1ST RALPH PROCTOR LECTURE OF ISSMGE - 2016
Railroad Performance with Special Reference to Ballast and Substructure Characteristics

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# Rail Geotechnics in a Nutshell – Key Themes

**Basics of track substructures and rail embankments**
Indraratna et al., 2011b; Iwinski, 2006; Li et al., 2015; Miura et al., 1998; Mundrey, 2009; Selig & Waters, 1994

**Experimental studies on ballast: deformation and degradation**
Aarsudikj et al., 2009; Brown et al., 2007; Chen et al., 2014b; Correia et al., 2007b; Indraratna et al., 1998, 2005, 2014; Ishikawa et al., 1997, 2011, 2014a; Kennedy et al., 2012; Lackenby et al., 2007; Le Pen & Powrie, 2011; Li & Selig, 1996; McDowell et al., 2003, 2004, 2005; Selig & Shaz, 1978; Suiker et al., 2005; Sun et al., 2016; Tutumluer et al., 2008; Woodward et al., 2014

**Track drainage and effects of ballast fouling**
Budiono et al., 2004; Darell, 2003; Dombrow et al., 2009; Ebrahimi et al., 2012, 2014; Feldman & Nissen, 2002; Giannakos, 2010; Hesse et al., 2014; Huang et al., 2009a; Indraratna et al., 2011a, 2013b; Trinh et al., 2012; Tutumluer et al., 2008

**Use of impact-attenuating synthetic mats**
Alves Ribeiro et al., 2015; Auersch, 2006; Dahlberg, 2010; Hanson & Singleton Jr., 2006; Indraratna et al., 2014c, 2014e; Insa et al., 2014; Johansson et al., 2008; Kaewunruen & Remennikov, 2015; Markine et al., 2011; Marschning & Veit, 2011; Nimblekar et al., 2012; Paixão et al., 2013; Schneider et al., 2011; Sol-Sánchez et al., 2014, 2015b, 2015a; Wang et al., 2016

**Subgrade performance, instability and implications on track response; Stabilisation of subgrade for railways**
Alves Costa et al., 2010; Cardoso et al., 2012; Correia & Cunha, 2014; Duong et al., 2013; Farris, 1970; Fatahi et al., 2015; Indraratna et al., 2010b; Li & Selig, 1996; Liu & Xiao, 2010; Miller et al., 2000; Potter & Cameron, 2005; Pretelletti et al., 2013; Read et al., 1994; Selig & Shaz, 1978

**Numerical modelling of track and DEM simulation**
Ahmed et al., 2015; Alves Costa et al., 2010, 2012; Chen et al., 2012; Correia & Cunha, 2014; D’Aguiar et al., 2012; Ferrillec & McDowell, 2012; Huang et al., 2009b, 2010; Huang & Tutumluer, 2011; Indraratna et al., 2012a, 2014a; Lu & McDowell, 2006, 2010; McDowell et al., 2006; Ngo et al., 2014, 2015; Quinn et al., 2010; Suiker & de Borst, 2003; Tutumluer et al., 2007, 2012

**Specific design functions including transition zones**
Coelho et al., 2011; Fernandes et al., 2012; Giner & López-Pita, 2009; Huang & Brennecke, 2013; Le Pen et al., 2014b; Li & Davis, 2005; Mishra et al., 2014a; Raymond, 1986; Varandas et al., 2014

**Track assessment using Image analysis**
Abadi et al., 2015; Ajayi et al., 2015; Fernlund, 2005; Le Pen et al., 2014a; Sun et al., 2014; Tutumluer et al., 2006, 2012

**Selected Practice Guides and Technical Specifications for ballasted tracks**

**Load distribution in track, moving loads and dynamic track analysis**
Choi, 2013; Correia et al., 2007a; Esveld, 2001; Ishikawa et al., 2011, 2014b; Kaewunruen & Remennikov, 2008; Monivoy et al., 2005; Powrie et al., 2007; Remennikov & Kaewunruen, 2008; Yang et al., 2009

**Theoretical aspects and constitutive modelling of ballast and sub-ballast**
Cui et al., 2013; Desai & Janardhanam, 1983; Einav, 2007a, 2007b; Indraratna et al., 2011b, 2012b, 2014b; Knothe & Grassie, 1993; Rowe, 1962; Suiker & de Borst, 2003; Tennakoon et al., 2015; Yang et al., 2008; Zhai et al., 2004, 2009

**Use of geosynthetics including geogrids, geotextiles and geocells**
Brown et al., 2007; Chen et al., 2014a; Dash & Shivadas, 2012; Fernandes et al., 2008; Indraratna & Nimblekar, 2013; Indraratna et al., 2010a, 2013a, 2014e; Leshchinsky & Ling, 2013; McDowell & Stickley, 2006; Mishra et al., 2014b; Qian et al., 2015; Raymond, 1986, 2002; Tatsuoka et al., 1992, 1996, 2008; Tutumluer et al., 2012

**Role of sub-ballast including capping layer and structural fills**
Chrismer & Davis, 2000; Fatahi et al., 2011; Fortunato et al., 2012; Haque et al., 2008; Indraratna et al., 2015; Radampola et al., 2008; Trani & Indraratna, 2010

**Ballast bonding (polyurethane) for improved track resiliency**
Dersch et al., 2010; Jubin, 2012; Keene et al., 2012, 2014; Kennedy et al., 2013; Woodward et al., 2007, 2014

**Field Instrumentation and performance verification**
Alves Costa et al., 2012; Choi, 2013; Indraratna et al., 2010a, 2010b, 2014d; Kaewunruen & Remennikov, 2015; Le Pen et al., 2014b; Read et al., 1994; Sánchez et al., 2014; Schneider et al., 2011; Woodward et al., 2007

**Aspects of track maintenance and scheduling**
Ebrahimi & Keene, 2011; Ferreira & Higgins, 1998; Higgins et al., 1999; Kaewunruen et al., 2015; Marschning & Veit, 2011; Peng et al., 2011; Quiroga & Schnieder, 2012; Thom, 2007; Woodward et al., 2007; Zhang et al., 2013

**Energy geotechnics and carbon footprint for track engineering**
Åkerman, 2011; Chang & Kendall, 2011; Federici et al., 2008; Kaewunruen et al., 2015; Kiani et al., 2008; Schwarz, 2008; UIC, 2013, 2015; Westin & Kågeson, 2012

Presentation Outline

- Ground Problems and Railroad Challenges
- Track Capacity for Fast Heavy Haul Demands
- Fundamental and Applied Research
- Field Applications and Performance Verification
- Industry Impact and Design Innovation
Introduction

- Demand for **freight and passenger transport** has increased in the past decade.
- Large repetitive loads from traffic cause **rapid degradation and deformation** of tracks.
- Inclusion of **resilient materials** (geosynthetics & shock mats) helps to enhance track response.

Figures from “Road and rail freight: competitors or complements?” Bureau of Infrastructure, Transport and Regional Economics, Australian Government Canberra.
Problems in Rail Track Substructure

- Ballast Crushing
- Poor Drainage
- Coal fouling
- Differential settlement (Courtesy, Prof AK Suiker)
- Void Clogging
- Subgrade Clay Pumping
- Poor Drainage
Track Buckling due to Insufficient Lateral (confining) pressure
Requirements for Heavy Haul Fast Tracks

1. Ballast: Reduced Degradation and lateral Movement for greater longevity.
2. Sub-ballast: Improved filtration and drainage under large cyclic loads.
3. Foundation soil (subgrade): Increased shear strength and reduced settlement.
4. Rail and Sleepers – Minimise Impact Damage at high speeds and axle loads


Use of geosynthetics in track for improved resiliency, better drainage and reduced deformation.

- Geotextile
- Bonded Geogrid
- PVD
- Placing of synthetic energy absorbing mats (SEAM)
Large-scale Cyclic Triaxial Rigs Built at UoW

- Prismoidal Triaxial Rig to Simulate a Track Section
  (Specimen: 800x600x600 mm)

- Cylindrical Triaxial Equipment
  (Specimen: 300 mm dia.x600 mm high)
Effect of Confining Pressure on Strain Behaviour of Ballast
Indraratna, Lackenby and Christie (2005), Geotechnique

Monotonic Loading

Cyclic Loading

Peak friction angle, $\phi_p$, of fresh ballast

Friction angle $\phi$ ($^\circ$)

Dilatancy (+)

Compression

Particle breakage

$\phi_f$ (excludes particle breakage and dilatancy)

$\phi_{fb}$ (includes breakage but excludes dilatancy)

$\sigma_3'$

$q_{max} = 500$ kPa

Volumetric Strain (%)

Axial Strain (%)

Effective confining pressure (kPa)

Confining Pressure (kPa)
Effect of Confining Pressure on Particle Degradation (Cyclic Loading)

Ballast Breakage Index (BBI)

Indraratna, Lackenby and Christie (2005)
Vol. 55(4), Geotechnique, ICE, UK.
Increasing Confining Pressure using: Intermittent Lateral Restraints or Embedded Winged Sleepers

Intermittent lateral restraints

Lateral restraints

Winged sleepers

Lackenby, Indraratna, McDowell and Christie (2007), Geotechnique
Lateral Resistance Offered by Shoulder Ballast

Preventing Particle Breakage – Computational Modelling

(Salim and Indraratna, 2000; Canadian Geotechnical Journal)

Before Loading

Voids

Ballast

After Loading

Asperity wear

New hairline micro-cracks

Sharp corners broken off

Broken particles fill voids (fouling)

\[
d\varepsilon_s^p = \frac{2\alpha\kappa}{M^2(1+e_i)} \left[ \frac{p}{p_{cs}} \left( 1 - \frac{p_{o(i)}}{p_{cs(i)}} \right) (9 + 3M - 2\eta^* M) \right] \eta d\eta
\]

\[
d\varepsilon_s^p = \frac{9(M - \eta)}{9 + 3M - 2\eta^* M} + \left( \frac{B}{p} \right) \left[ \frac{\chi + \mu(M - \eta^*)}{9 + 3M - 2\eta^* M} \right]
\]
Constitutive model: Critical State capturing particle breakage


\[ M_c = M_{c0} - \left[ 1 - \exp\left( -\alpha \cdot BBI \right) \right] \]

*\( M_{c0} \) is critical state stress ratio for \( BBI = 0 \)

\[ \nu_c = \Gamma_{ref} - a \cdot \exp\left( b \cdot BBI \right) - \lambda \ln \rho' \]
Effect of frequency on the axial strain of ballast


Range I: Plastic shakedown (5 Hz ≤ f ≤ 20 Hz)
Range II: Plastic shakedown followed by Ratcheting (30 Hz ≤ f ≤ 50 Hz)
Range III: Plastic collapse (f = 60 Hz)

\[ q_{\text{max,cyc}} = 230 \text{ kPa}; \]
\[ q_{\text{min,cyc}} = 45 \text{ kPa}; \]
\[ \sigma_3' = 30 \text{ kPa} \]
Dynamic Track Analysis and Substructure Response

Transient vertical deflection of typical sleeper and development of the ground Mach Cone


Impact loading that leads to track damage

Different wheel and rail irregularities contribute to Impact loading

- Worn wheel surface
- Worn rail surface
- Wheel flats
- Rail corrugation
- Bad welds, joints and switches
- Unsupported sleepers

Field Measurements

Cyclic stresses transmitted to the ballast by coal train with 100 ton wagons having wheel irregularities

Indraratna et al. (2010). JGGE, ASCE
Use of Energy Absorbing Rubber Mats to Prevent Impact Damage

<table>
<thead>
<tr>
<th>Subgrade type</th>
<th>Location of shock mat</th>
<th>Ballast Breakage Index (BBI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without shock mat</td>
<td></td>
</tr>
<tr>
<td>Stiff</td>
<td>-</td>
<td>0.170</td>
</tr>
<tr>
<td>Soft</td>
<td>-</td>
<td>0.080</td>
</tr>
<tr>
<td></td>
<td>With Shock mat</td>
<td></td>
</tr>
<tr>
<td>Stiff</td>
<td>Above ballast</td>
<td>0.145</td>
</tr>
<tr>
<td></td>
<td>Below ballast</td>
<td>0.129</td>
</tr>
<tr>
<td>Stiff</td>
<td>Above &amp; below ballast</td>
<td>0.091</td>
</tr>
<tr>
<td>Soft</td>
<td>Above ballast</td>
<td>0.055</td>
</tr>
<tr>
<td></td>
<td>Below ballast</td>
<td>0.056</td>
</tr>
<tr>
<td>Soft</td>
<td>Above &amp; below ballast</td>
<td>0.028</td>
</tr>
</tbody>
</table>

Role of Ballast Fouling on Track Performance

Void Contaminant Index (VCI) proposed by UOW

\[
VCI = \left(1 + e_f\right) \times \frac{G_{s.b}}{e_b} \times \frac{M_f}{G_{s.f} M_b} \times 100
\]

- \(e_b\) = Void ratio of clean ballast
- \(e_f\) = Void ratio of fouling material
- \(G_{s.b}\) = Specific gravity of clean ballast
- \(G_{s.f}\) = Specific gravity of fouling material
- \(M_b\) = Dry mass of clean ballast
- \(M_f\) = Dry mass of fouling material

Impeded Track Drainage due to Ballast Contamination

Large-scale permeability test apparatus

Hydraulic Conductivity ($k$) of fouled ballast

\[ k = \frac{k_b \times k_f}{k_f + \frac{VCI}{100} \times (k_b - k_f)} \]

- $k_b$ = Hydraulic conductivity of clean ballast
- $k_f$ = Hydraulic conductivity of fouling material

Variation of hydraulic conductivity vs. Void Contaminant Index
Recommended New Railway Ballast Grading

- **Recommended Grading**
- **Australian Standards (AS 2758.7)**

- $C_u = 2.2 - 2.6$
- $C_u = 1.5 - 1.7$
DEM Modelling of Railway Ballast under Monotonic and Cyclic Triaxial Loading


Practical Implications: Train Speed vs Particle Breakage

Hossain, Indraratna, Darve, & Thakur (2007). J. of Geomechanics, ASCE

Particle Breakage near the top plate

Model particle shapes and sizes

Initial assembly

Axial compression

Breakage zone

Ballast Breakage Index, BBH (%) vs Frequency of Loading, f (Hz)

- Corner breakage
- Densification without much breakage
- Splitting of particles

N = 1000, 10000, 100000
DEM Model with Different Parts of Track Fouled by Coal Dust

Modelling particle angularity in DEM

Spherical particle → 2–particle clump → 5–particle clump → 10–particle clump

Ngo, Indraratna, and Rujikiatkamjorn (2014). Computers & Geotechnics
DEM Modelling Geogrid-reinforced Ballast under Shearing Loads

Comparison of shear stress and displacements for DEM simulation of reinforced ballast

DEM Model for Geogrid-reinforced Ballast under Direct Shearing
Geogrids for preventing particle movement and breakage

<table>
<thead>
<tr>
<th>Geogrid type</th>
<th>Aperture shape</th>
<th>Aperture size (mm)</th>
<th>$T_{ult}$ (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>Square</td>
<td>$38 \times 38$</td>
<td>30</td>
</tr>
<tr>
<td>G2</td>
<td>Triangle</td>
<td>36</td>
<td>19</td>
</tr>
<tr>
<td>G3</td>
<td>Square</td>
<td>$65 \times 65$</td>
<td>30</td>
</tr>
<tr>
<td>G4</td>
<td>Rectangle</td>
<td>$44 \times 42$</td>
<td>30</td>
</tr>
<tr>
<td>G5</td>
<td>Rectangle</td>
<td>$36 \times 24$</td>
<td>30</td>
</tr>
<tr>
<td>G6</td>
<td>Square</td>
<td>$33 \times 33$</td>
<td>40</td>
</tr>
<tr>
<td>G7</td>
<td>Rectangle</td>
<td>$70 \times 110$</td>
<td>20</td>
</tr>
</tbody>
</table>

Field Trial on Instrumented Track near Wollongong (Bulli)

Details of instrumented track

Section of ballasted track bed with geocomposite layer
Geocomposite layer (geogrid+geotextile) before ballast placement

Ballast placement over the geocomposite

Recycled Ballast
from Chullora Quarry, Sydney

Fresh Ballast
Bombo Quarry, Wollongong

Bonded Geogrid
Field Instrumentation – Town of Bulli

Settlement pegs placed near edge of sleeper

Concrete Sleeper

Displacement Transducers

Ballast

Capping layer

Subgrade

Settlement peg placed underneath rail

Settlement pegs installed at ballast-capping interface

Displacement transducers installed at sleeper-ballast interface
Field Monitoring: Town of Singleton near Newcastle (NSW)

Geogrid layer placed above the capping

Settlement pegs placement in the track

Mudies Creek Bridge pressure cells installation

Placing of shock mat on bridge deck, Feb. 2010
Role of Geosynthetics - Field Monitoring of Track Response

Singleton Track: Indraratna et al. (2014). ICE Proc. Ground Improvement, 167(1), 24-34

Bulli Track

- Average vertical strain of ballast, $\varepsilon_{avg}$ (%)
- Average vertical deformation of ballast, $S_{v}$ (mm)

Singleton Track

- Type of Section
- Aperture Size (mm)
  - Geogrid 1: 44 x 44
  - Geogrid 2: 65 x 65
  - Geogrid 3: 40 x 40
  - Geocomposite: 31 x 31

Recycled ballast: broadly-graded compared to uniform fresh ballast – so performed better!

Optimum aperture size of geogrids is about $1.2D_{50}$ of ballast.
Finite Element Analysis of Track: 2D Plane Strain

Effective confining pressure $\sigma_3' = 50$ kPa

Deviator Stress, $q = \sigma_1' - \sigma_3'$ (kPa)

Axial Strain, $\varepsilon_a$ (%)
Track transverse section deformation

Deformed mesh
(Step 0)
Track longitudinal section deformation
FEM modelling of Transition Zones

Performance assessment and numerical solutions for transition zones – approaching bridge deck

Seara and Correia (2010), Semana de Engenharia Escola de Engenharia da Universidade do Minho.
Cyclic Response of Soft Subgrade with Vertical Drains under High Speed Rail Conditions

Indraratna, Attya and Rujikiatkamjorn (2009) JGGE, ASCE, Vol. 135(6), 835-839

Specimens without PVD fail very quickly as the excess pore pressure rises rapidly!
Short PVD Applications to Rail Embankment at Sandgate and FEM Analysis

Class A Prediction (Indraratna et al, ASCE, JGGE, 2010)
Geocell stabilisation of capping layer to minimise mud pumping
Indraratna et al. (2015). JGGE, ASCE, Vol. 141(1), 1-16

Geocells provide confinement to the capping layer and prevent lateral spreading
Interaction of Trees and Ground for Stabilising Rail Corridors

Indraratna et al. (2006), ICE Proceedings, Vol. 159, 77-90
Laboratory and Field Measurements: Role of Soil Suction

Tensiometer - suction
Computational Tree Root Model Validation

Example: A single, 14m high lime tree in U.K (Biddle 1983)

Contours of volumetric soil moisture content reduction (%) in the vicinity of a lime tree

Field measurements by Biddle (1983)

Predictions by Indraratna et al. (2006)

FEM modeling of a single native tree

Contours of volumetric soil moisture content reduction (%) in the vicinity of a lime tree
Track Condition Monitoring - Ground Penetration Radar (GPR)

Lab testing (Uni. of Wollongong)

Field testing (Wollongong)
GPR Lab and Field Testing

Bottom of ballast layer

Fouled, high moisture content

Slightly fouled, low moisture content

Clean, low moisture content
New Design Procedures – UoW Method
(Supplementary Method of Analysis of Rail Track – SMART)

Key features:

- a set of MATLAB subroutines: design and analysis of track based on research outcomes;
- stand-alone computer application: user-friendly interfaces for data input and output.
Cone Penetration Test and Trial Pit

Mixed metastable sands with fine sediments (organic) at shallow depths followed by undisturbed coarser sand at greater depths.
Ground condition assessment using cone penetration test (CPT)

Observe the coconut palm trees!
Conclusions and Recommendations

• Geosynthetics: increase internal **confining pressure** and **reduce particle movement** and **breakage** at elevated train speeds.

• **Computational FEM & DEM models** to predict track **degradation** with time, (c.f. empirical assessments).

• **Energy Absorbing Shock Mats** for minimizing impact damage

• **Application of PVDs** for improving soft subgrade soils and prevent mud pumping

• **Condition Monitoring via Field trials**: insight to complex track behaviour - performance verification.

• **Native Vegetation** – Green Corridors provide increased subgrade shear strength and less settlement

• **Ground Penetration Radar** can identify potential “adverse patterns” of hazards in track.
Acknowledgment

- Australian Research Council (ARC)
- ISSMGE-TC202: Transport Geotechnics
- Centre for Geomechanics and Railway Engineering, University of Wollongong, Australia
- Past and Present research students, Research Associates and Technical Staff
- Industry Organisations: RailCorp (NSW), ARTC, QLD Rail, ARUP, Coffey Geotechnics, Douglas Partners. Roads & Traffic Authority, QLD Main Roads, Port of Brisbane Corporation, Port Kembla Port Corporation