3rd Proctor Lecture
Railway track substructure: recent research and future directions

Presented by
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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

![Graph showing deviation from level over a length of track](image)

- **Deflection under load**

![Diagram showing deflection under load](image)

- **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/m²)
Vertical geometry (level): as smooth as possible (no lumps or dips)
**Level**: settlement of ballasted track and restoration of level by tamping

Source: Selig & Waters, 1994
Settlement is not just due to the ballast: Traditional embankment construction by end-tipping

Image source: http://www.transportarchive.org.uk/
Embankment construction by end tipping

Image source: http://www.transportarchive.org.uk/
Earthwork settlement over time

Hawkwell embankment: cross section through north side

Inclinometer, extensometer and Geo-piezometers at crest and midslope

Neutron probe access tubes

Deep standpipe and Geo-piezometer at toe

Ash

Embankment fill

Underlying London Clay

Deep standpipe and Geo-piezometer at toe
Seasonal cycles of shrinkage and swelling

Photo: Graham Birch, Network Rail
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: 
\( k = \text{sleeper end stiffness in MN/m} \div \text{sleeper spacing in m} \)

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

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

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

Bending stiffness of the rail \( EI, \text{MN.m}^2 \)

Position and number of wheels at speed \( \mathbf{v} \) and time \( t \)

\[
L = \sqrt[4]{\frac{4EI}{k}}
\]
Effect of track support stiffness: BOEF model deflections

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)

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

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


Deflection and stiffness measured using MEMS accelerometers
Field data: deflections and system support modulus

![Graph showing deflection and support modulus over sleeper numbers.](image-url)
Vehicle track interaction: simulations

Track stiffness and level from measurements

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Level</th>
<th>Track Modulus</th>
<th>Voiding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Measured*</td>
<td>Uniform 30MPa</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>Smooth</td>
<td>Measured†</td>
<td>None</td>
</tr>
<tr>
<td>3</td>
<td>Measured*</td>
<td>Measured†</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>Measured*</td>
<td>Measured†</td>
<td>Included</td>
</tr>
</tbody>
</table>

* From total station
† From accelerometers
Simulated sleeper deflections

Measured initial track level, modulus 30 MN/m²
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/m²
- 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

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)


Under sleeper pads

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

The graph shows the plastic settlement of the ballast layer under different conditions:

- Mono-block
- Mono-block-USP A
- Mono-block-USP B

The x-axis represents the number of cycles, and the y-axis represents the permanent settlement in millimeters.
Sleepers rest on relatively few ballast grains

G44 sleeper, base area 2.5 m × 0.285 m

Pressure sensitive paper shows contact history after 2.5M load cycles

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)
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
Plastic settlement of ballast layer

- Ballast layer 300 mm thick
- Experiment carried out at 3 Hz
Random fibre reinforcement
increases ballast ductility


suppresses dilation
and reduces plastic settlement
Steep ballast shoulder
Reducing the shoulder slope

![Graph showing the relationship between number of cycles and permanent settlement. The graph compares Baseline and RPS data, with Baseline showing a steeper decrease in permanent settlement over fewer cycles compared to RPS.](image)

- **Number of cycles:** 10, 100, 1000, 10000, 100000, 1000000
- **Permanent settlement (mm):** 0, 1, 2, 3, 4, 5, 6
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

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

Defect

Twin-Block Bearers

Flexible UTX
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
<table>
<thead>
<tr>
<th>Material</th>
<th>Layer thickness (m)</th>
<th>Stiffness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast</td>
<td>0.3</td>
<td>150</td>
</tr>
<tr>
<td>UTX bedding</td>
<td>0.2</td>
<td>40</td>
</tr>
<tr>
<td>Embankment (firm clay)</td>
<td>1.7</td>
<td>24</td>
</tr>
<tr>
<td>Natural ground</td>
<td>14</td>
<td>$30 + (7 \times \text{depth})$</td>
</tr>
</tbody>
</table>

Ground profile at flexible UTX site
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
FEA of flexible UTX site: initial gaps between the track and the ballast reflecting measured track movements
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.
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
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


14% clay

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 $\omega$: $x = A \cdot \cos(\omega t)$; $a_{max} = \omega^2 \cdot A = \frac{\omega^2 F}{k}$ (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

Maximum accelerations in triaxial tests

<table>
<thead>
<tr>
<th>Cell pressure</th>
<th>6 Hz</th>
<th>12 Hz</th>
<th>18 Hz</th>
<th>24 Hz</th>
<th>30 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kPa</td>
<td>0.09g</td>
<td>0.35g</td>
<td>0.90g</td>
<td>3.6g</td>
<td>5.0g</td>
</tr>
<tr>
<td>30 kPa</td>
<td>0.12g</td>
<td>0.47g</td>
<td>0.86g</td>
<td>2.3g</td>
<td>5.0g</td>
</tr>
<tr>
<td>60 kPa</td>
<td>0.08g</td>
<td>0.40g</td>
<td>0.72g</td>
<td>1.5g</td>
<td>3.6g</td>
</tr>
</tbody>
</table>

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.

\[
k_{\text{system}} = 40 \text{ MPa} \\
k_{\text{system}} = 10 \text{ MPa}
\]
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

<table>
<thead>
<tr>
<th>Train</th>
<th>No. Vehicles</th>
<th>L_v</th>
<th>L_b</th>
<th>L_w</th>
</tr>
</thead>
<tbody>
<tr>
<td>Javelin</td>
<td>6</td>
<td>20</td>
<td>14.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Voyager</td>
<td>5</td>
<td>23</td>
<td>16</td>
<td>2.6</td>
</tr>
<tr>
<td>Pendolino</td>
<td>11</td>
<td>23.9</td>
<td>17</td>
<td>2.7</td>
</tr>
<tr>
<td>Valero</td>
<td>16</td>
<td>24.8</td>
<td>17</td>
<td>2.5</td>
</tr>
</tbody>
</table>

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).

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 attenuate more rapidly with:

- Displacements measured at different depths

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 aid of 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.
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Thank You!

Questions?