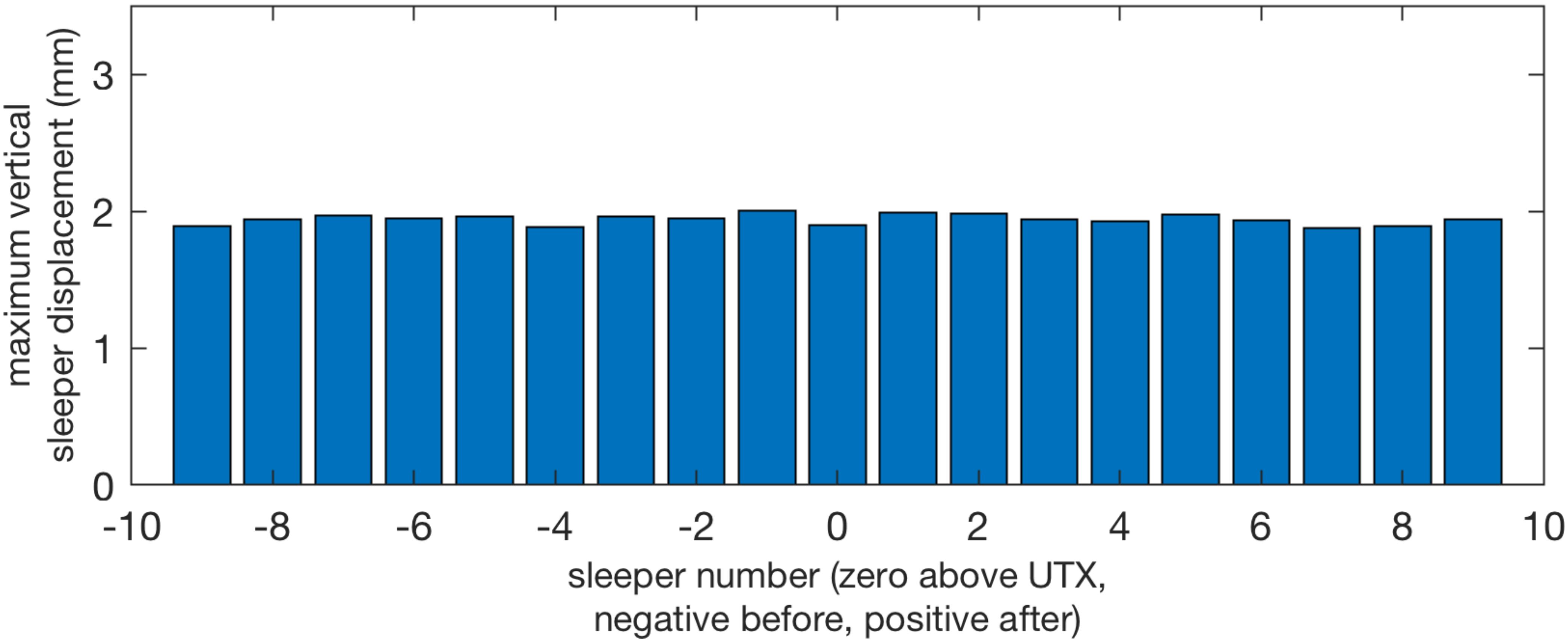
Material	Layer thickness (m)	Stiffness (MPa)
Ballast	0.3	150
UTX bedding	0.2	40
Embankment (firm clay)	1.7	24
Natural ground	14	$30 + (7 \times depth)$

Ground profile at flexible UTX site

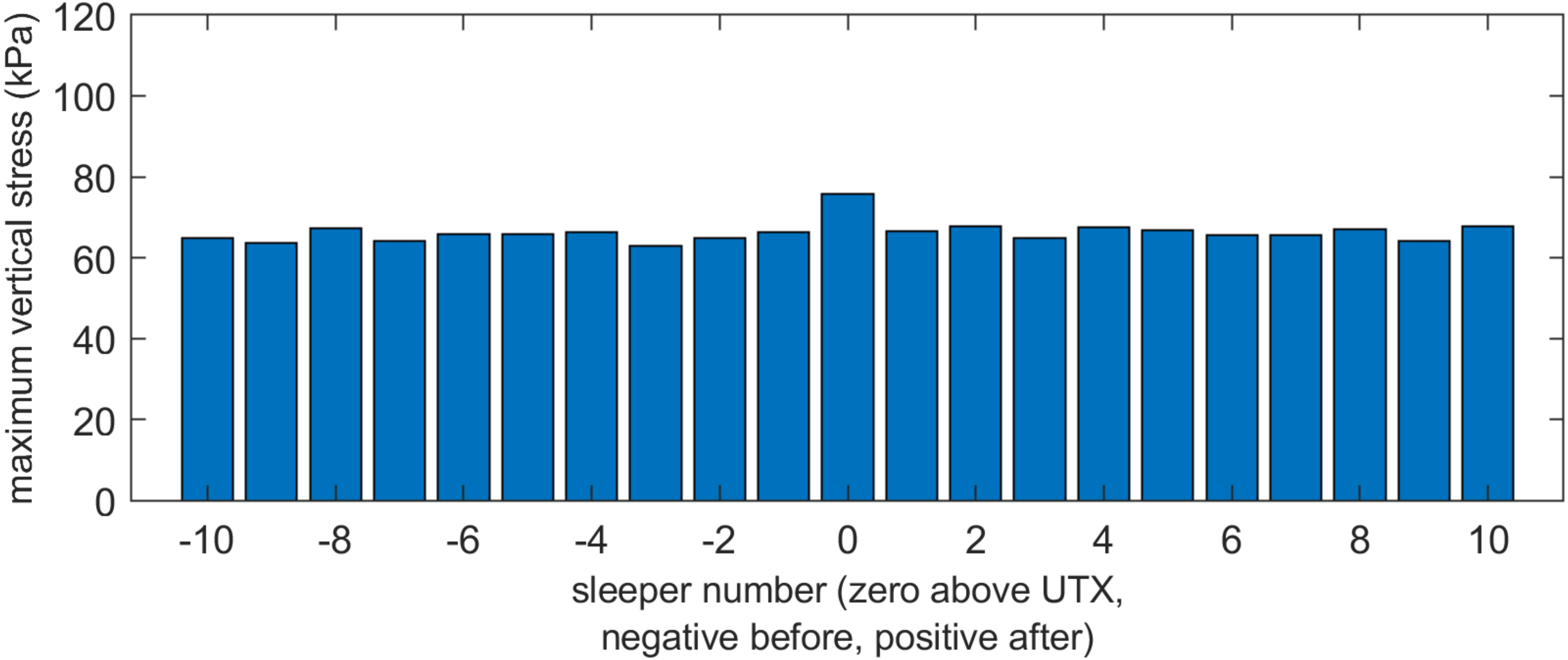
With audio. Thunderer

FEA of flexible UTX site (a single plastic duct UTX below the ballast): perfect track / ballast contact



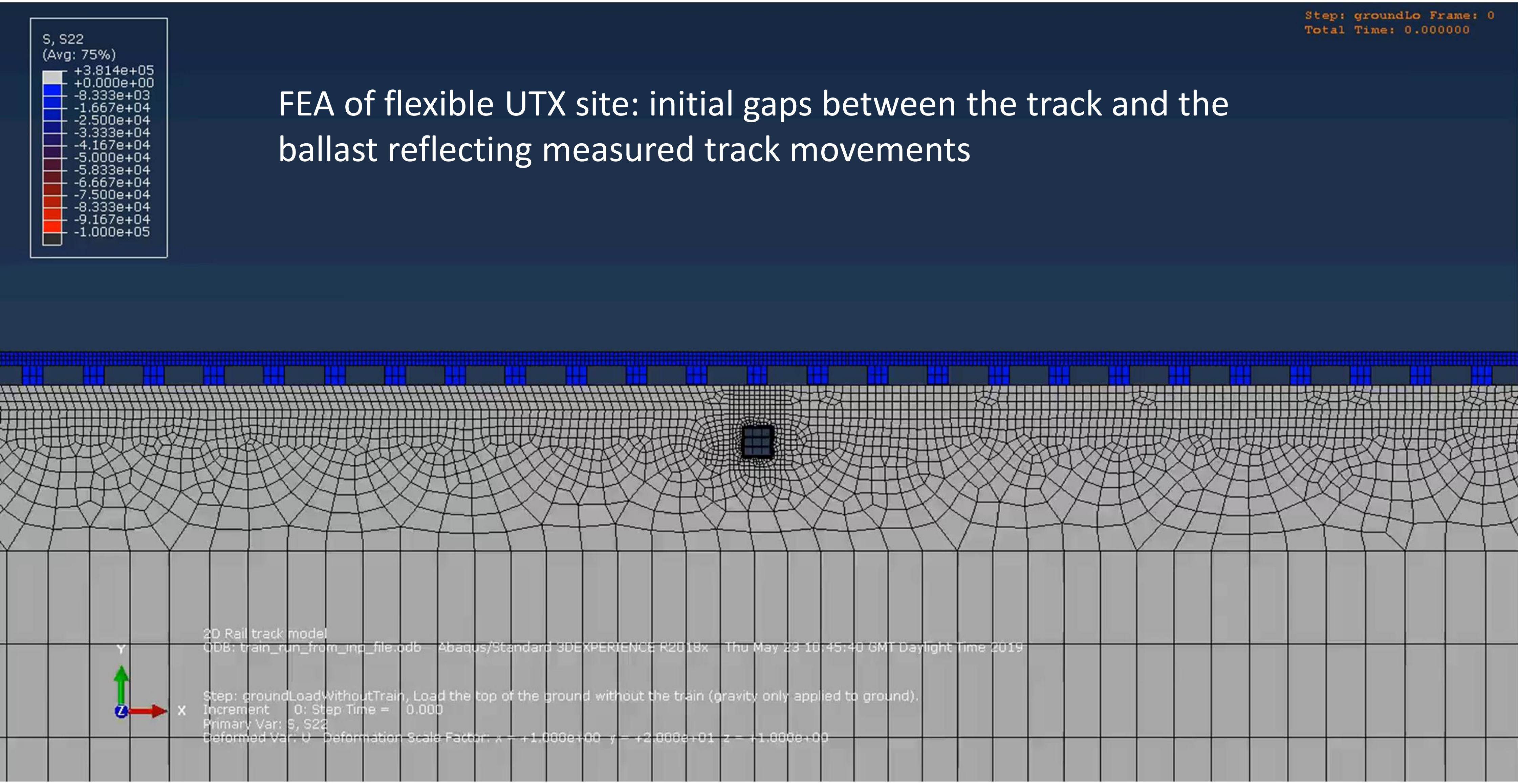


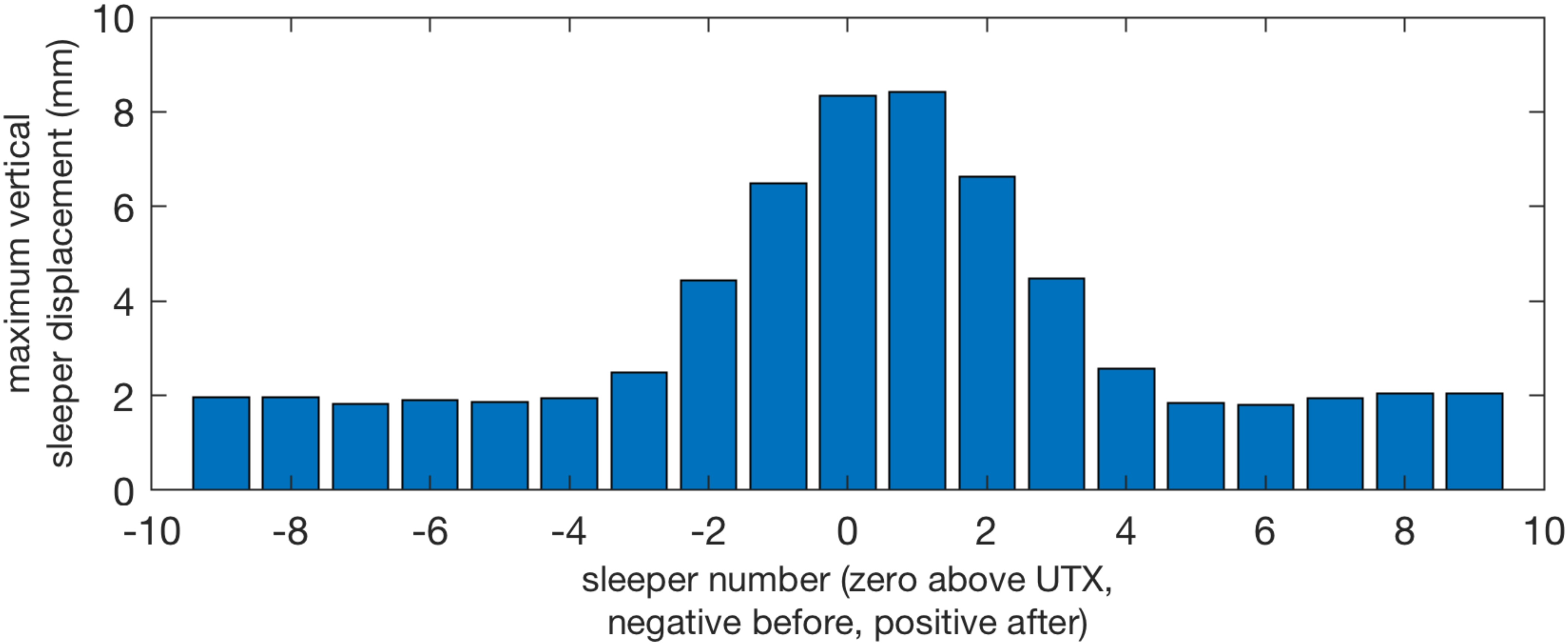
FEM model of flexible UTX site: sleeper movements with perfect sleeper/ballast contact



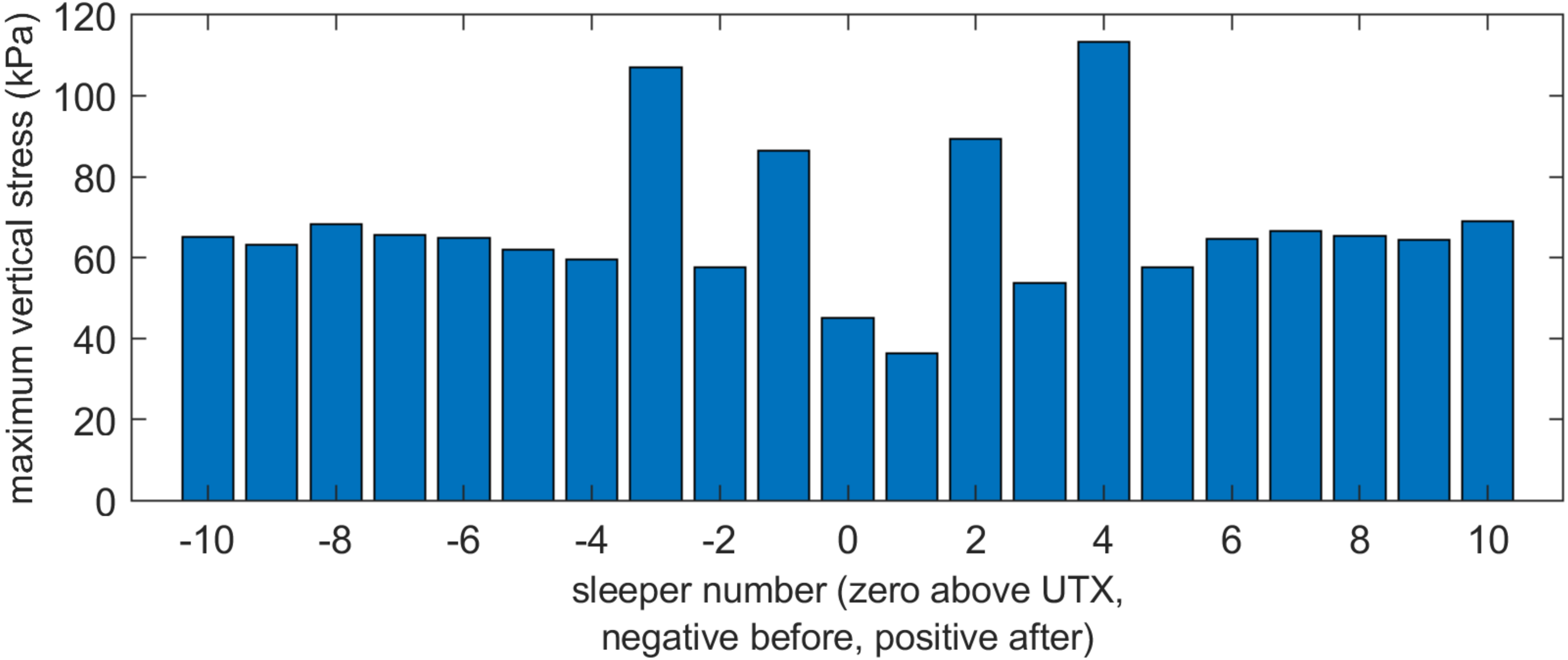
FEM model of flexible UTX site: vertical stresses below sleepers with perfect sleeper/ballast contact

With audio. Stars and stripes





Calculated sleeper movements after gaps introduced into FEM model approximating measured movements at flexible UTX site

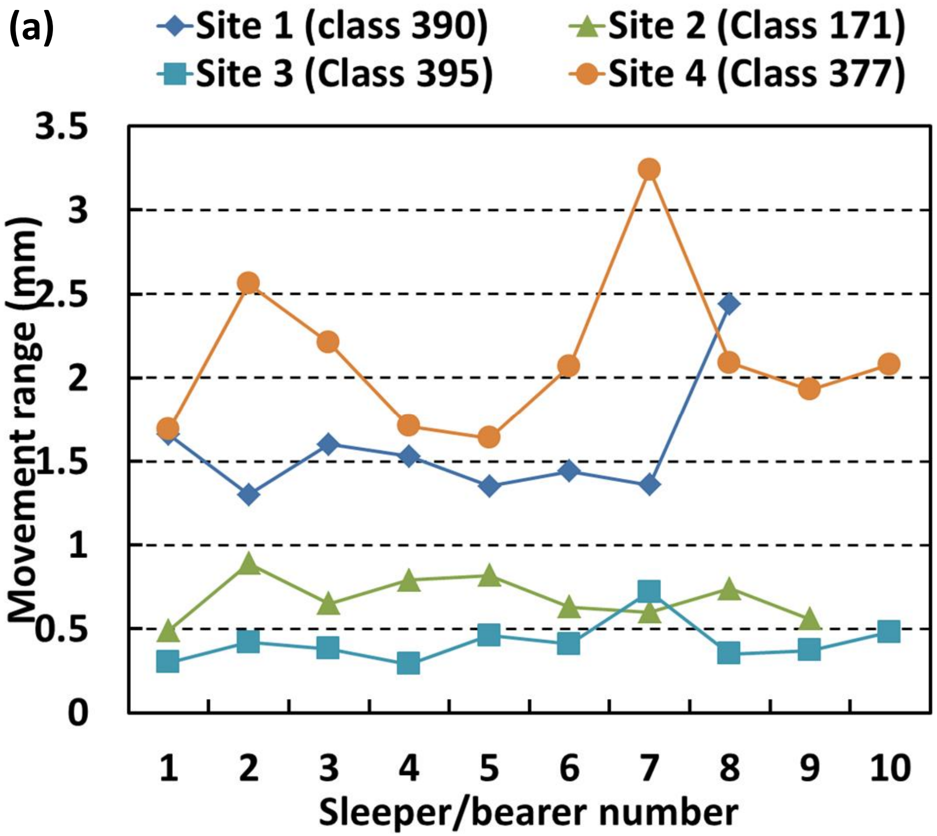


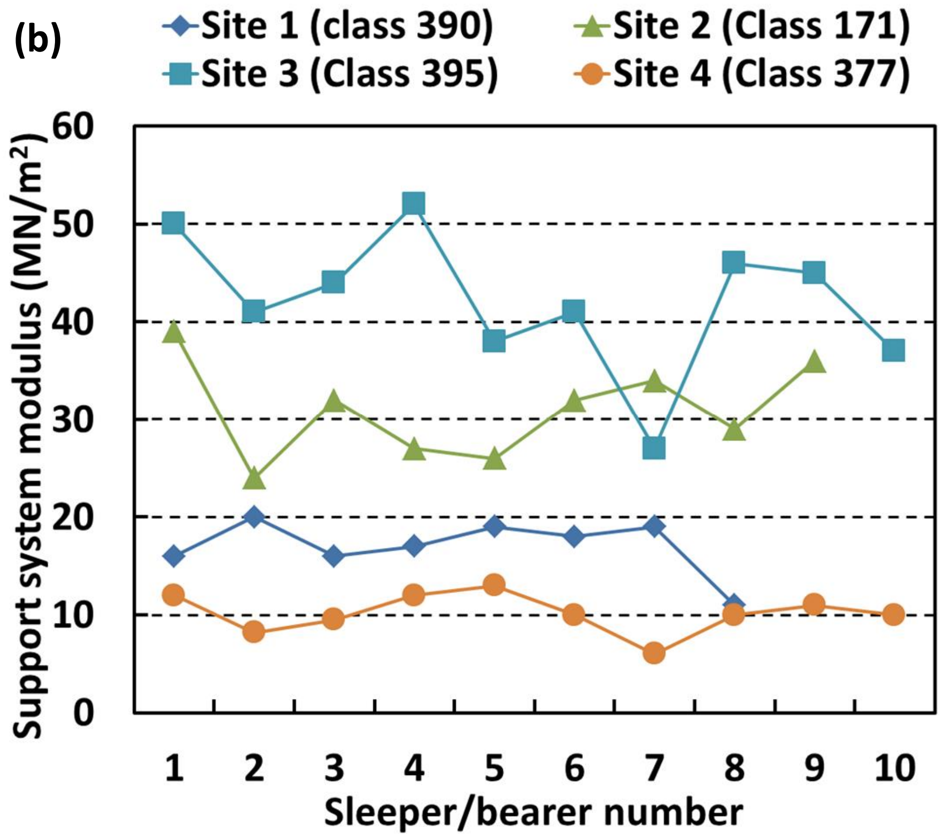
FEM model of UTX site: maximum vertical stresses below sleepers after the introduction of gaps

Comments

- The difference in support stiffness at the UTX has little effect on the calculated deflections and stresses if the sleepers are in perfect contact with the ballast
- To model the measured deflections, it was necessary to introduce gaps below the sleepers into the analysis
- It is these gaps (geometry imperfections), not changes in support stiffness as such, that cause the large variations in deflection and stress transmitted to the subgrade

Track stiffness – well performing track

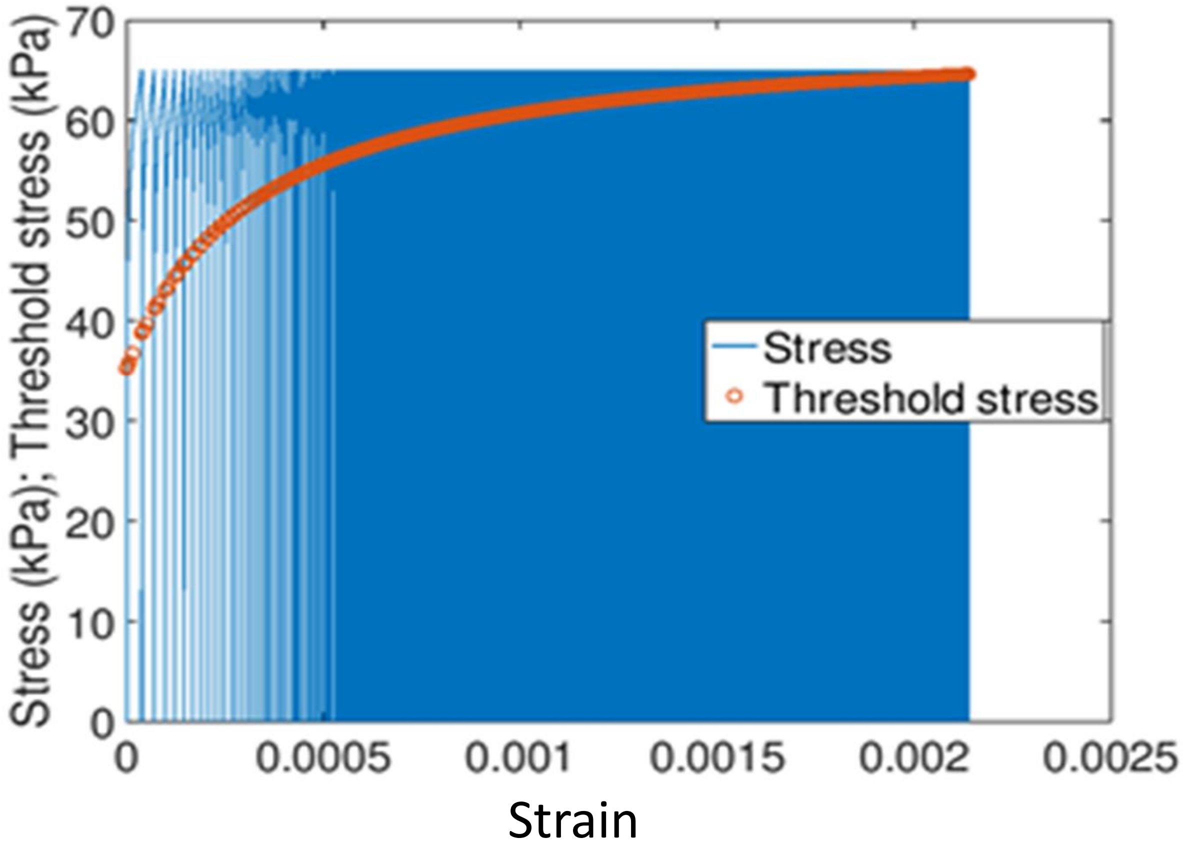




Data from well performing track: (a) measured sleeper movements (b) inferred support system modulus seen by the rail

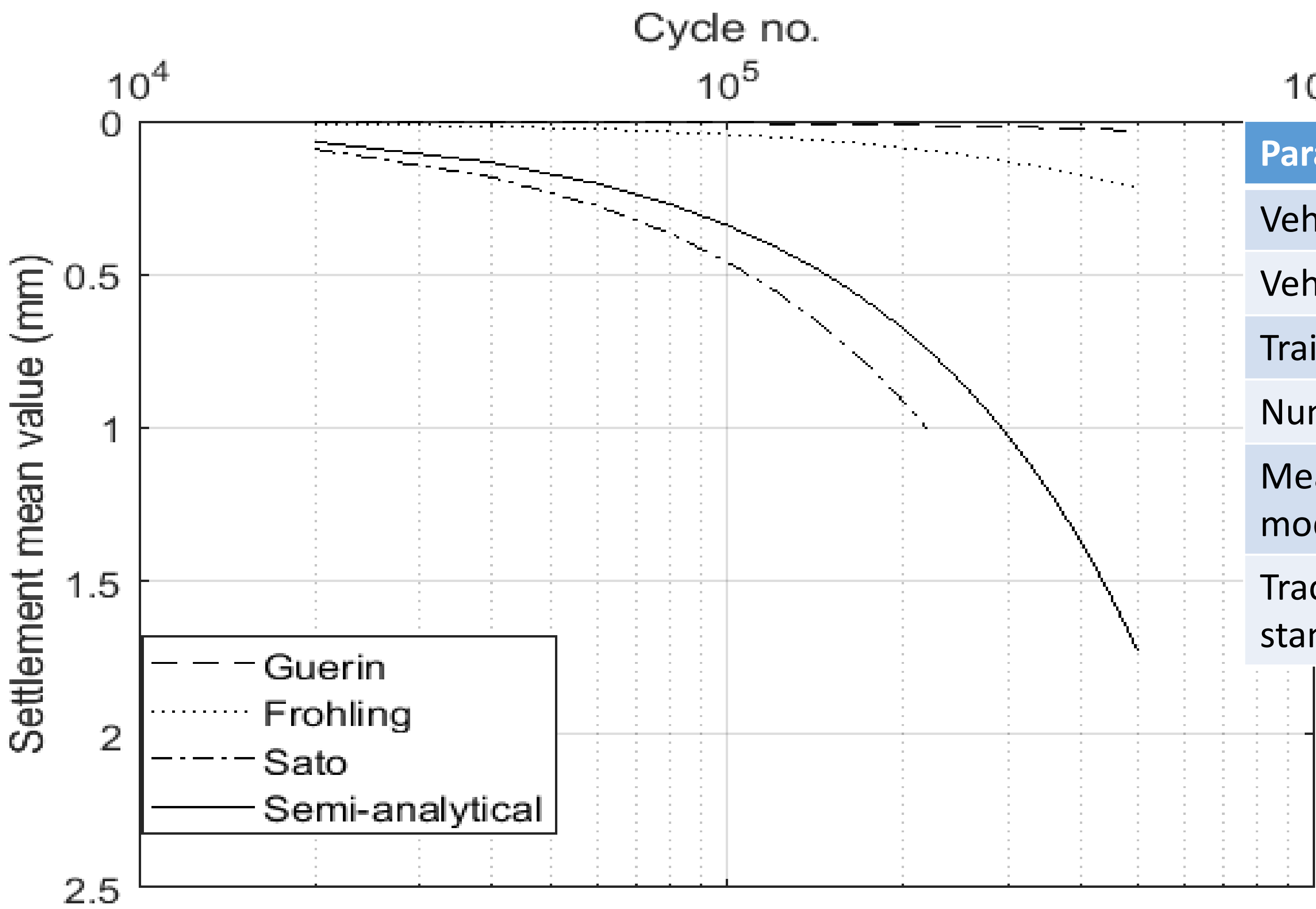
Predicting track settlements

Subgrade model: evolution of plastic strains



- Plastic strains occur above a certain threshold stress
- Threshold stress increases with number of cycles when exceeded
- Threshold stress is higher for materials of higher stiffness

Evolution of plastic settlement calculated in vehicle-track interaction analysis

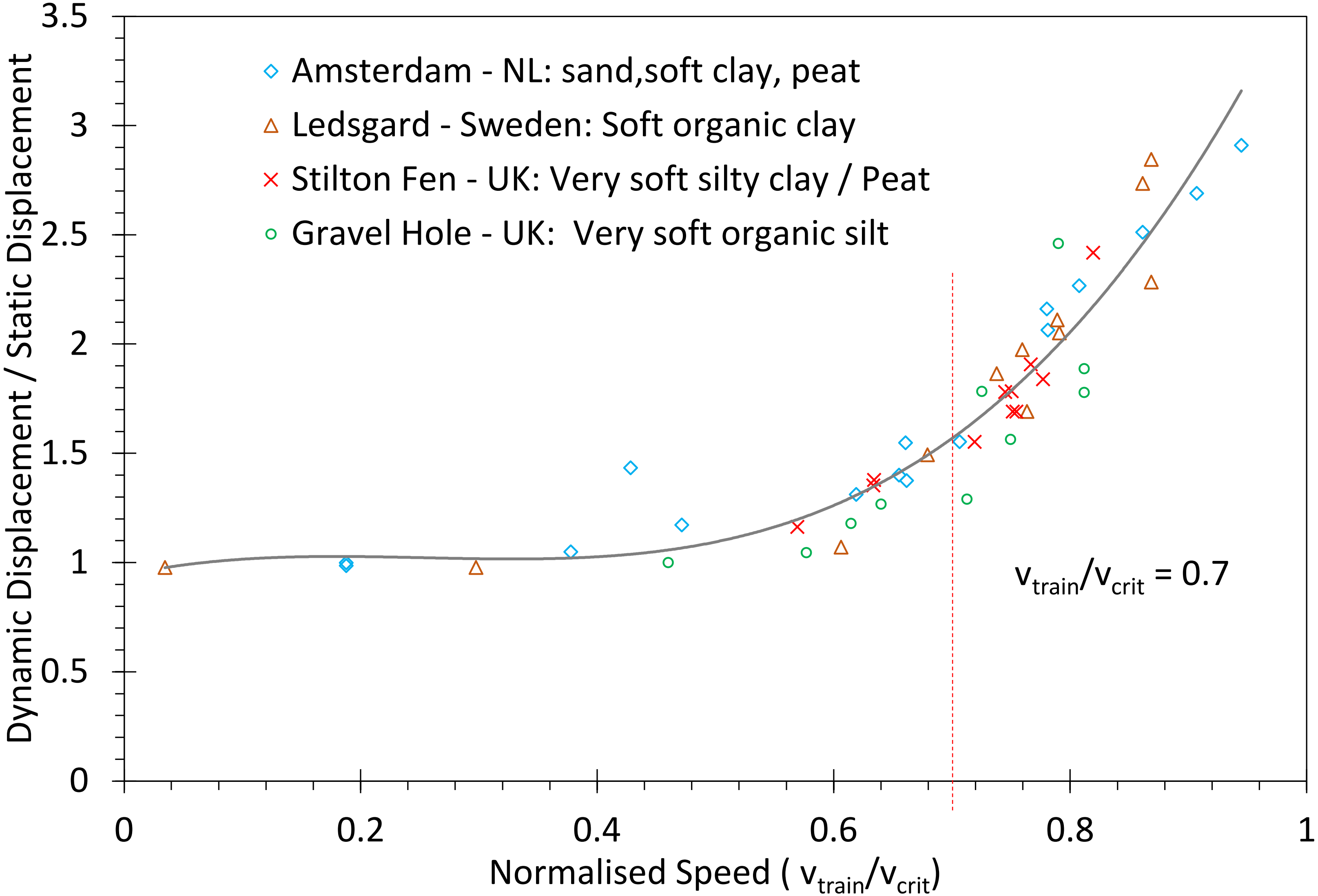


Parameter	Value
Vehicle axle load	22.5 tonnes
Vehicle unsprung mass	1350 kg
Train speed	80 km/hour
Number of sleepers	80
Mean trackbed modulus	168.7 MN/m^2
Trackbed modulus standard deviation	22.9 MN/m^2

Modelling railway ballasted track settlement in vehicle-track interaction analysis. I Grossoni, W Powrie, A Zervos, Y Bezin and L Le Pen. *Transportation Geotechnics* **26**, January 2021, 100433

The needs of speed

Critical velocity: normalised displacement vs normalised speed

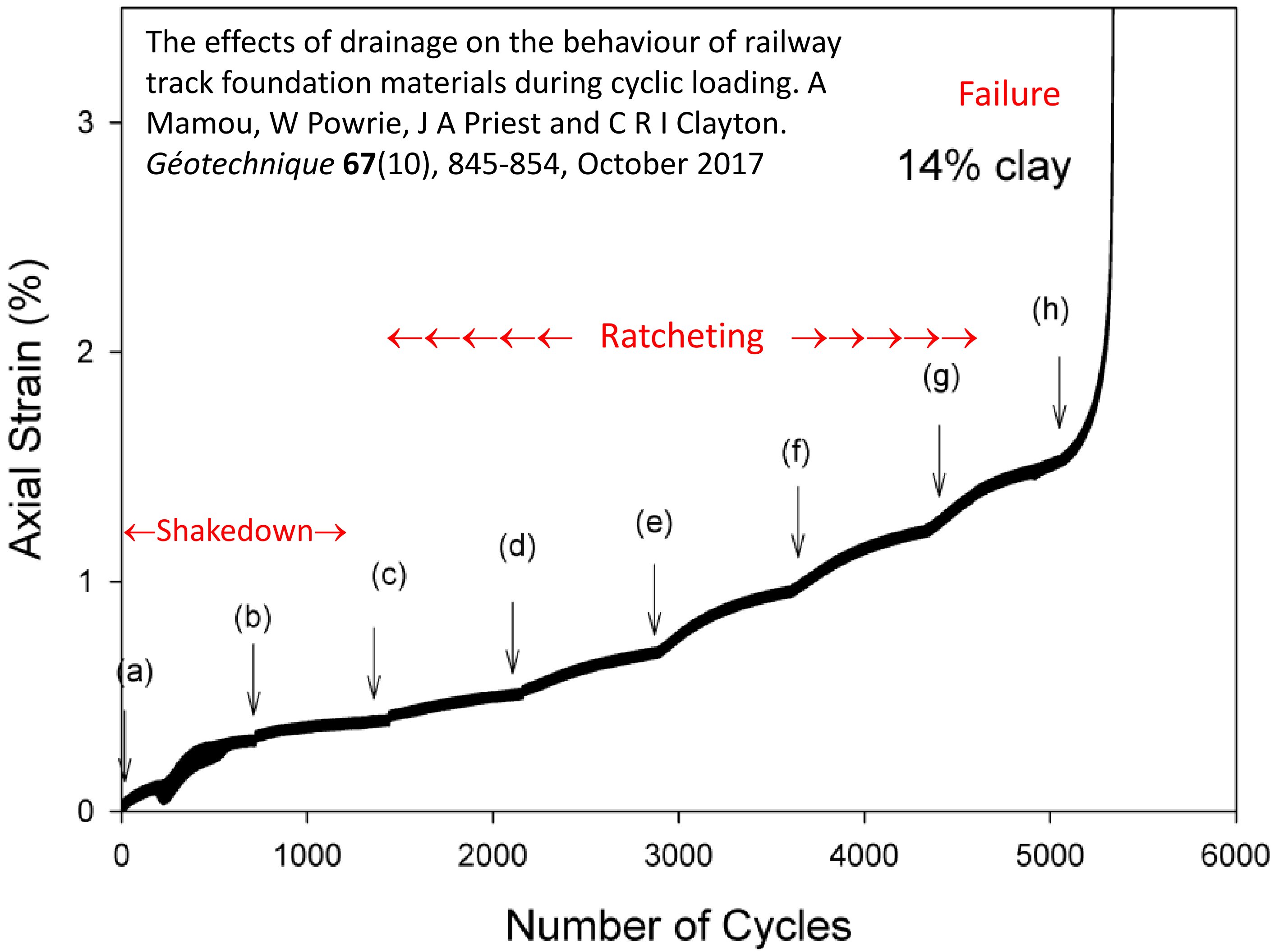


The normalised plot masks the fact that displacements decrease with increasing stiffness / critical speed

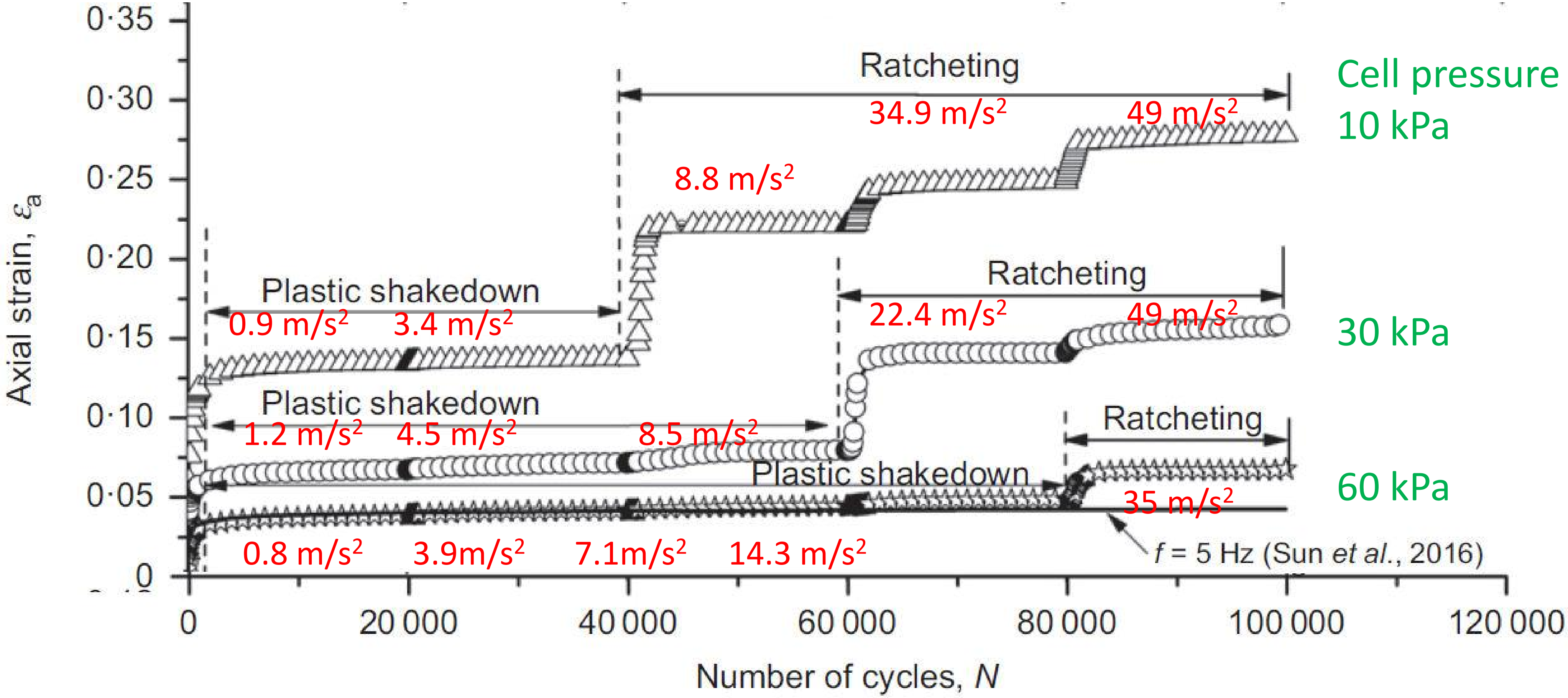
Plot: Alice Duley

Cycling above a threshold stress leads to ratcheting / failure

(a) q=30kPa $\tau\theta z = \pm$ 8.5kPa
(b) q=30kPa $\tau\theta z = \pm$ 11.5kPa
(c) q=30kPa $\tau\theta z = \pm$ 14.5kPa
(d) q=30kPa $\tau\theta z = \pm$ 17.5kPa
(e) q=30kPa $\tau\theta z = \pm$ 20.5kPa
(f) q=30kPa $\tau\theta z = \pm$ 23.5kPa
(g) q=30kPa $\tau\theta z = \pm$ 26.5kPa
(h) q=30kPa $\tau\theta z = \pm$ 29.5kPa



Cyclic loading of railway ballast at different frequencies (6-12-18-24-30 Hz)



Q Sun, B Indraratna, N T Ngo (2018). Effect of increase in load and frequency on the resilience of railway ballast *Géotechnique* [https://doi.org/10.1680/jgeot.17.P.302]

Frequency of loading and acceleration

- Maximum acceleration a_{max} depends on amplitude A and frequency ω: $x = A.cos(\omega t); a_{max} = \omega^2.A = \frac{\omega^2 F}{k}$ (stiffness k)
- Sato (1995) suggests ballast degradation increases with $1/\sqrt{k}$ to account for higher ballast accelerations
- Duration is important: a short duration acceleration will not transfer enough energy to have an effect
- Eurocode EN1990:2002+A1: a_{max} = 0.35g @ 30 Hz

Sato, Y (1995): Japanese Studies on Deterioration of Ballasted Track. *Vehicle System Dynamics* **24,** 197-208

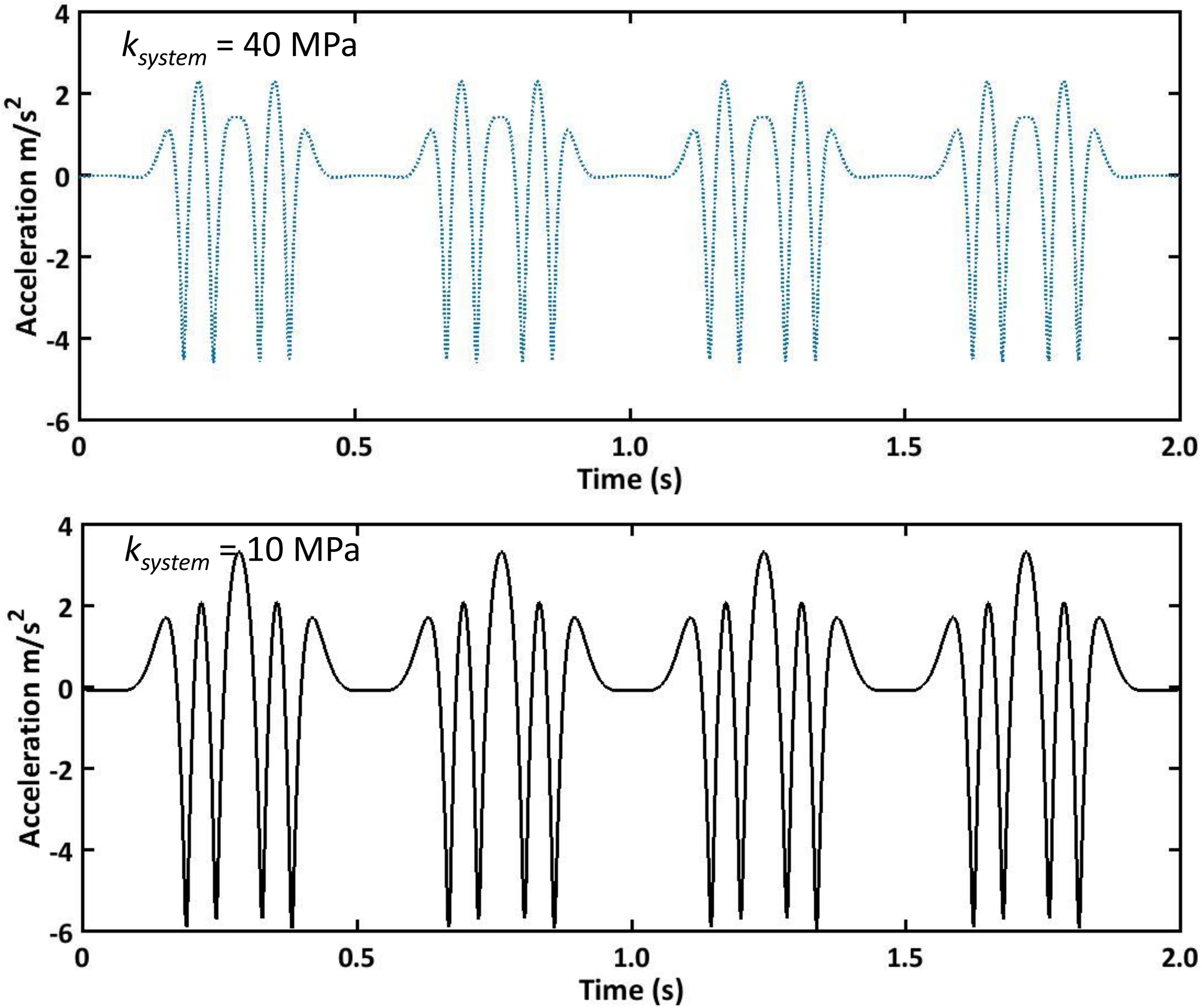
Maximum accelerations in triaxial tests

Cell pressure	6 Hz	12 Hz	18 Hz	24 Hz	30 Hz
10 kPa	0.09g	0.35g	0.90g	3.6g	5.0g
30 kPa	0.12g	0.47g	0.86g	2.3g	5.0g
60 kPa	0.08g	0.40g	0.72g	1.5g	3.6g

Cells shaded green: shakedown. Cells shaded red: ratcheting

Q Sun, B Indraratna, N T Ngo (2018). Effect of increase in load and frequency on the resilience of railway ballast Géotechnique AOP [https://doi.org/10.1680/jgeot.17.P.302]

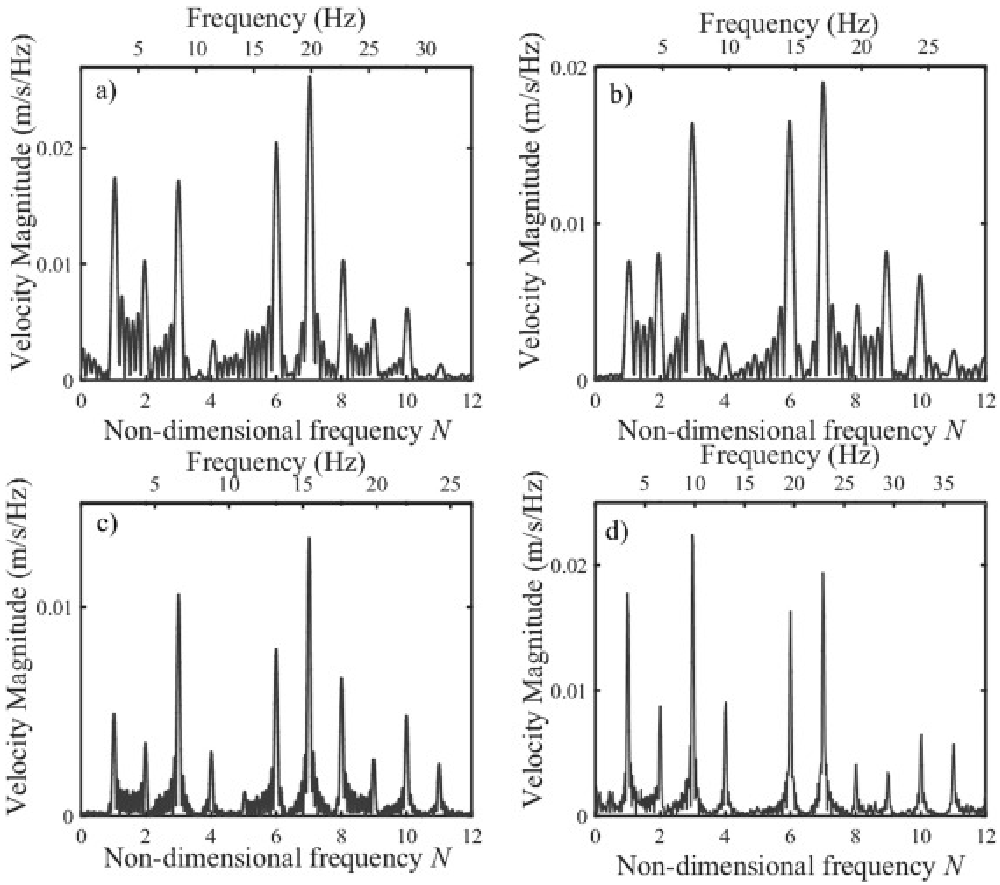
Importance of track system stiffness: BOEF model accelerations



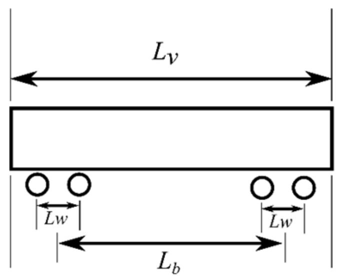
- For normally performing track, accelerations do not usually approach *g* except where the support stiffness is very low and then only for a very short duration.
- In the figure, the accelerations are calculated every 1/500 of a second.
- If they are evaluated every 1/30 of a second the peak calculated acceleration is roughly halved

Frequency analysis of train loading

- The velocity spectra of common train types show prominent peaks at multiples of the car passing frequency – in agreement with theory
- The relative magnitudes of these frequencies depend on track stiffness and vehicle geometry



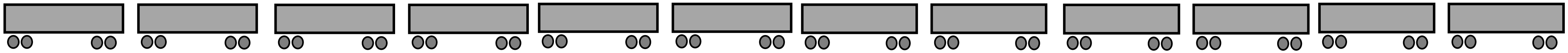
Magnitude of the Fourier transform of measured sleeper velocities. a) 6 car Javelin (56.4 m/s); b) 5 car Voyager (56.1 m/s); c) 11 car Pendolino (54.4 m/s); d) 16 car Valero (80.8 m/s).

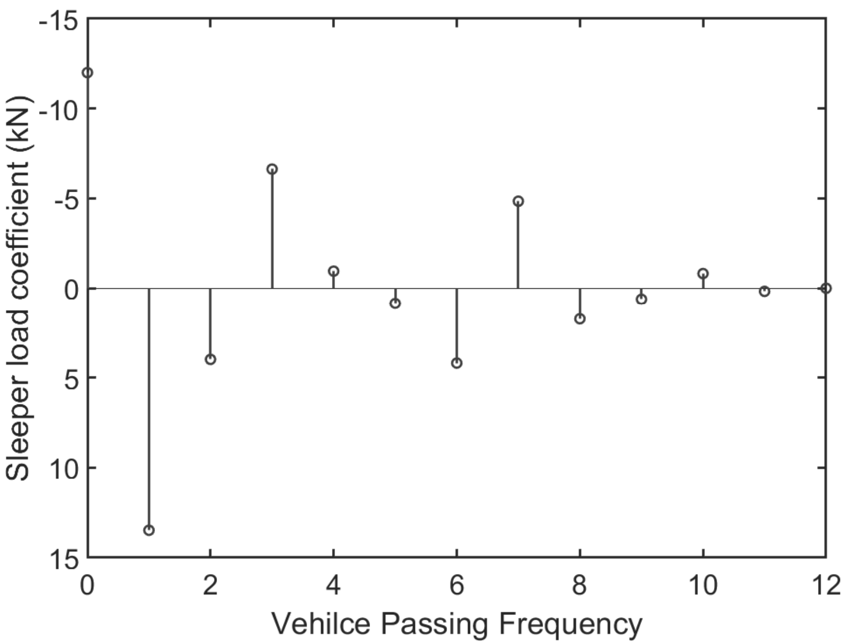


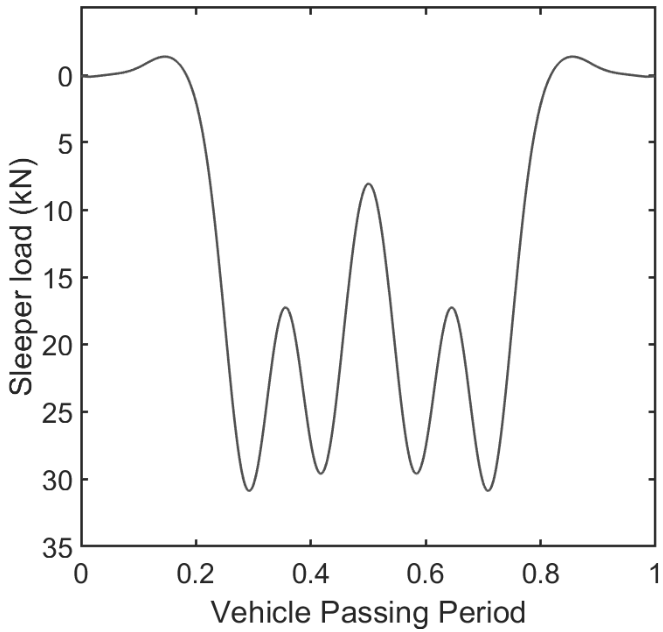
Train	No. Vehicles	L_v	L_b	L_w
a) Javelin	6	20	14.2	2.6
b) Voyager	5	23	16	2.6
c) Pendolino	11	23.9	17	2.7
d) Valero	16	24.8	17	2.5

Properties of train load frequencies and their applications. D R M Milne, L M Le Pen, D J Thompson and W Powrie. *Journal of Sound and Vibration* **397**, 123-140 (2017).

Frequency analysis: components of load



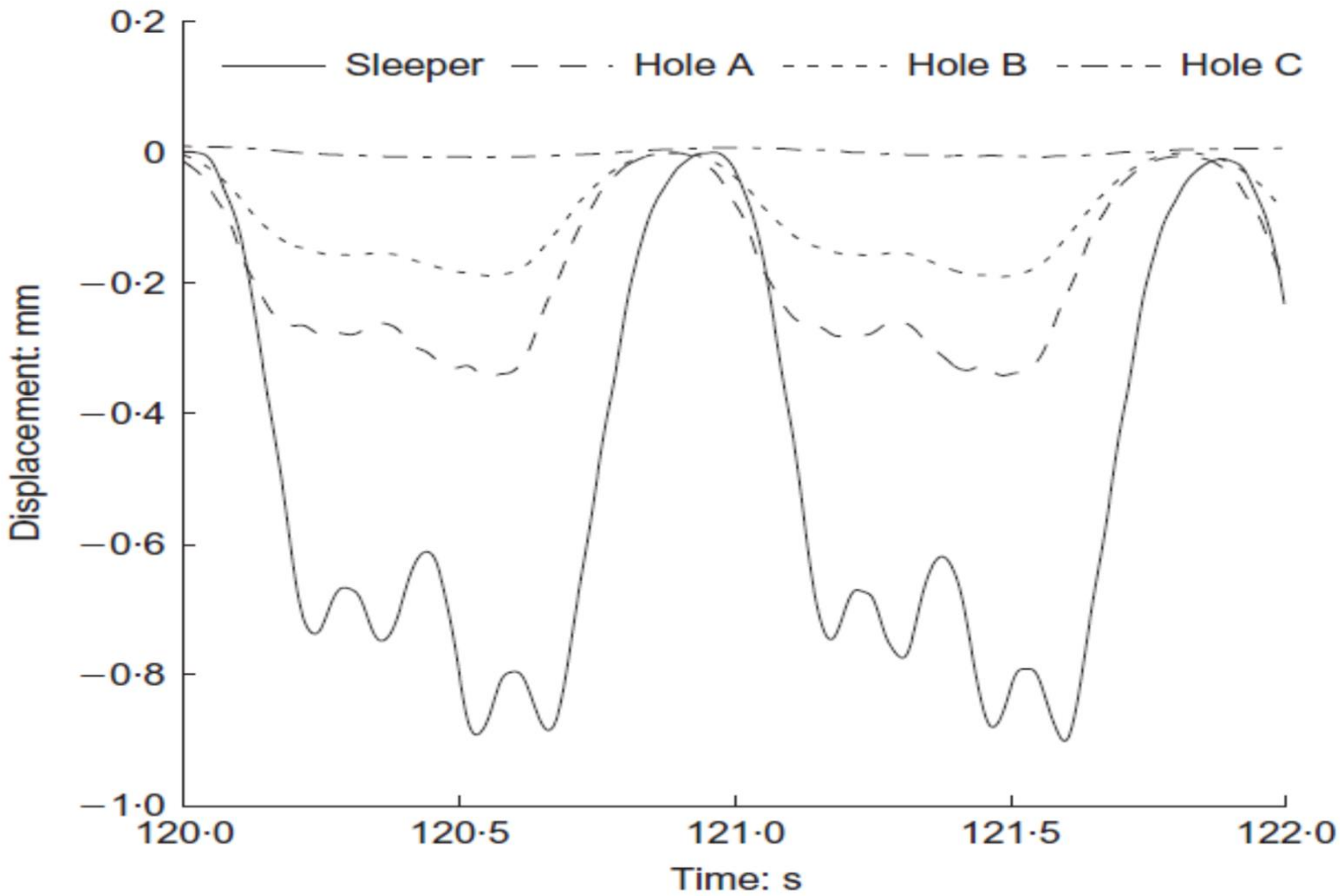




A spectrum of loading is applied to a sleeper. This may be idealised as a complex Fourier series, with loading coefficients at multiples of the vehicle passing frequency.

Higher frequencies of loading atteniuate more rapidly with

- Displacements measured at different depths



Priest J A, Powrie W, Yang L A, Grabe P J and Clayton C R I (2010) Measurements of transient ground movements below a ballasted railway line. *Géotechnique* **60**, 667-677

Reasons to be cheerful

- Normalised plot masks the reduction in displacement with increasing ground stiffness (3 × 10 mm is a worry; 3 × 0.1 mm is not)
- Loading is not a single value at a single frequency: it is a spectrum of loads at different frequencies based on multiples of the car passing frequency
- Real system will be damped, by the material properties (of which we need better understanding) and through the attenuation of higher frequency components with depth

Conclusions

Conclusions (1)

- Key performance indicators for railway track are the track support stiffness and the vertical alignment or level, and the rate at which the level deteriorates due to plastic settlement
- Variations in track level and hanging sleepers are likely to be much more damaging than variations in a continuous track support stiffness
- It is important to avoid unsupported (hanging) sleepers; such localised defects can be assessed, repaired and their effectiveness checked with the aidof targeted monitoring
- For conventional railways, there is a fairly wide range of acceptable support stiffness

Conclusions (2)

- Various interventions can reduce the rate of plastic settlement of ballast. Some (under sleeper pads, revised ballast grading) have been adopted in countries round the world
- Reducing the ballast shoulder slope (or containing the ballast laterally) is perhaps the most effective but least adopted
- Preventing plastic settlement of the subgrade at an affordable cost (in terms of both money and carbon) is a challenge, perhaps especially for high speed railways
- We need a better understanding of train loading, and better models for material dynamic behaviour and the development of plastic settlement

Acknowledgements

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- David Thompson
- Geoff Watson
- Antonis Zervos

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Thank You!

Questions?

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