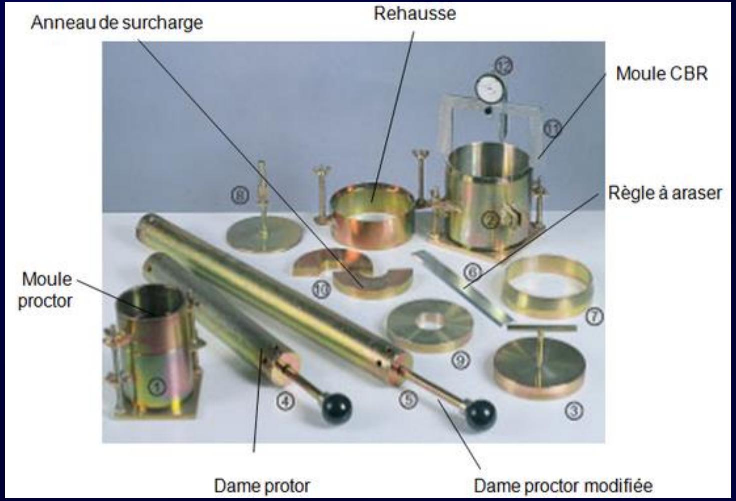
1ST RALPH PROCTOR LECTURE OF ISSMGE - 2016

Railroad Performance with Special Reference to Ballast and Substructure Characteristics

Ralph Roscoe Proctor
1894-1962



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Centre for Geomechanics and Railway Engineering GRE

3rd ICTG 2016
04-07 September 2016, Guimarães, Portugal

SIMSG ISSMGE

UNIVERSITY OF WOLLONGONG

Rail Geotechnics in a Nutshell – Key Themes

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

2 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; Momoya et al., 2005; Powrie et al., 2007; Remennikov & Kaewunruen, 2008; Yang et al., 2009

3 Experimental studies on ballast: deformation and degradation
Aursudkij et al., 2009; Brown et al., 2007; Chen et al., 2014b; Correia et al., 2007b; Indraratna et al., 1998, 2005, 2014f; 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 & Sluz, 1978; Suiker et al., 2005; Sun et al., 2016; Tutumluer et al., 2008; Woodward et al., 2014

4 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, 2014f; Knothe & Grassie, 1993; Rowe, 1962; Suiker & de Borst, 2003; Tennakoon et al., 2015; Yang et al., 2008; Zhai et al., 2004, 2009

5 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

6 Use of geosynthetics including geogrids, geotextiles and geocells
Brown et al., 2007; Chen et al., 2014a; Dash & Shivadas, 2012; Fernandes et al., 2008; Indraratna & Nimbalkar, 2013; Indraratna et al., 2010a; 2013a; 2014e; 2015; 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

7 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; Marschnig & Veit, 2011; Nimbalkar et al., 2012; Paixão et al., 2015; Schneider et al., 2011; Sol-Sánchez et al., 2014, 2015b, 2015a; Wan et al., 2016

8 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

9 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; Preteseille et al., 2013; Read et al., 1994; Selig & Sluz, 1978

10 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

11 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; Ferellec & 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

12 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

13 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

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

15 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

16 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

17 Selected Practice Guides and Technical Specifications for ballasted tracks
AREMA, 2003, 2015; British Standards Institution, 2003; Canadian National Railway, 2015; German Institute for Standardisation, 2008, 2013; Indian Railway Specification, 2004; International Union of Railways, 2008; IRPWM, 2004; Japanese Standards Association, 2014; Railtrack, 2000; Standards Australia, 2015

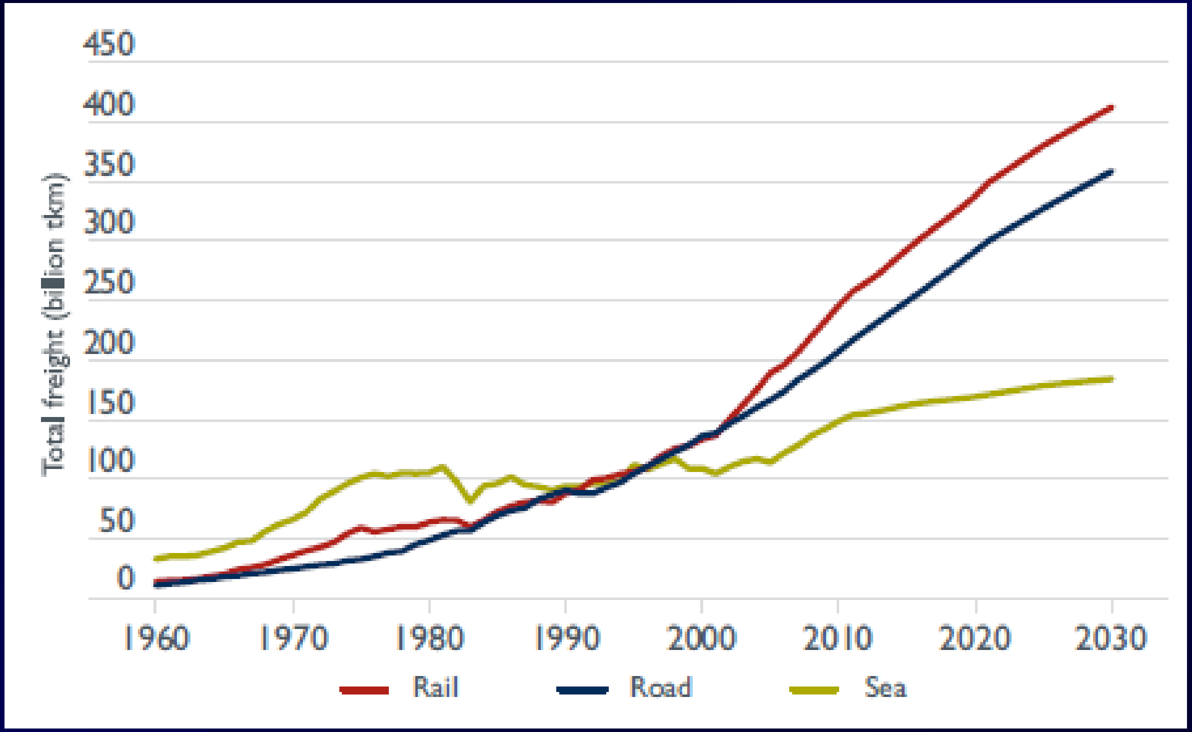
Ref: Table 1 - Indraratna (2016), 1st Proctor Lecture of ISSMGE, Transportation Geotechnics, Vol. 7: 74–114.

Presentation Outline

- Ground Problems and Railroad Challenges
- Track Capacity for Fast Heavy Haul Demands
- Fundamental and Applied Research
- Field Appilcations 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


Subgrade Clay Pumping


Coal fouling


Void Clogging


Differential settlement (Courtesy, Prof AK Suiker)


Poor Drainage

Track Buckling due to Insufficient Lateral (confining) pressure

Requirements for Heavy Haul Fast Tracks

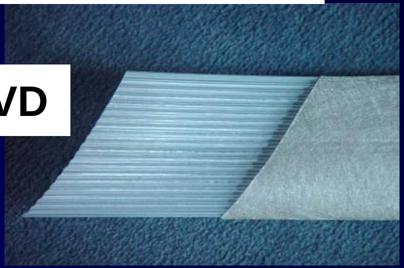
1. Ballast: Reduced Degradation and lateral Movement for greater longevity.
2. Sub-ballast: Improved filtration and drainage under large cyclic loads.
3. Foundation soil (subgrade): Increased shear strength and reduced settlement.
4. Rail and Sleepers – Minimise Impact Damage at high speeds and axle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

OUTCOME: New Standards, Design Innovation and Construction Alternatives.

Placing of synthetic energy absorbing mats (SEAM)

Geotextile

Bonded Geogrid



PVD

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

Large-scale Cyclic Triaxial Rigs Built at UoW

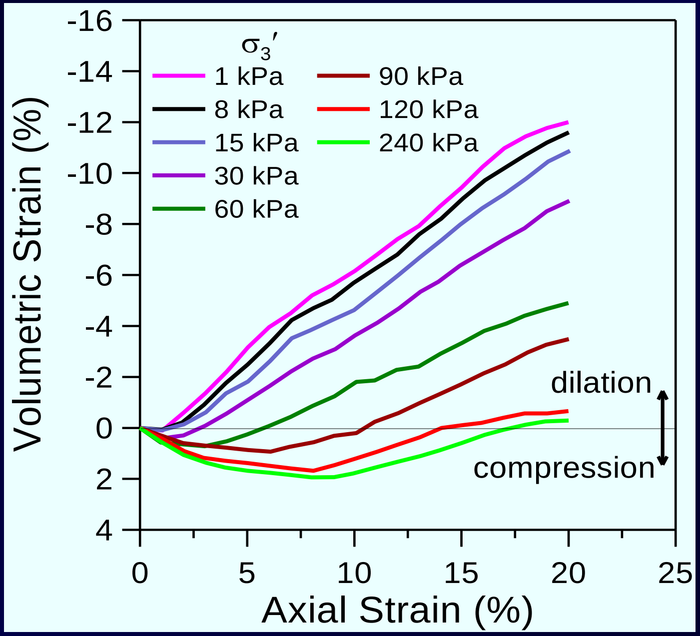
Prismoidal Triaxial Rig to Simulate a Track Section
(Specimen: 800x600x600 mm)

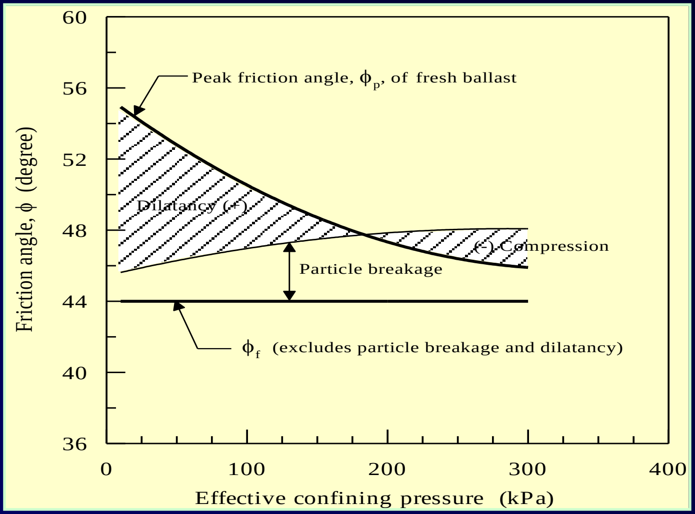
Cylindrical Triaxial Equipment
(Specimen: 300 mm dia.x600 mm high)

Effect of Confining Pressure on Strain Behaviour of Ballast

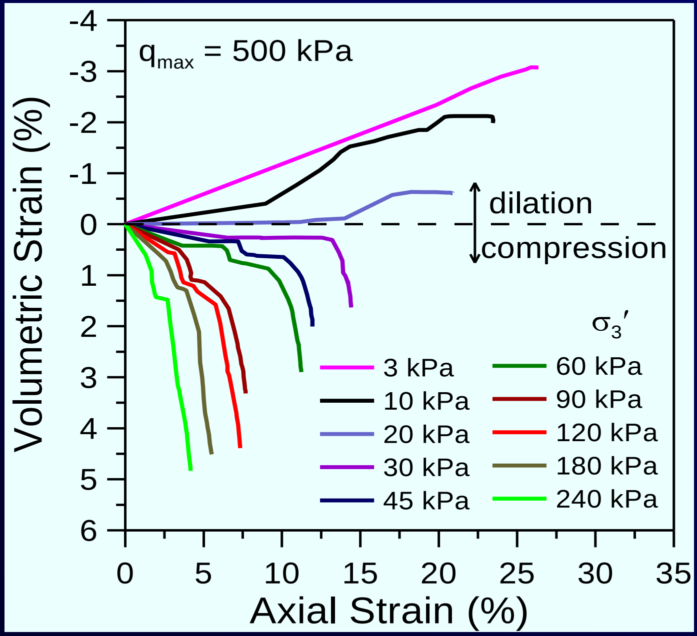
Indraratna, Lackenby and Christie (2005), Geotechnique

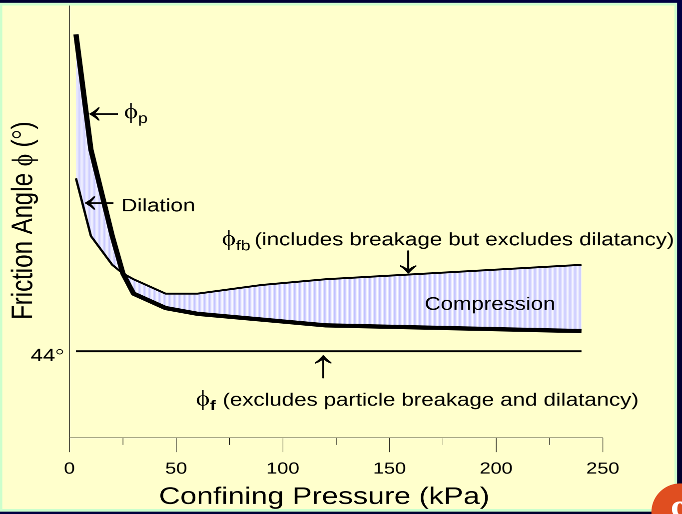
Monotonic Loading



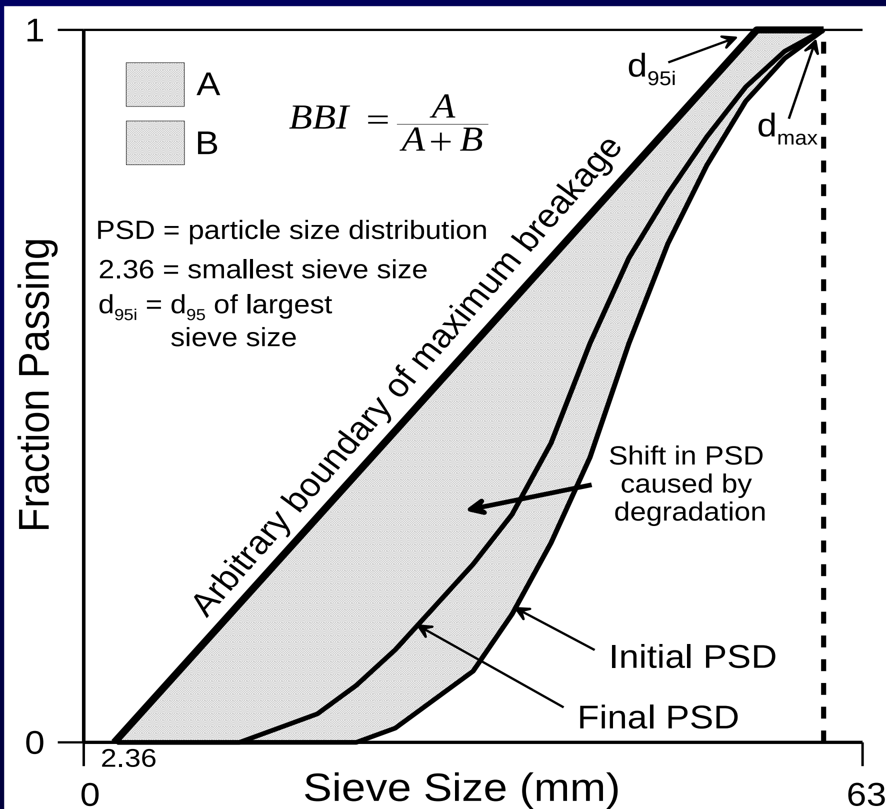


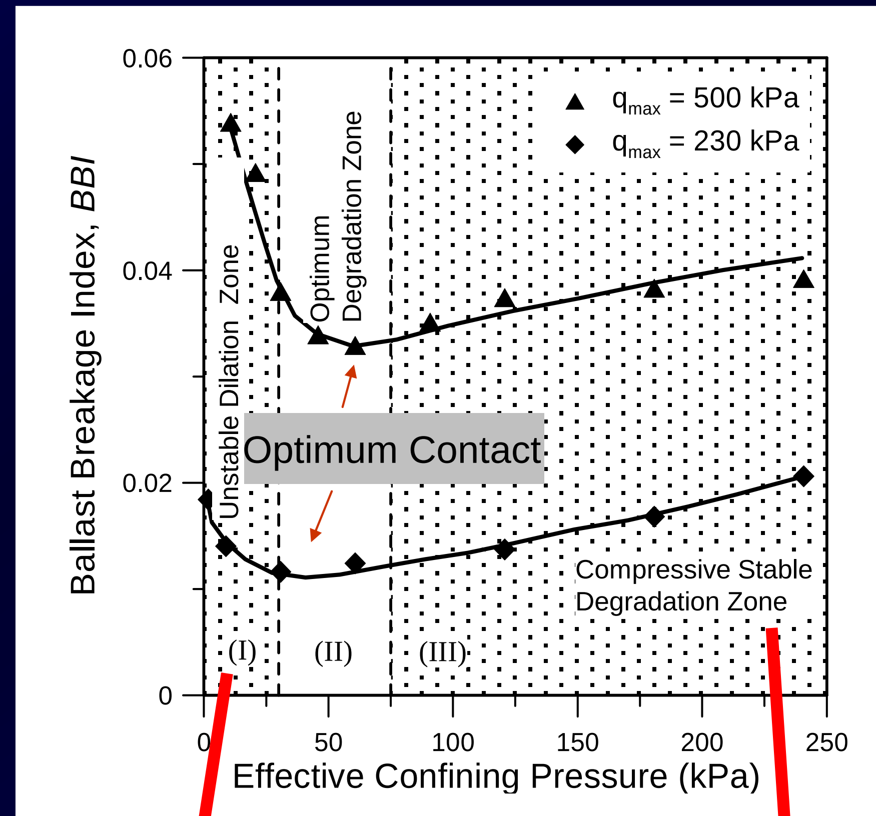
Cyclic Loading



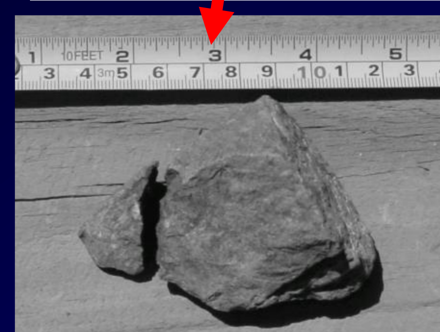


Effect of Confining Pressure on Particle Degradation (Cyclic Loading)





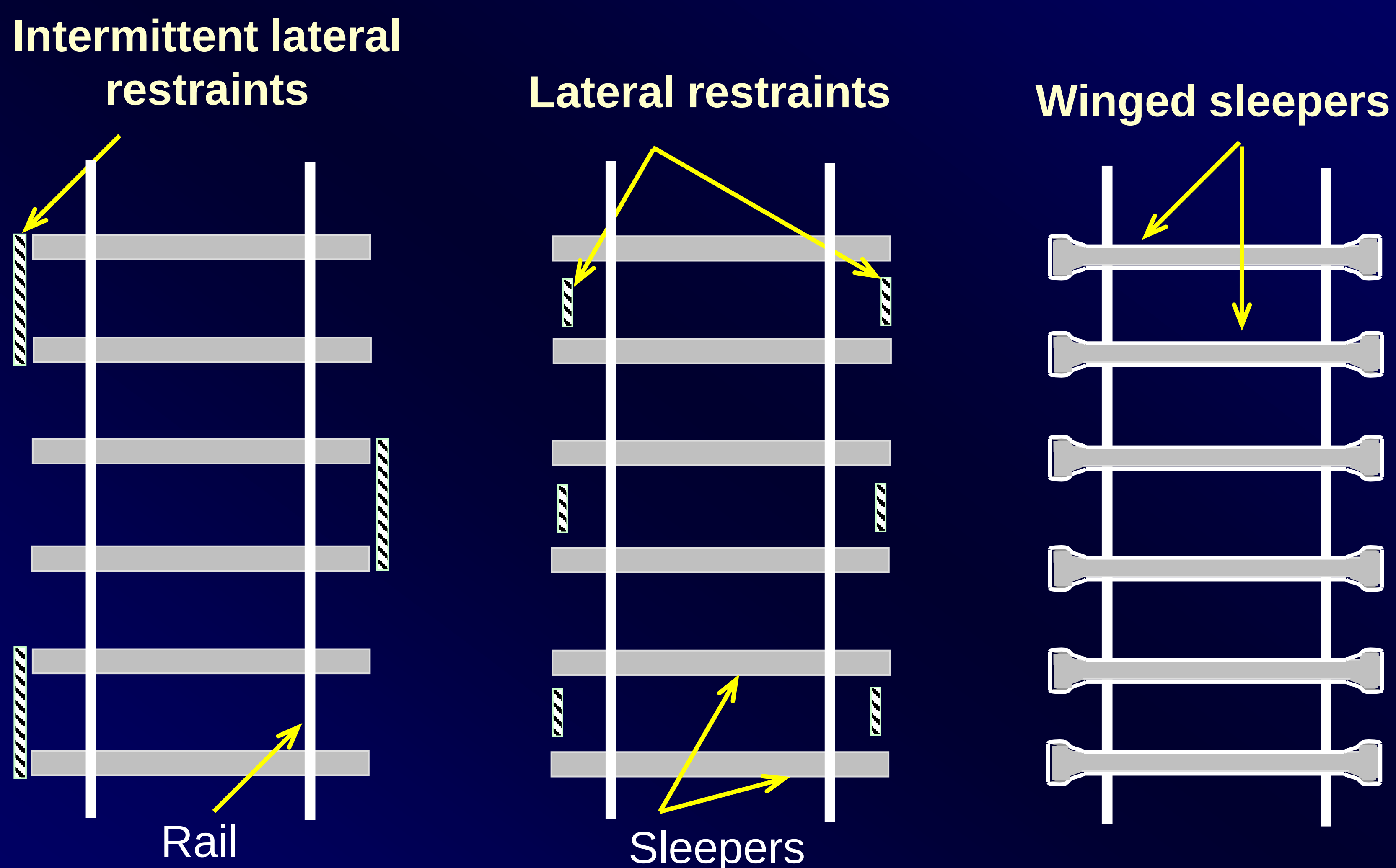
Ballast Breakage Index (BBI)



Indraratna, Lackenby and Christie (2005)

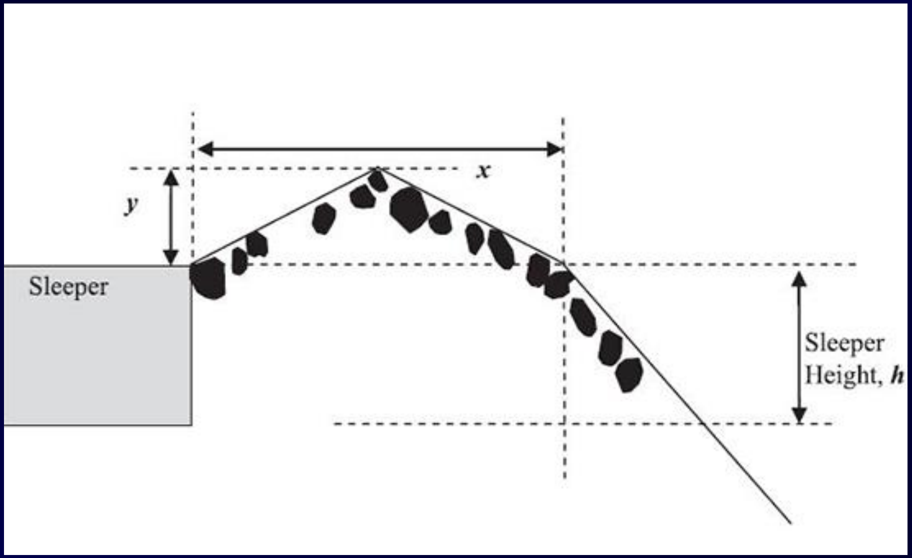
Vol. 55(4), Geotechnique, ICE, UK.

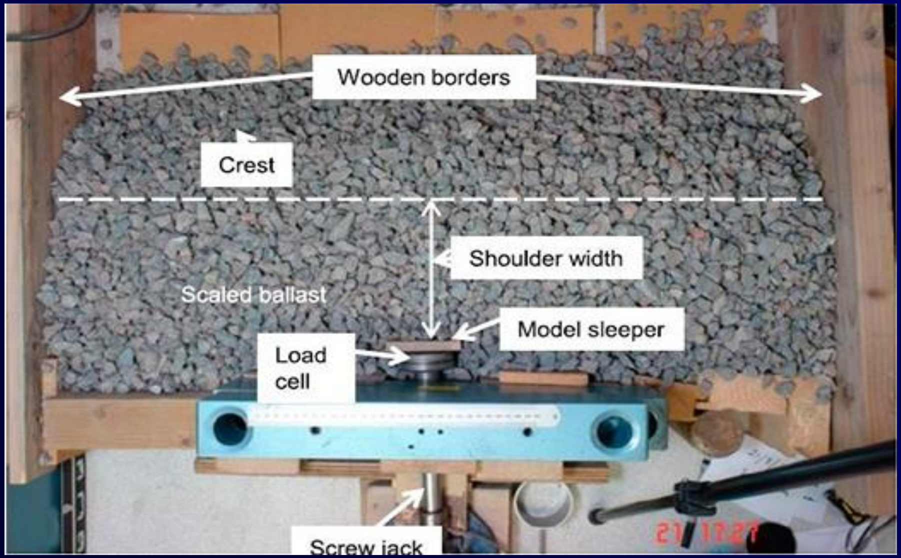
Increasing Confining Pressure using: Intermittent Lateral Restraints or Embedded Winged Sleepers

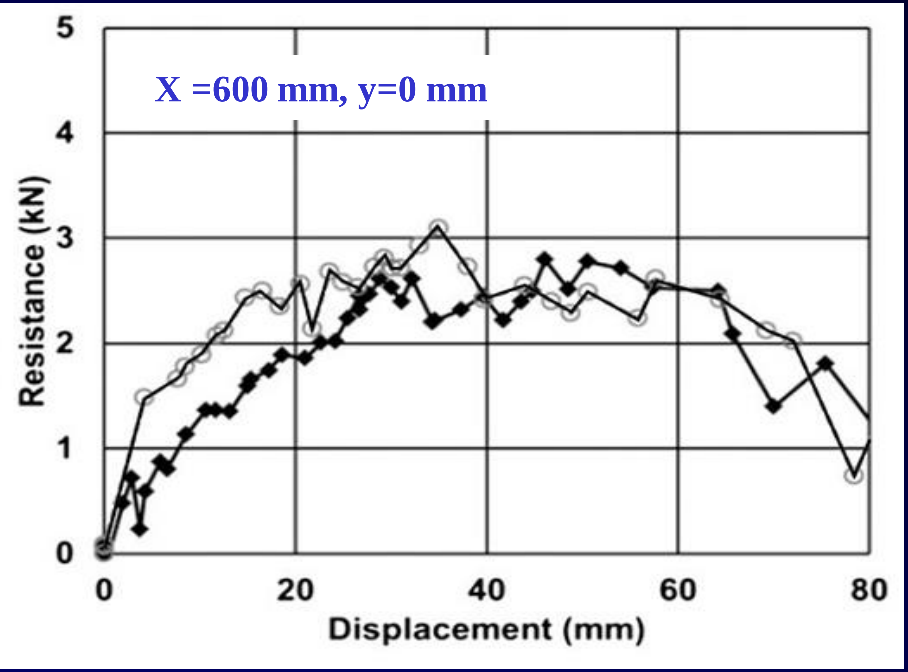


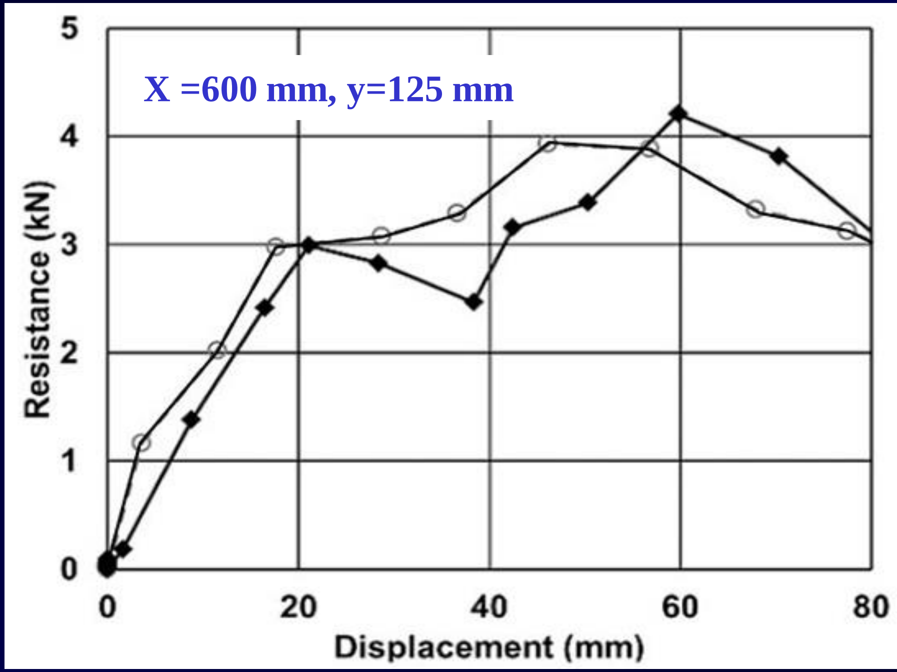
Lackenby, Indraratna, McDowell and Christie (2007), Geotechnique

Lateral Resistance Offered by Shoulder Ballast









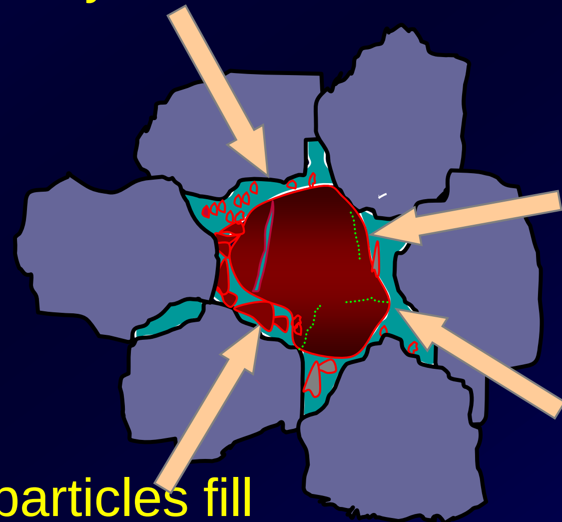
Le Pen, Bhandari, and Powrie (2014). JGGE, ASCE, 140(5).

Preventing Particle Breakage – Computational Modelling

(Salim and Indraratna, 2000; Canadian Geotechnical Journal)

Before Loading

After Loading



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

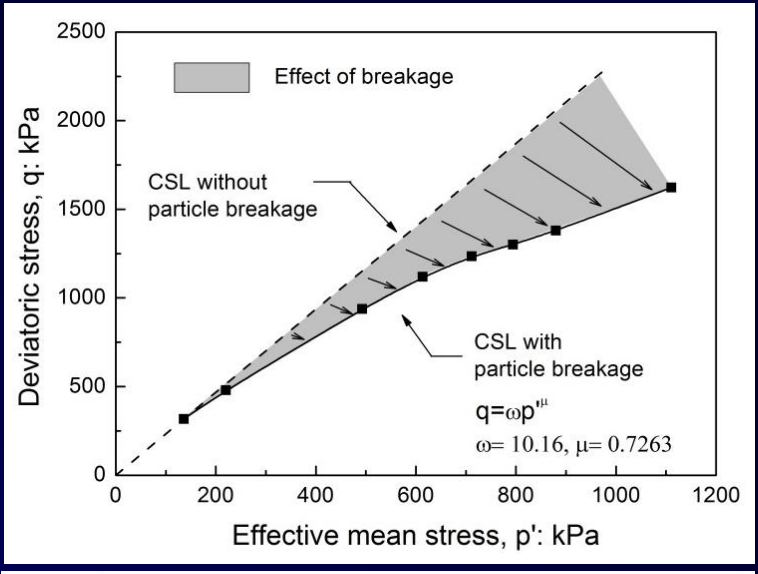
$$\frac{d\varepsilon_v^p}{d\varepsilon_s^p} = \frac{9(M-\eta)}{9+3M-2\eta^* M} + \left(\frac{B}{p}\right)\left[\frac{\chi+\mu(M-\eta^*)}{9+3M-2\eta^* M}\right]$$

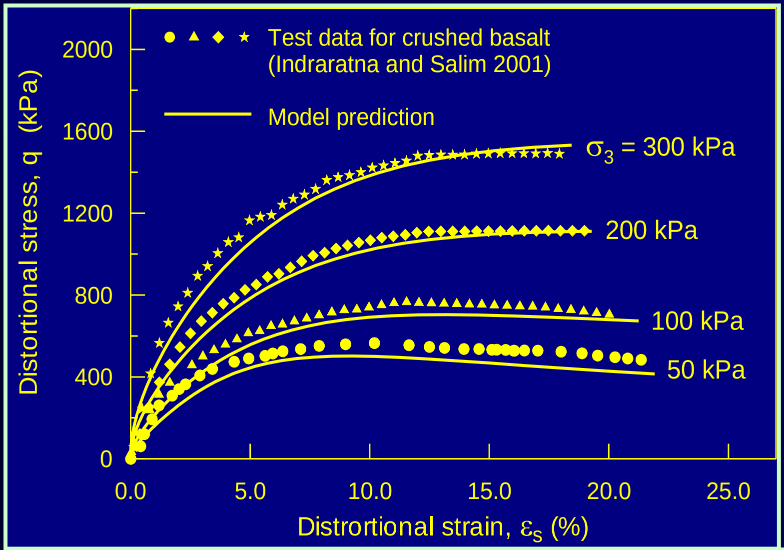
Constitutive model: Critical State capturing particle breakage

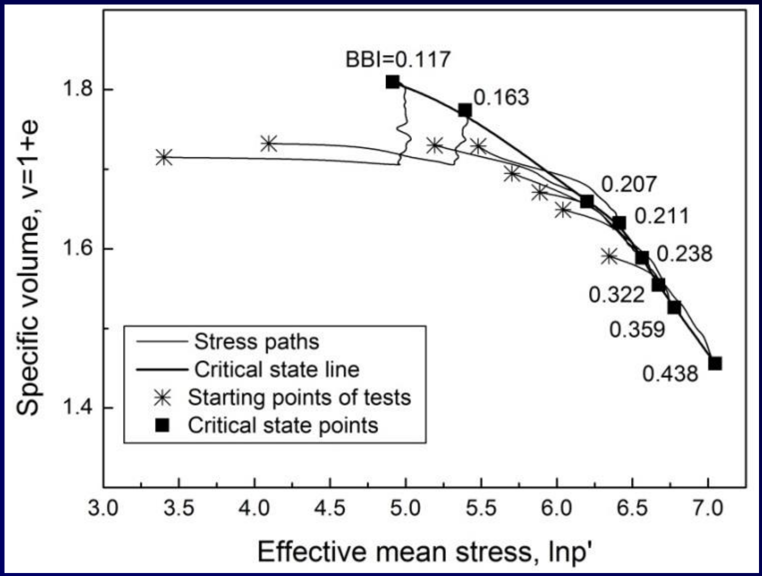
Indraratna, Sun & Nimbalkar (2014), Canadian Geotechnical Journal, Vol. 52(1), 73-86

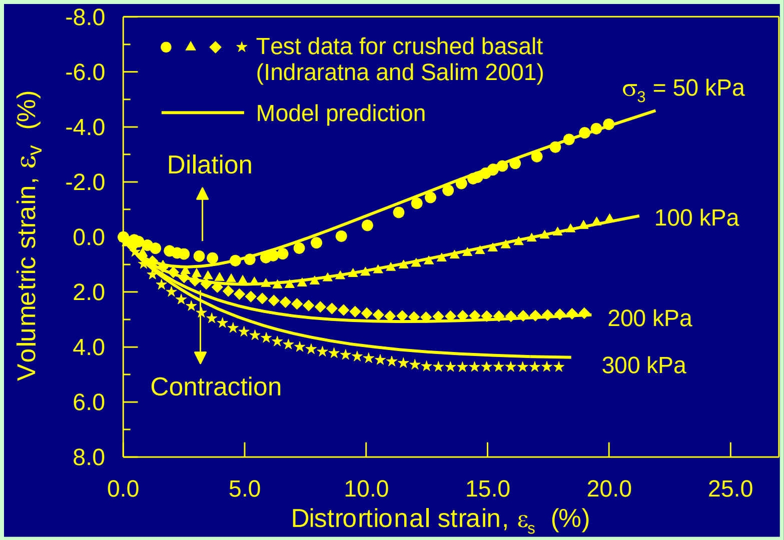
$$M_c = M_{c0} - \left[1 - exp\left(-\alpha \cdot BBI\right)\right]$$

M_{c0} is critical state stress ratio for BBI = 0





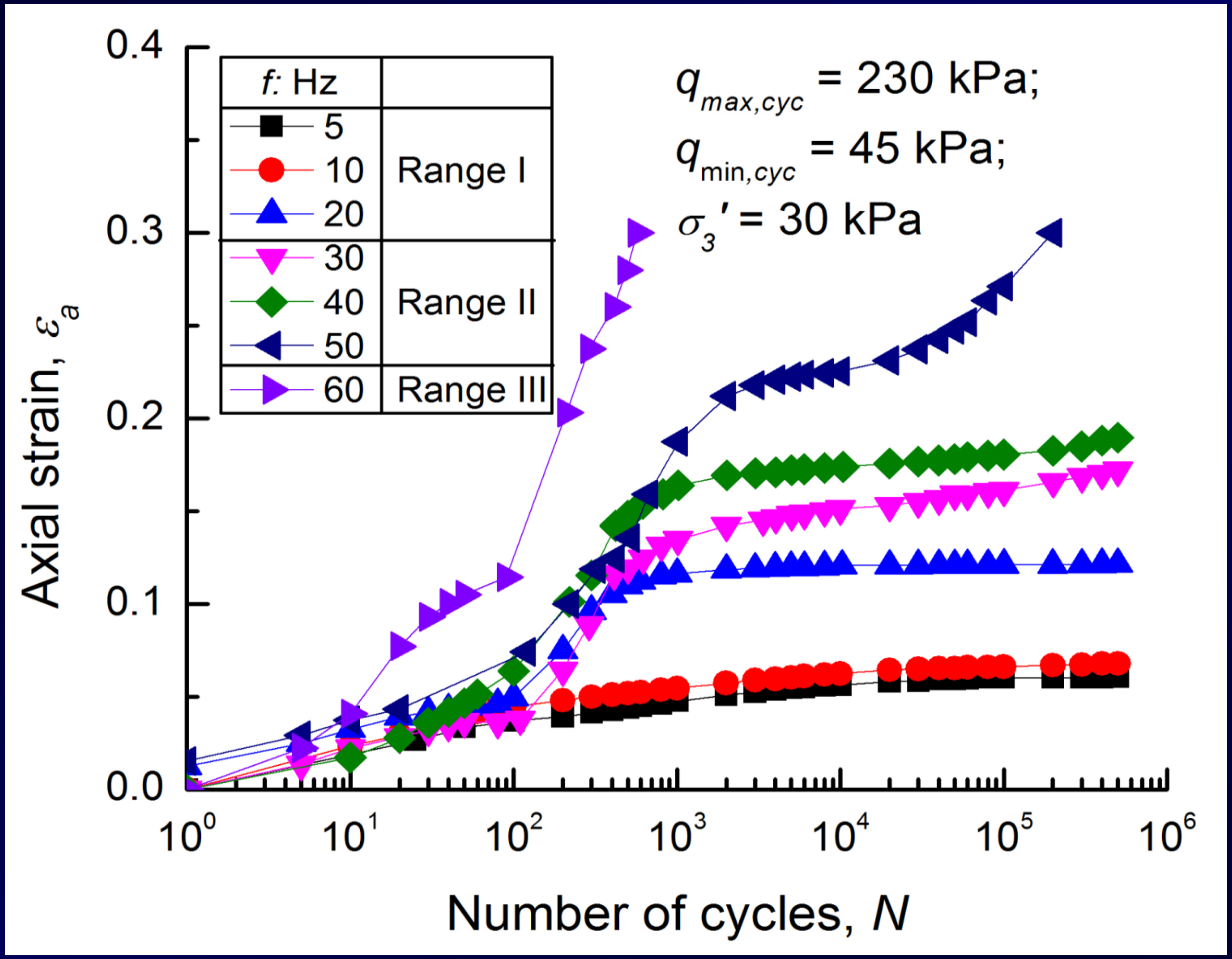




$$\upsilon_c = \Gamma_{ref} - a \cdot exp\left(b \cdot BBI\right) - \lambda \ln p'$$

Effect of frequency on the axial strain of ballast

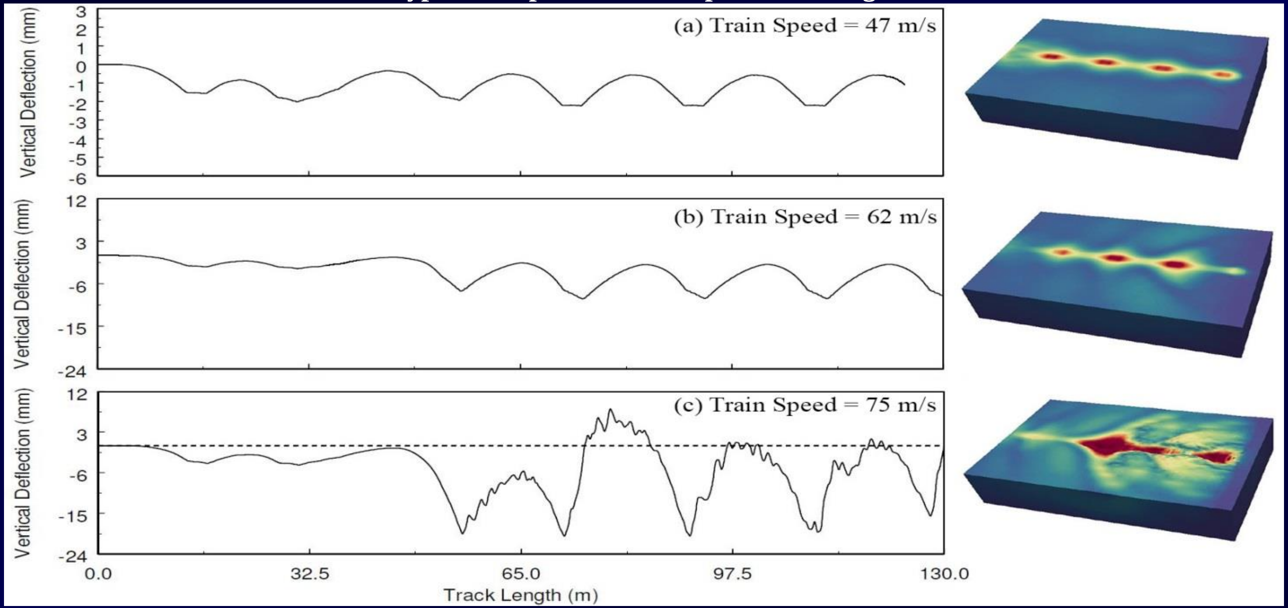
Sun, Q., Indraratna, B. & Nimbalkar, S. (2014). Géotechnique, Vol. 64(9), 746-751.



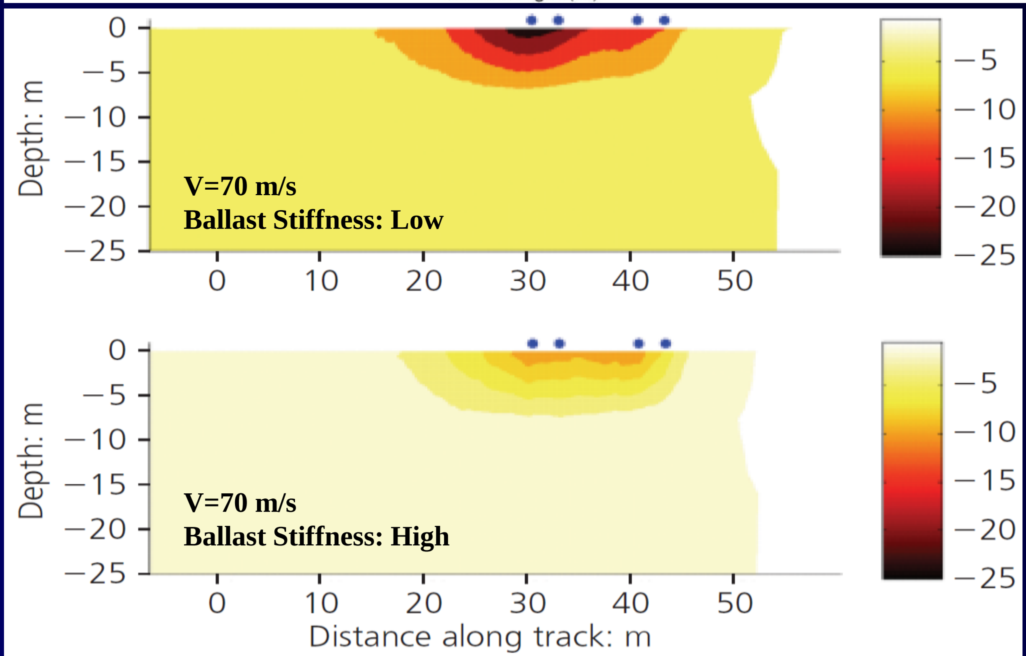
Range I: Plastic shakedown (5Hz ≤ f ≤ 20 Hz)
Range II: Plastic shakedown followed by Ratcheting (30 Hz ≤ f ≤ 50 Hz)
Range III: Plastic collapse (f = 60 Hz)

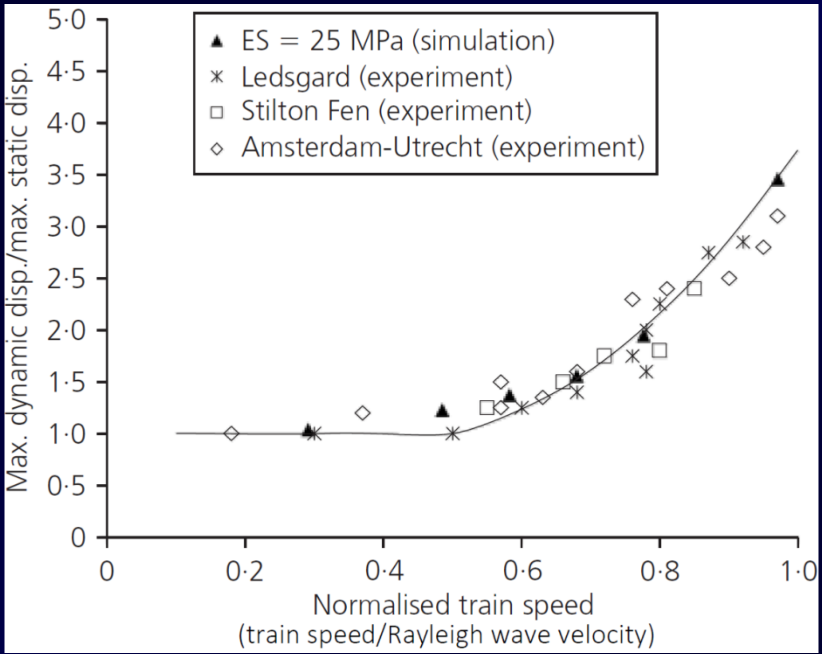
Dynamic Track Analysis and Substructure Response

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



Woodward, Laghrouche, and El-Kacimi (2013). *11th International Conference on Vibration Problems*, Lisbon, Portugal.





Banimahd, Woodward, Kennedy, and Medero (2013). Proc. ICE-Transport, 166(2): 113-123.

Impact loading that leads to track damage

Different wheel and rail irregularities contribute to Impact loading

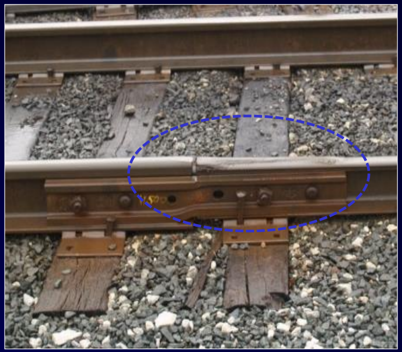
Worn wheel surface

Worn rail surface

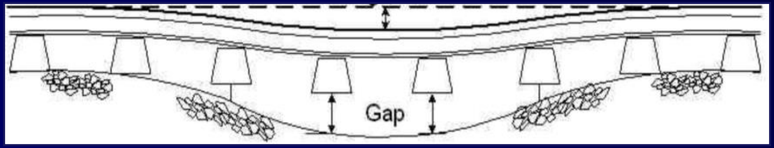
Wheel flats

Rail corrugation

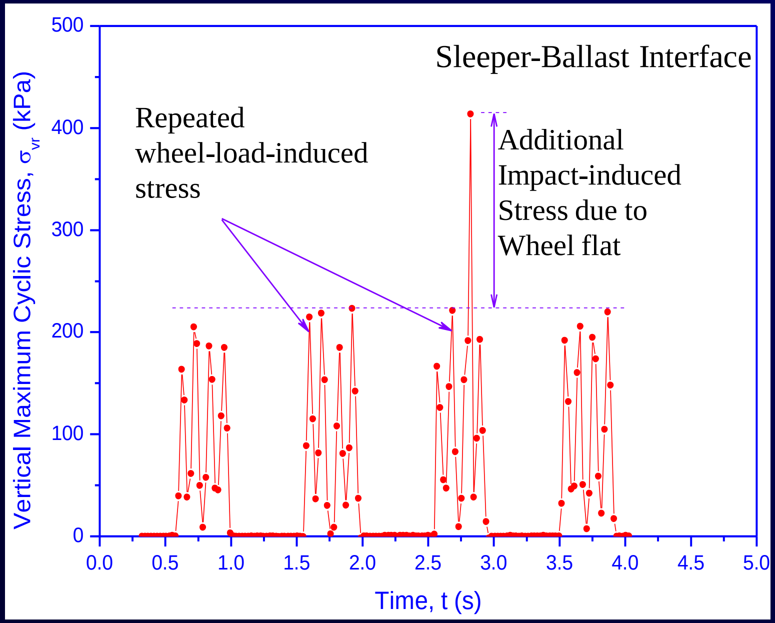
Bad welds, joints and switches



Unsupported sleepers



Field Measurements



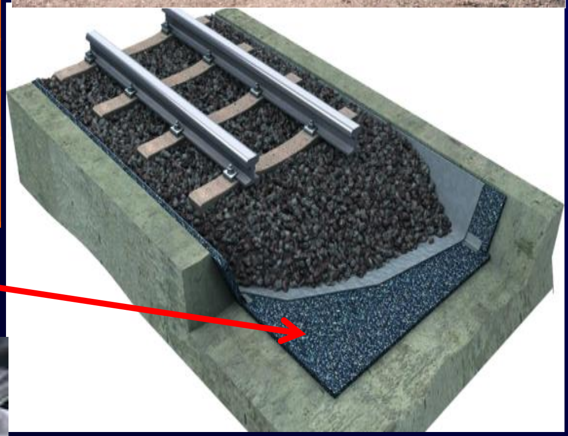
Cyclic stresses transmitted to the ballast by coal train with 100 ton wagons having wheel irregularities

Indraratna et al. (2010). JGGE, ASCE

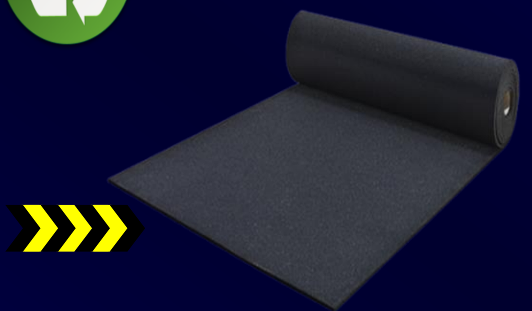
Use of Energy Absorbing Rubber Mats to Prevent Impact Damage

Subgrade type	Location of shock mat	Ballast Breakage Index (BBI)
Without shock mat		
Stiff	**-**	**0.170**
Soft	**-**	**0.080**
With Shock mat		
Stiff	**Above ballast**	**0.145**
Stiff	**Below ballast**	**0.129**
Stiff	**Above & below ballast**	**0.091**
Soft	**Above ballast**	**0.055**
Soft	**Below ballast**	**0.056**
Soft	**Above & below ballast**	**0.028**

Shock Mat

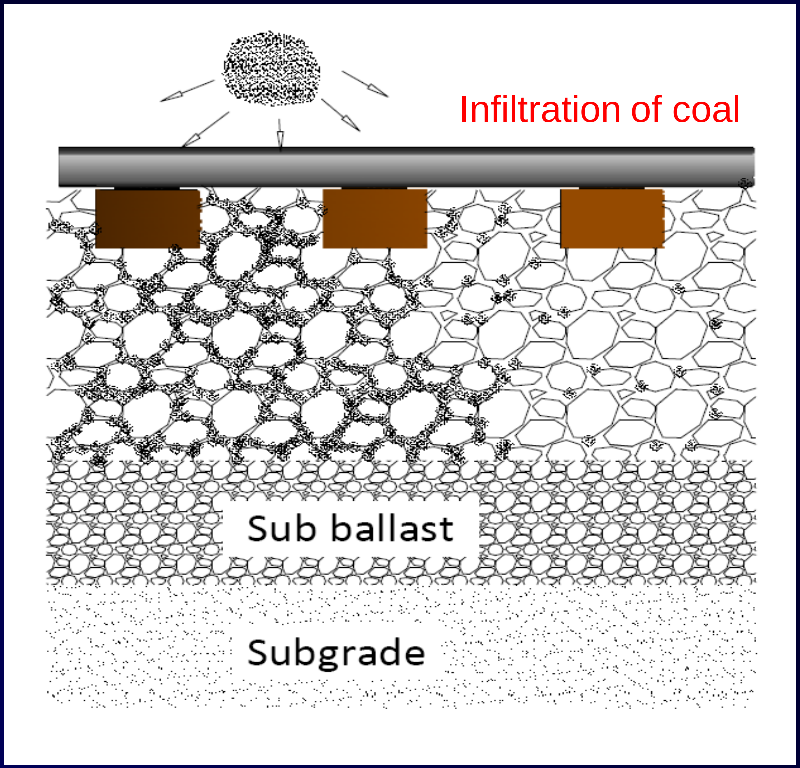


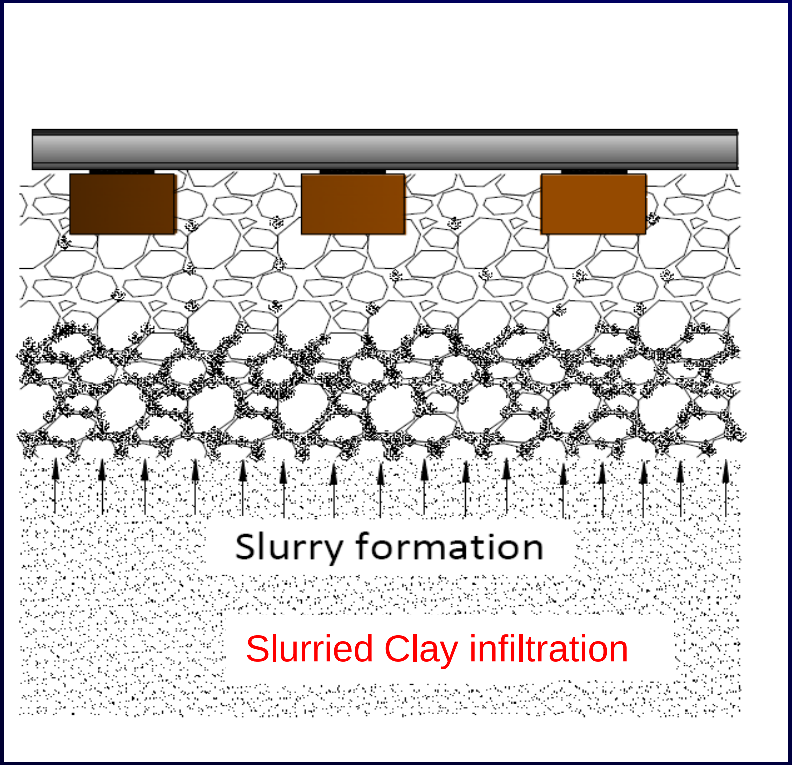
WASTE TURNS INTO VALUE



Nimbalkar, Indraratna, Dash & Christie (2012). JGGE, ASCE, 138(3): 281-294.

Role of Ballast Fouling on Track Performance





Void Contaminant Index (VCI) proposed by UOW

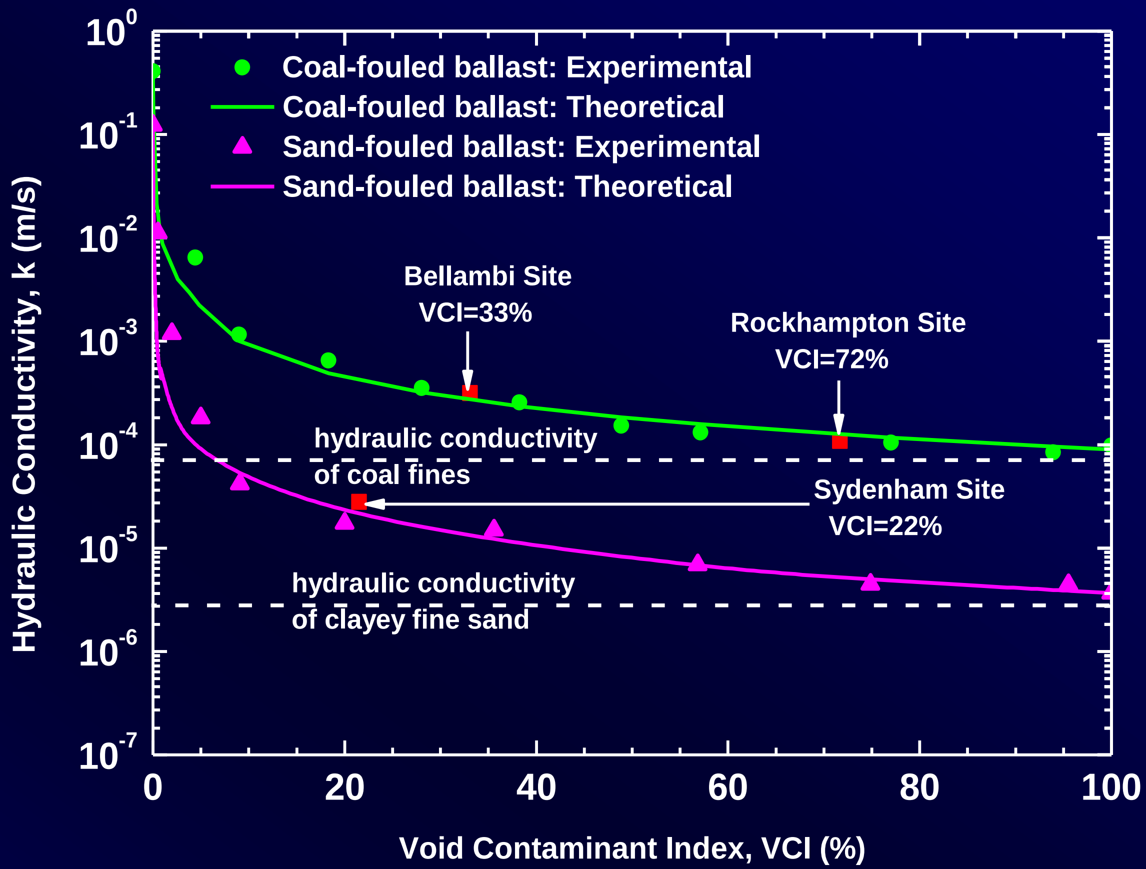
$$VCI = \frac{(1+e_f)}{e_b} \times \frac{G_{s.b}}{G_{s.f}} \times \frac{M_f}{M_b} \times 100$$

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

Tennakoon, Indraratna, Cholachat, Nimbalkar and Neville (2012) ASTM Geotechnical Testing Journal, 35(4): 1-12

Impeded Track Drainage due to Ballast Contamination

Large-scale permeability test apparatus



Variation of hydraulic conductivity vs. Void Contaminant Index

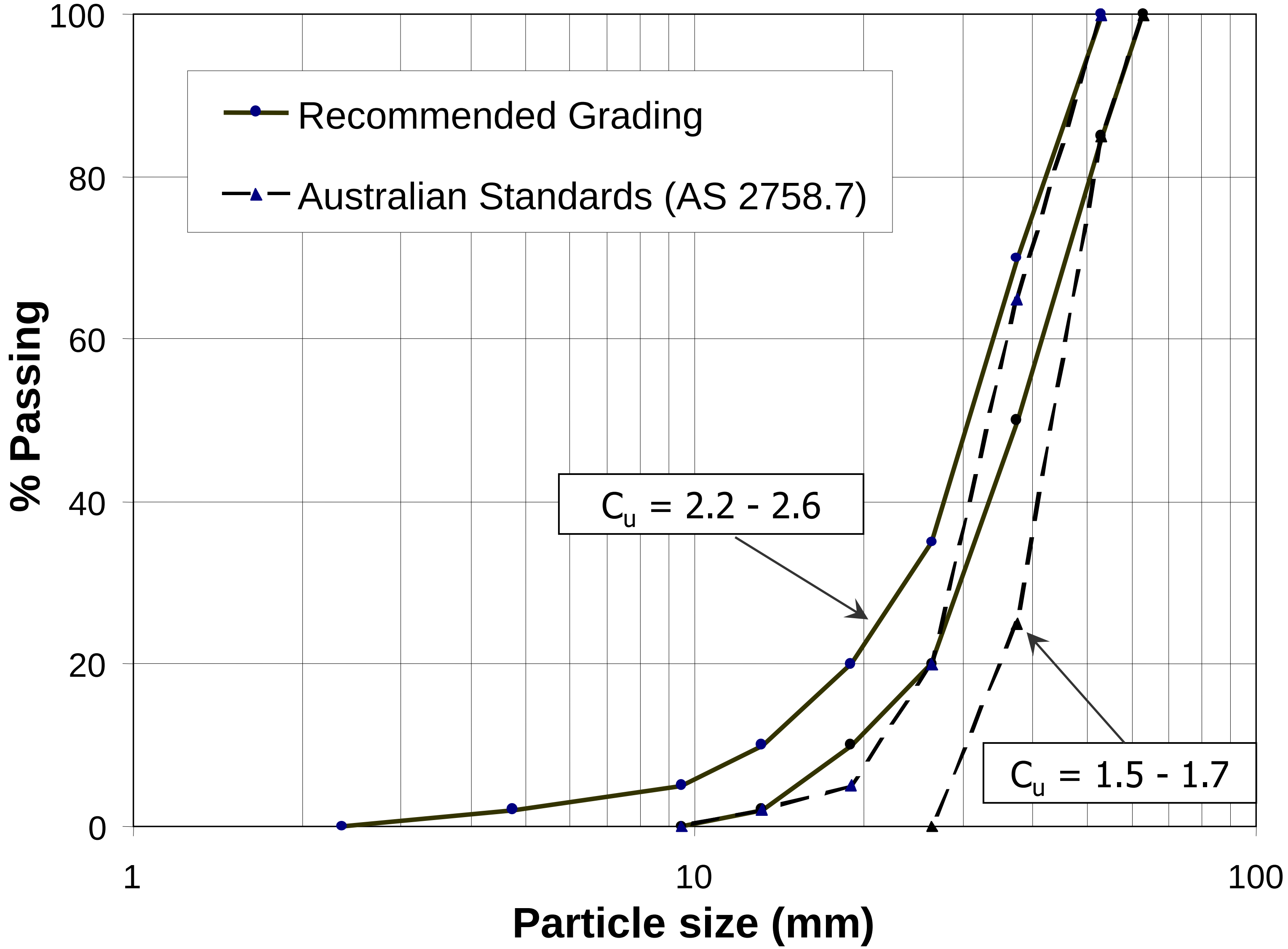
Hydraulic Conductivity (k) of fouled ballast

$$k = \frac{k_b \times k_f}{k_f + {VCI}/{100} \times (k_b - k_f)}$$

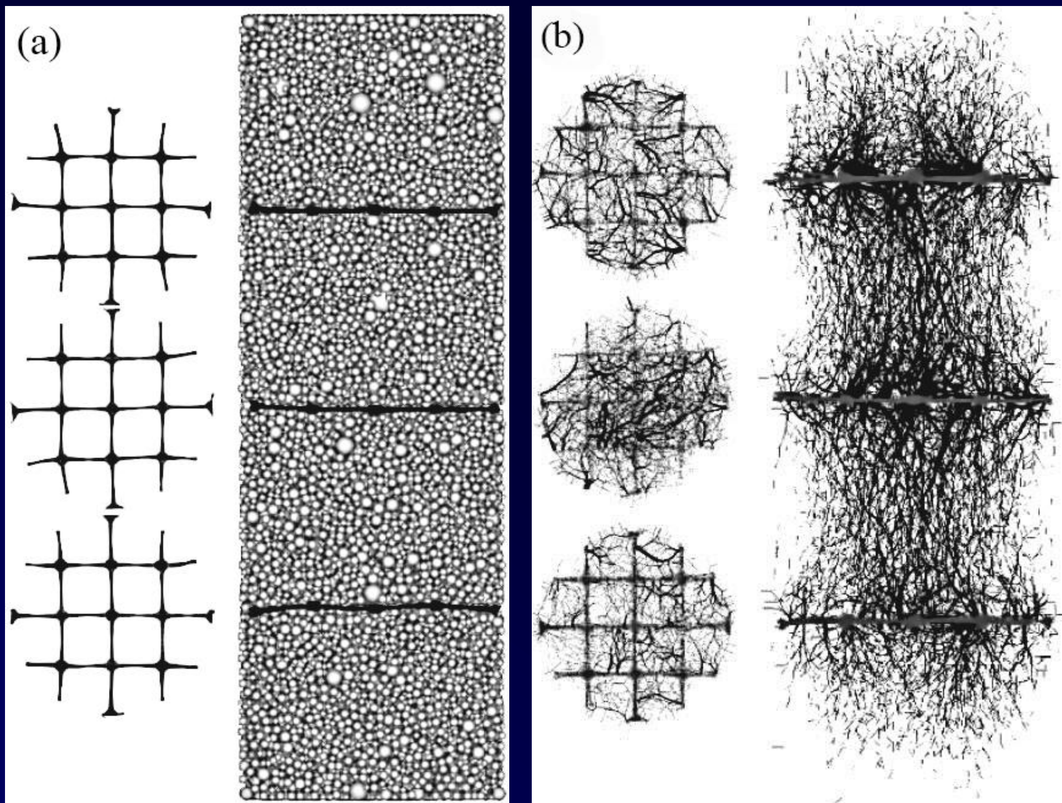
k_b = Hydraulic conductivity of clean ballast

k_f = Hydraulic conductivity of fouling material

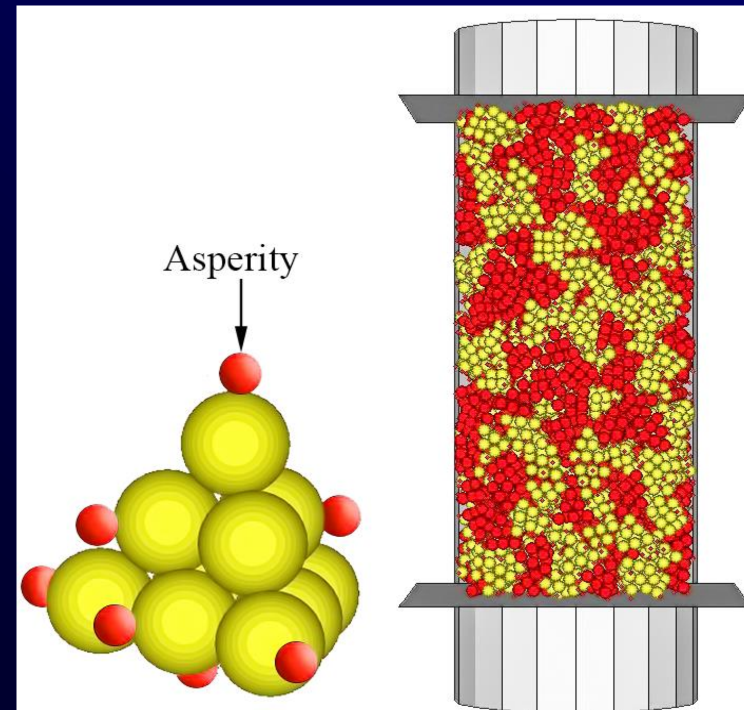
Recommended New Railway Ballast Grading

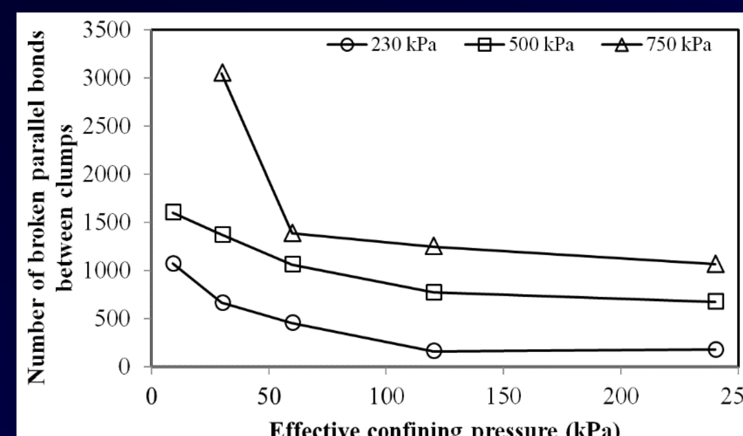


DEM Modelling of Railway Ballast under Monotonic and Cyclic Triaxial Loading



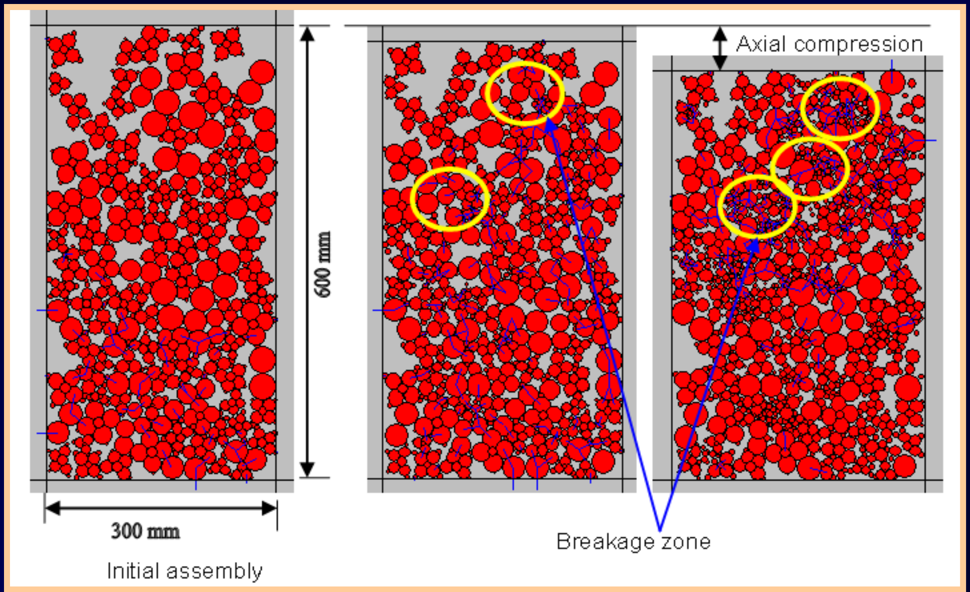
McDowell, Harireche, Konietzky, Brown, and Thom (2006), Proc. ICE-Geotechnical Engineering, 159(1): 35-48.

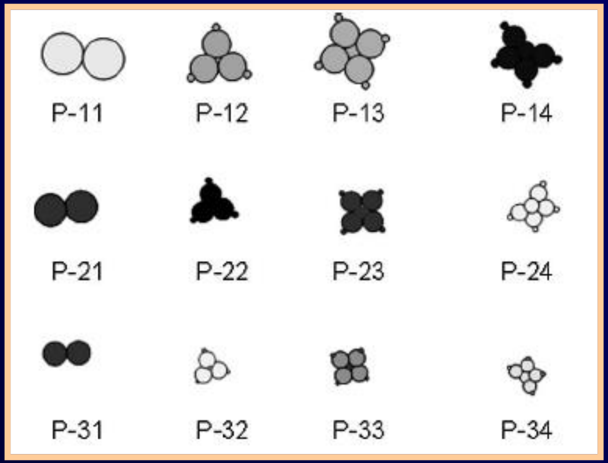




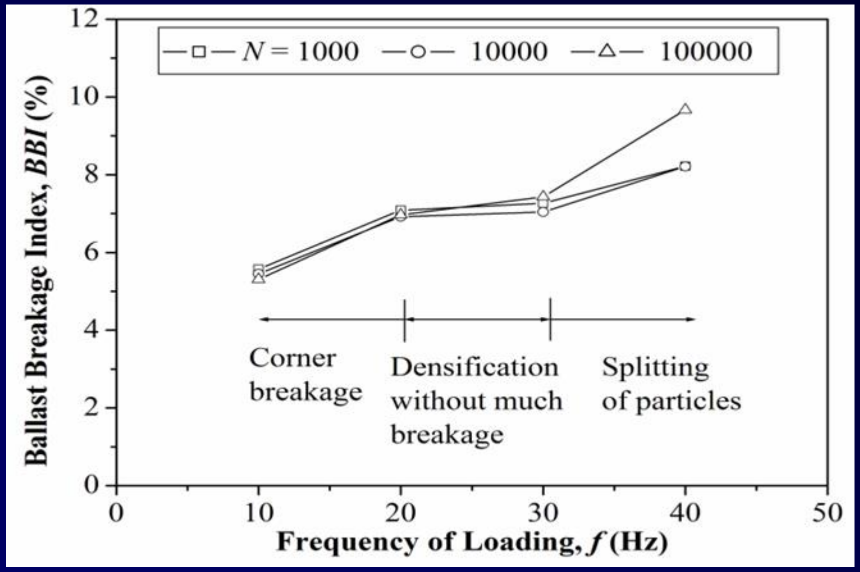
Lu & McDowell (2010), Géotechnique, 60(6): 459–467.

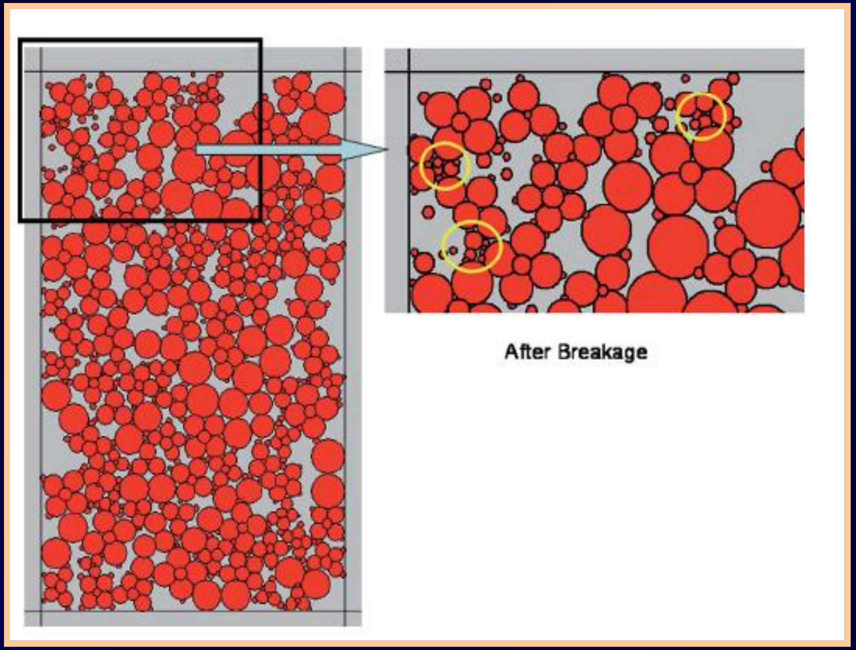
Practical Implications: Train Speed vs Particle Breakage





Model particle shapes and sizes

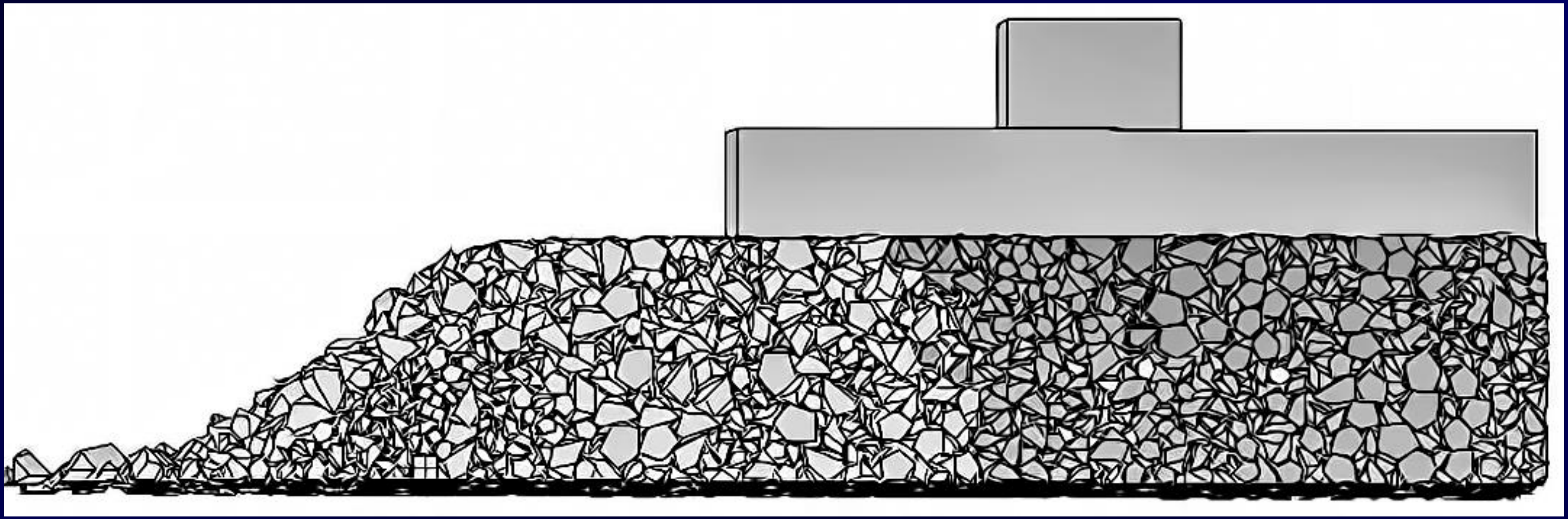


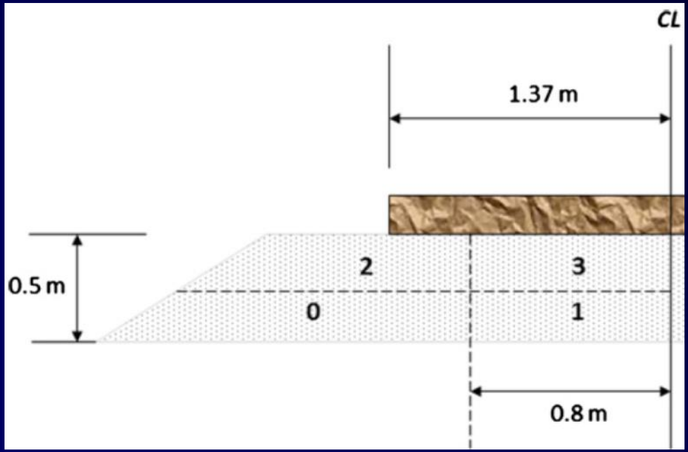


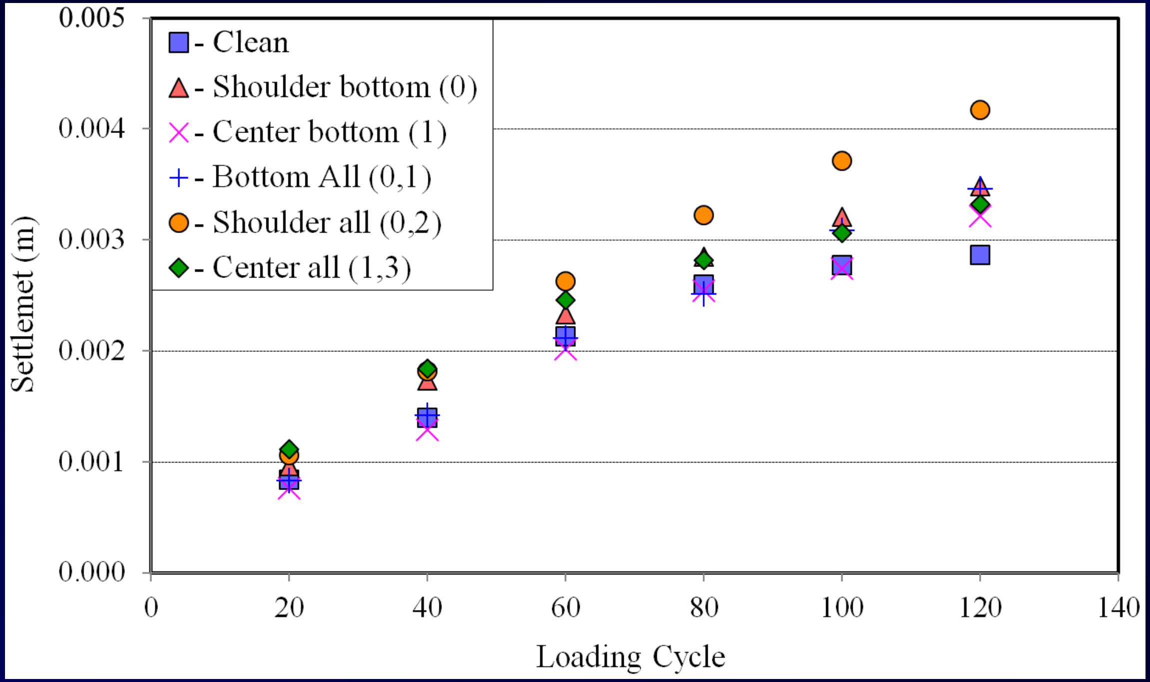
Hossain, Indraratna, Darve, & Thakur (2007).
J. of Geomechanics, ASCE

Particle Breakage near the top plate

DEM Model with Different Parts of Track Fouled by Coal Dust

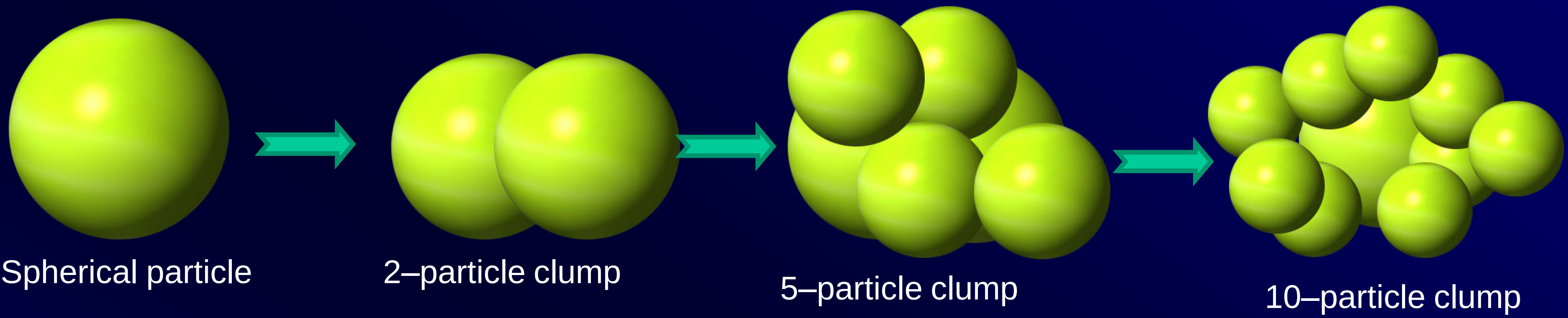


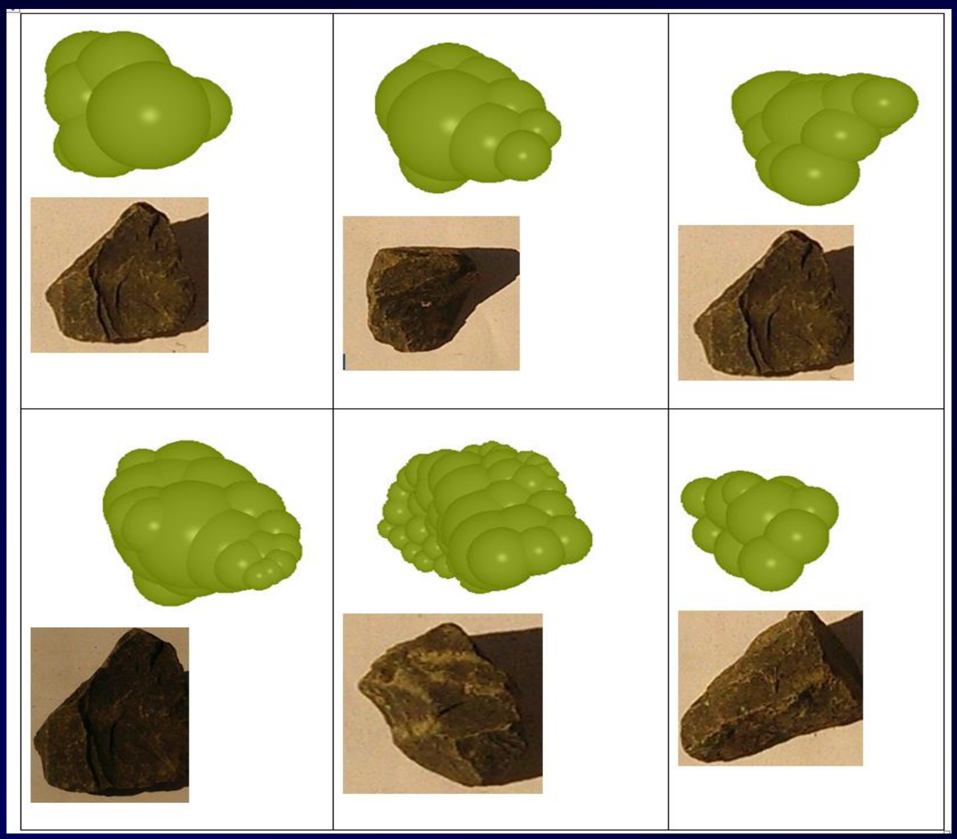




Huang and Tutumluer (2011), *Construction and Building Materials*, 25(8): 3306-3312.

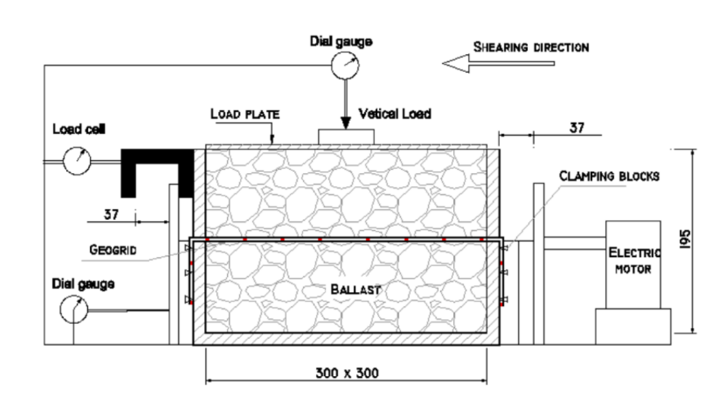
Modelling particle angularity in DEM

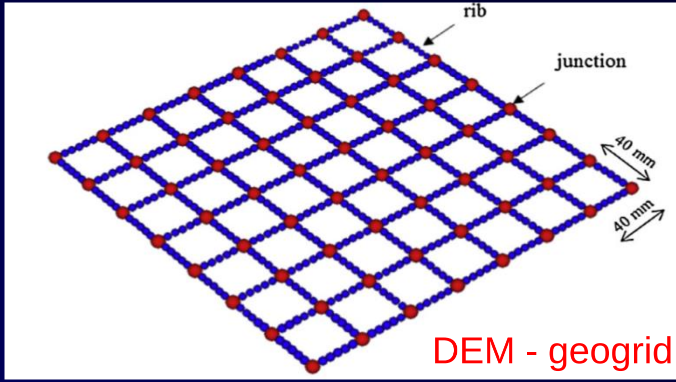


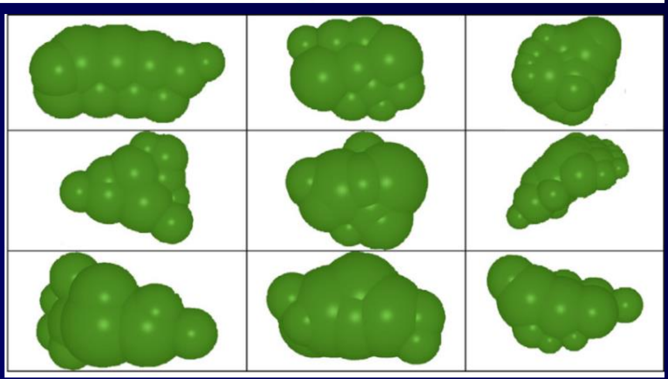


Ngo, Indraratna, and Rujikiatkamjorn (2014). Computers & Geotechnics

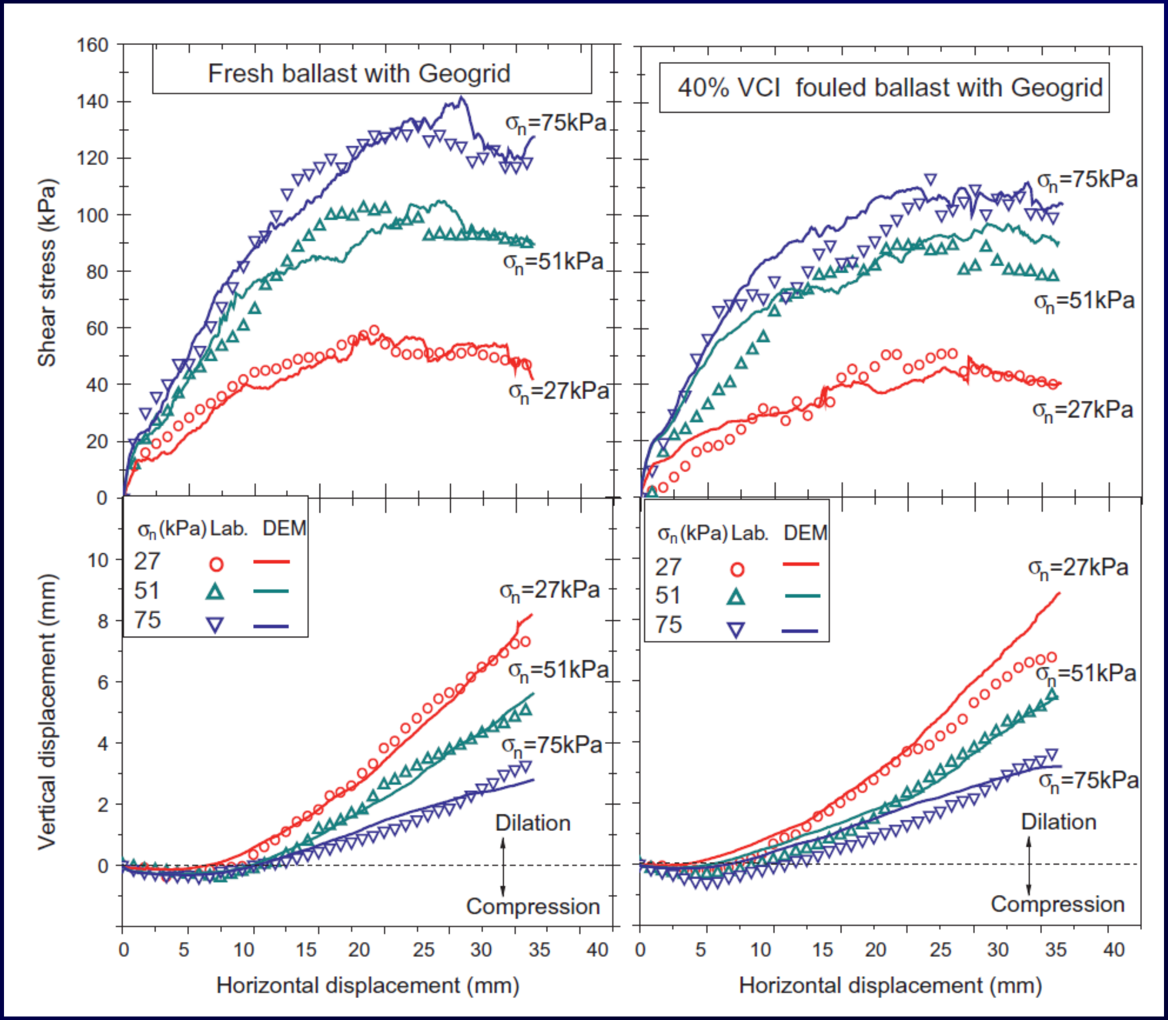
DEM Modelling Geogrid-reinforced Ballast under Shearing Loads







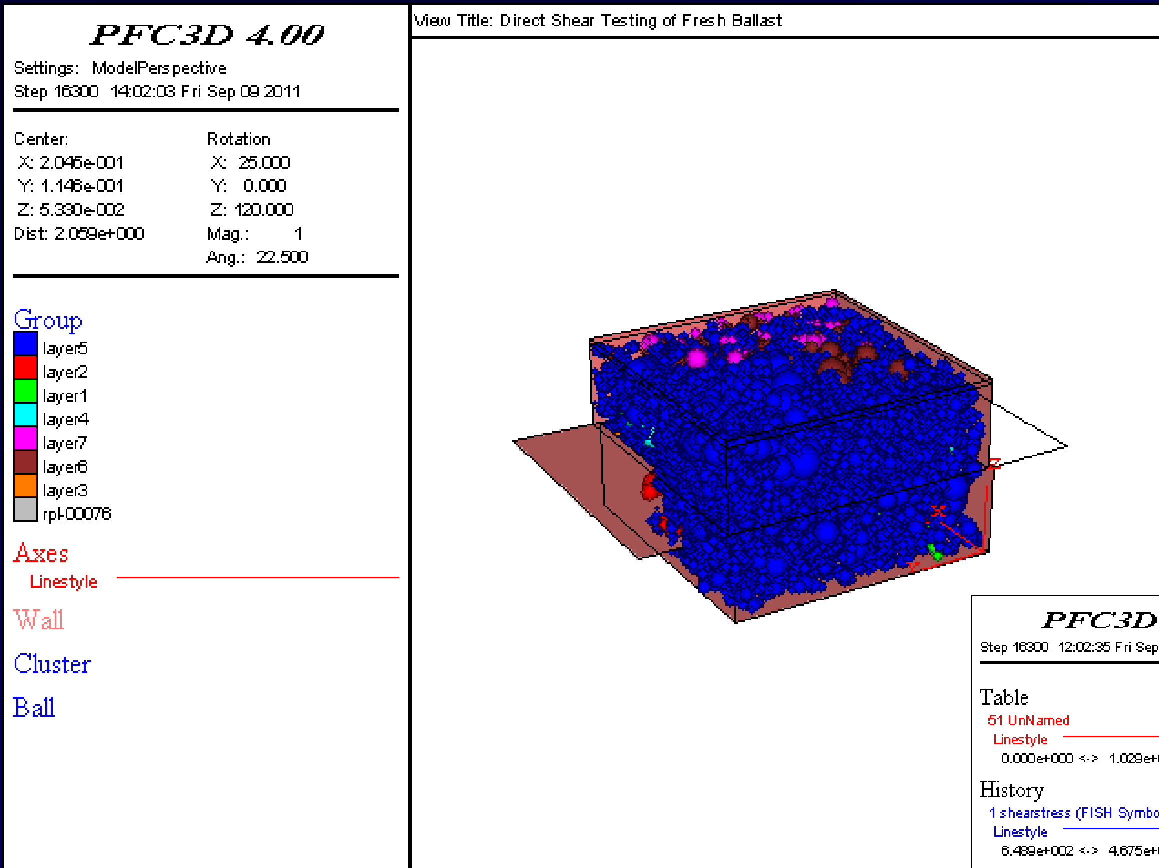
DEM particle shapes and sizes

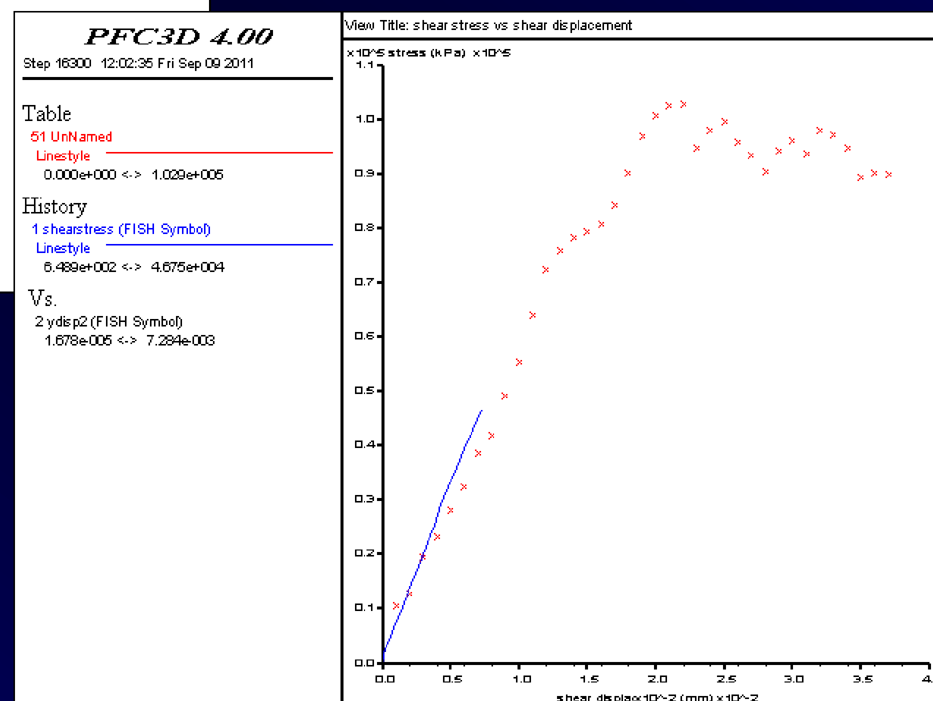


Comparison of shear stress and displacements for DEM simulation of reinforced ballast

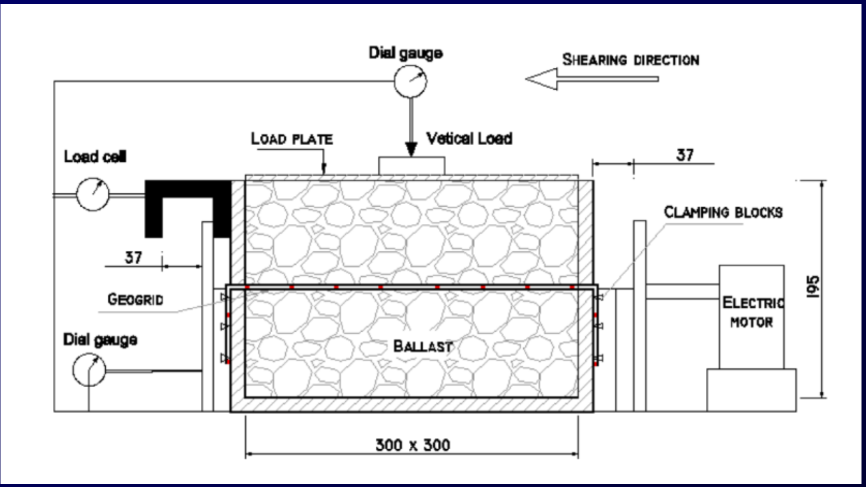
Ngo, Indraratna, and Rujikiatkamjorn (2014). Computers & Geotechnics, Vol. 55, 224-231

DEM Model for Geogrid-reinforced Ballast under Direct Shearing



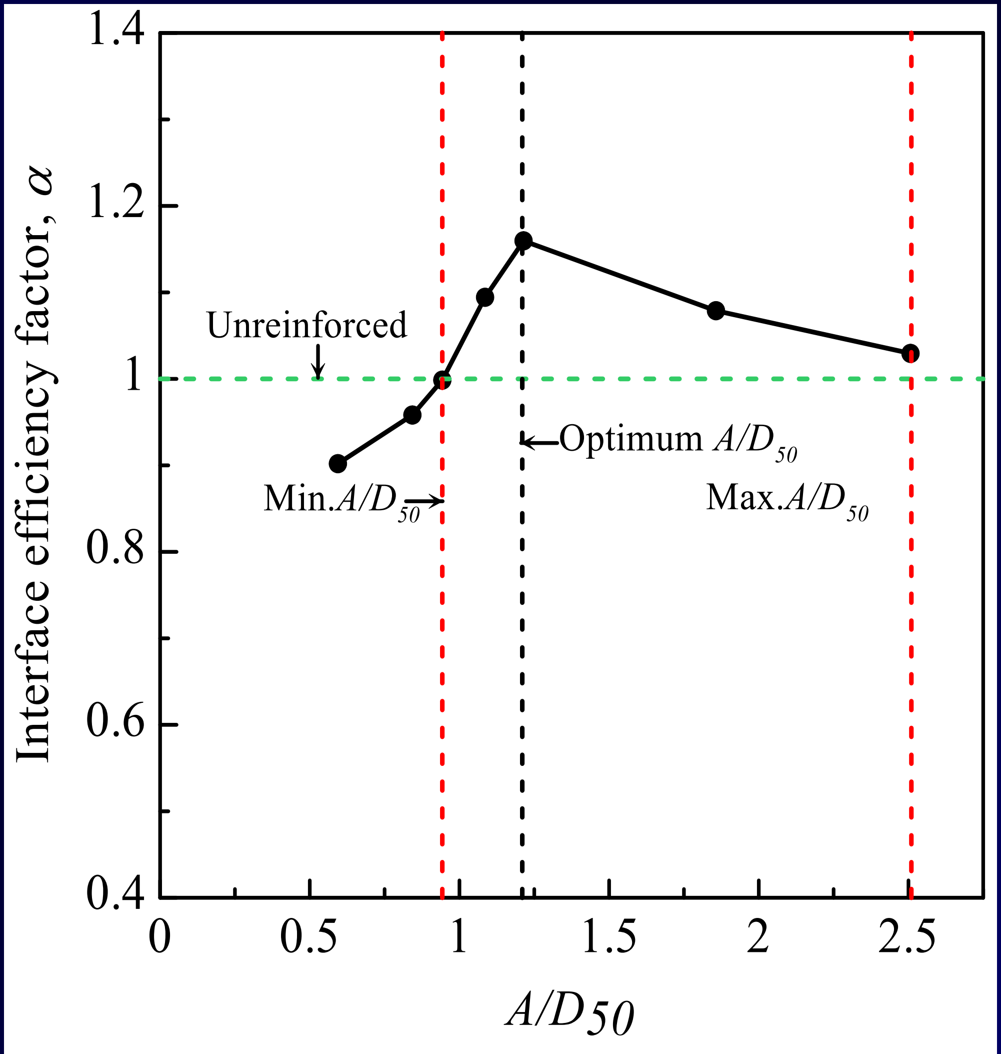


Geogrids for preventing particle movement and breakage



Geogrids Used for Testing

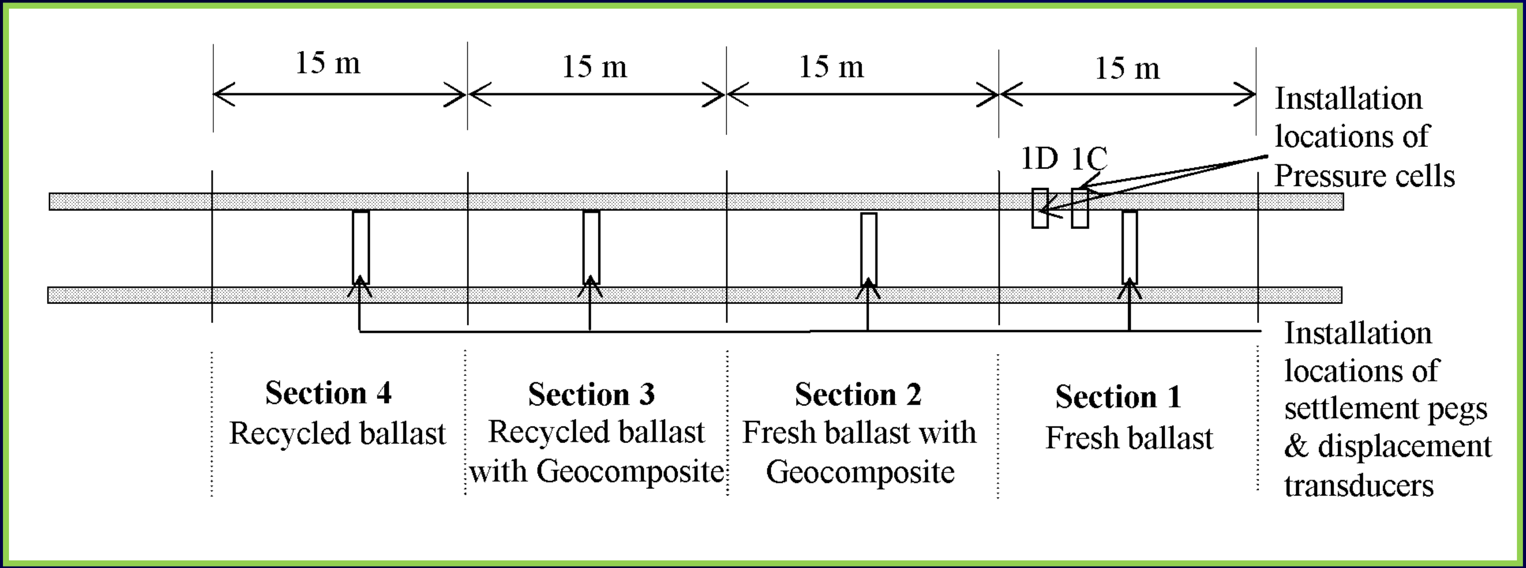
Geogrid type	Aperture shape	Aperture size (mm)	T_{ult} (kN/m)
G1	Square	38 × 38	30
G2	Triangle	36	19
G3	Square	65 × 65	30
G4	Rectangle	44 × 42	30
G5	Rectangle	36 × 24	30
G6	Square	33 × 33	40
G7	Rectangle	70 × 110	20



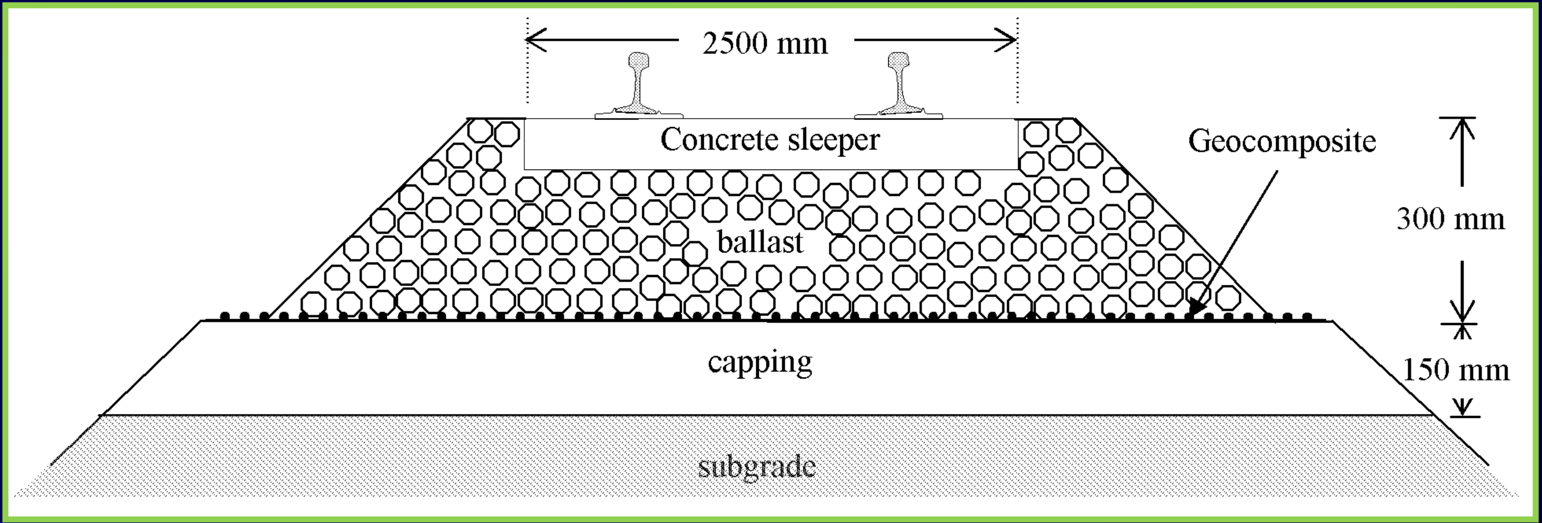
Optimum Aperture Size of Geogrids

Indraratna, Hussaini and Vinod (2011). ASTM Geotechnical Testing Journal, 35: 1-8

Field Trial on Instrumented Track near Wollongong (Bulli)



Details of instrumented track



Section of ballasted track bed with geocomposite layer

Field Trial on Instrumented Track – Town of Bulli

Geocomposite layer (geogrid+geotextile) before ballast placement

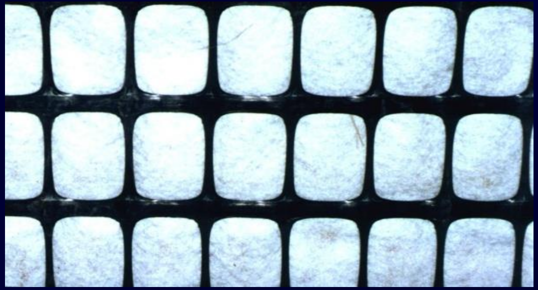
Ballast placement over the geocomposite

Recycled Ballast

from Chullora Quarry, Sydney

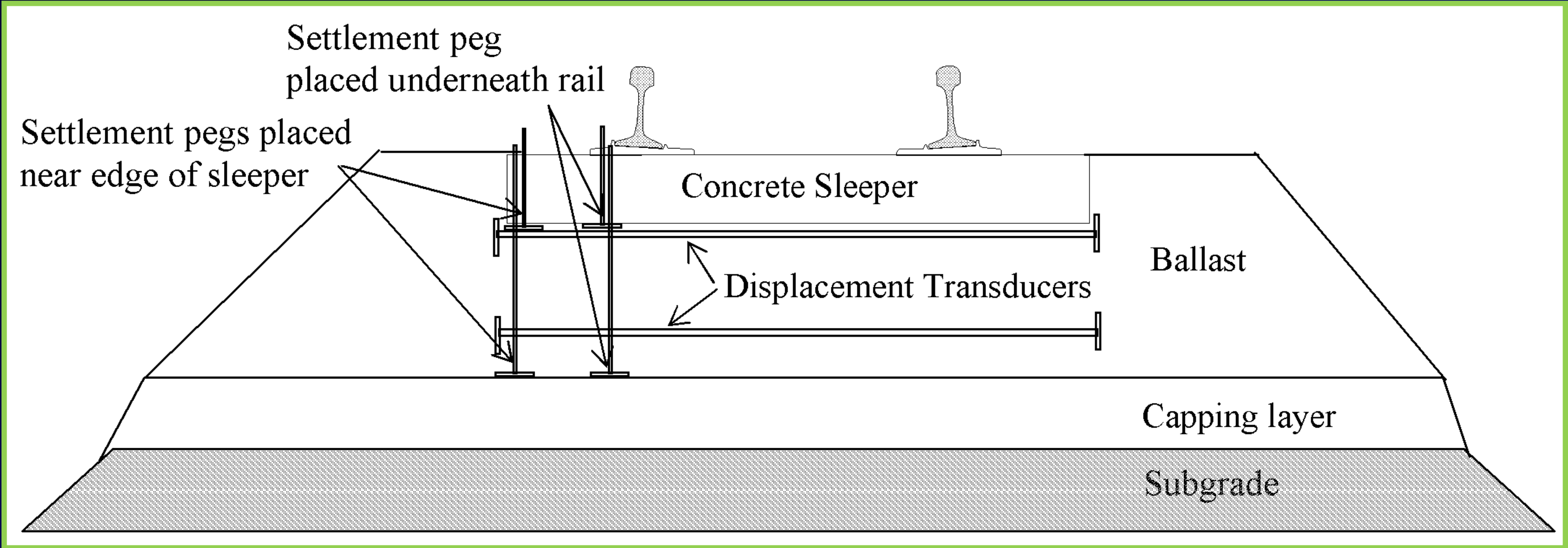
Fresh Ballast

Bombo Quarry, Wollongong



Bonded Geogrid

Field Instrumentation – Town of Bulli



Settlement pegs installed at ballast-capping interface

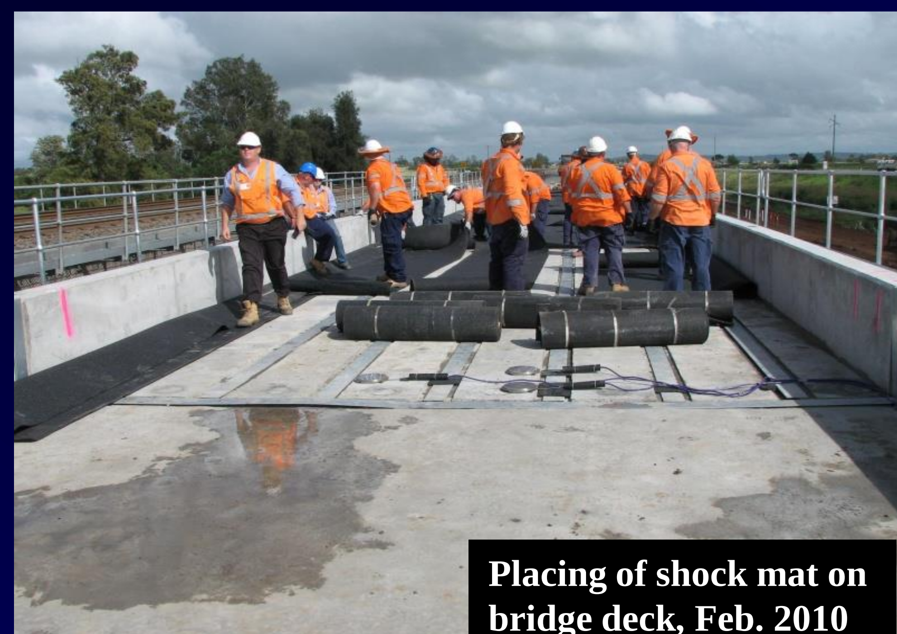
Displacement transducers installed at sleeper-ballast interface

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

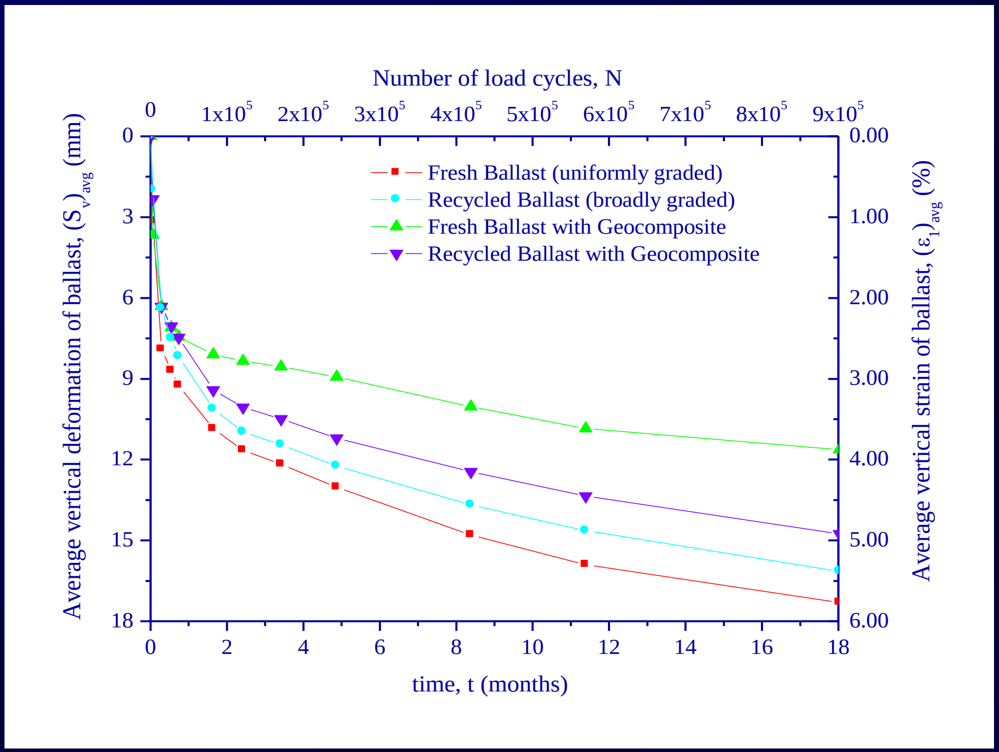


Placing of shock mat on bridge deck, Feb. 2010

Role of Geosynthetics - Field Monitoring of Track Response

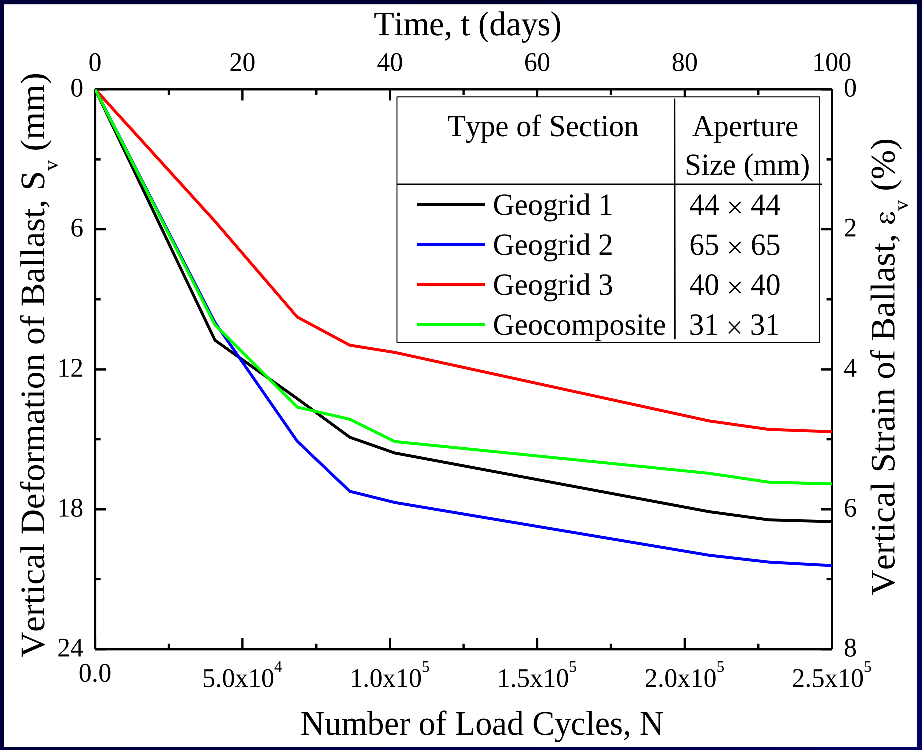
Bulli Track: Indraratna et al. (2010). JGGE, ASCE, Vol. 136(7), 907-917
Singleton Track: Indraratna et al. (2014). ICE Proc. Ground Improvement, 167(1), 24-34

Bulli Track



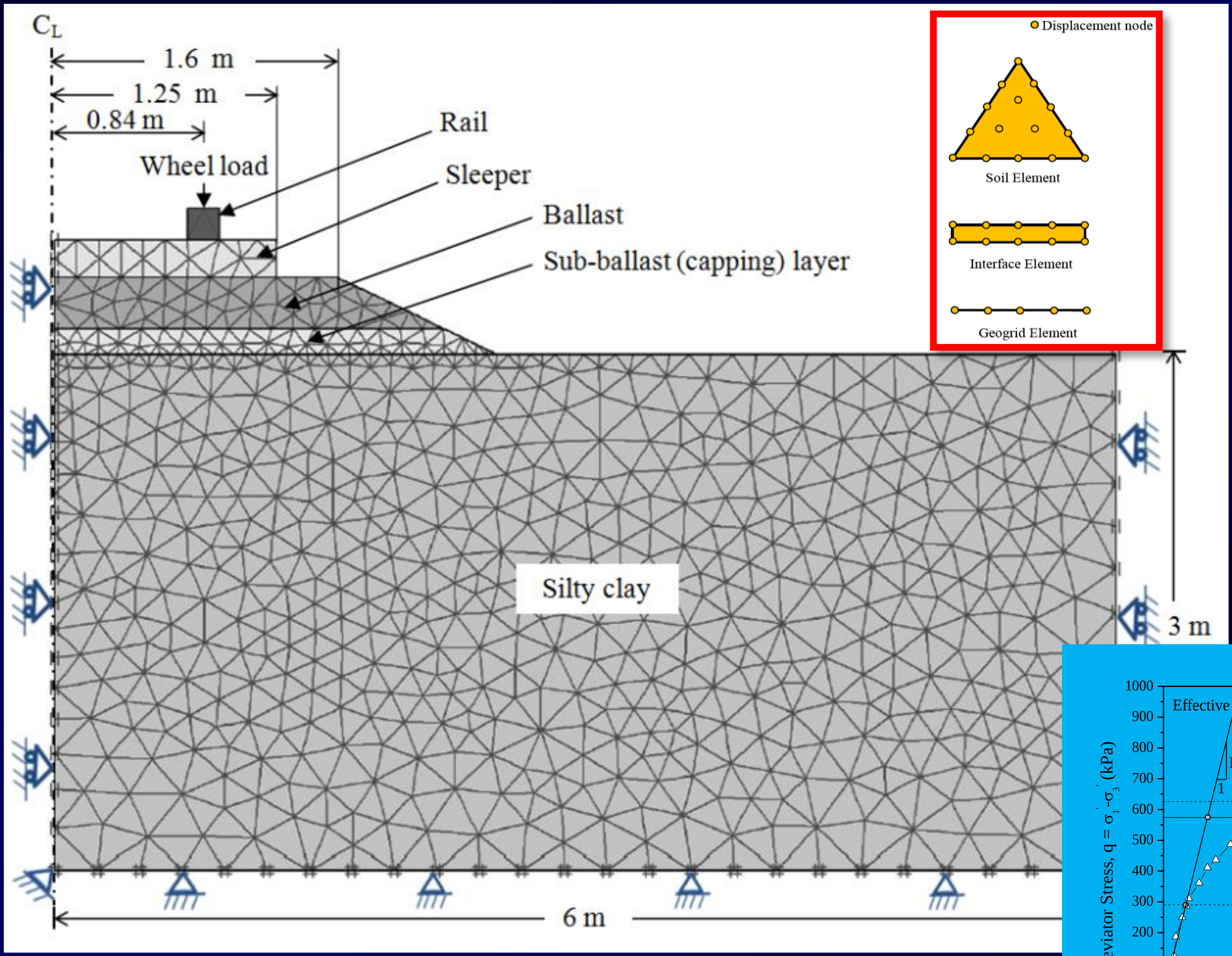
Recycled ballast: broadly-graded compared to uniform fresh ballast – so performed better !

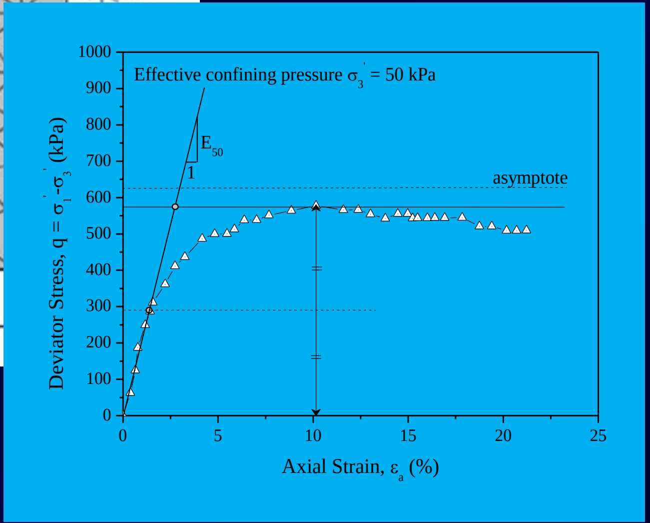
Singleton Track



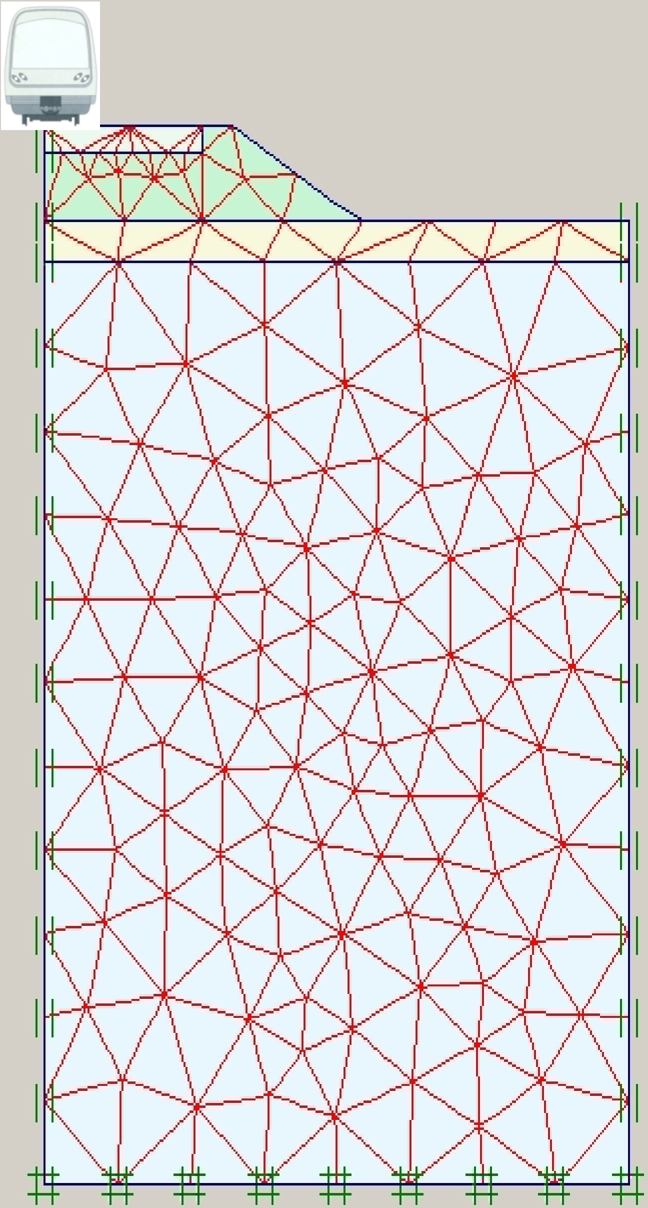
Optimum aperture size of geogrids is about $1.2D_{50}$ of ballast.

Finite Element Analysis of Track: 2D Plane Strain



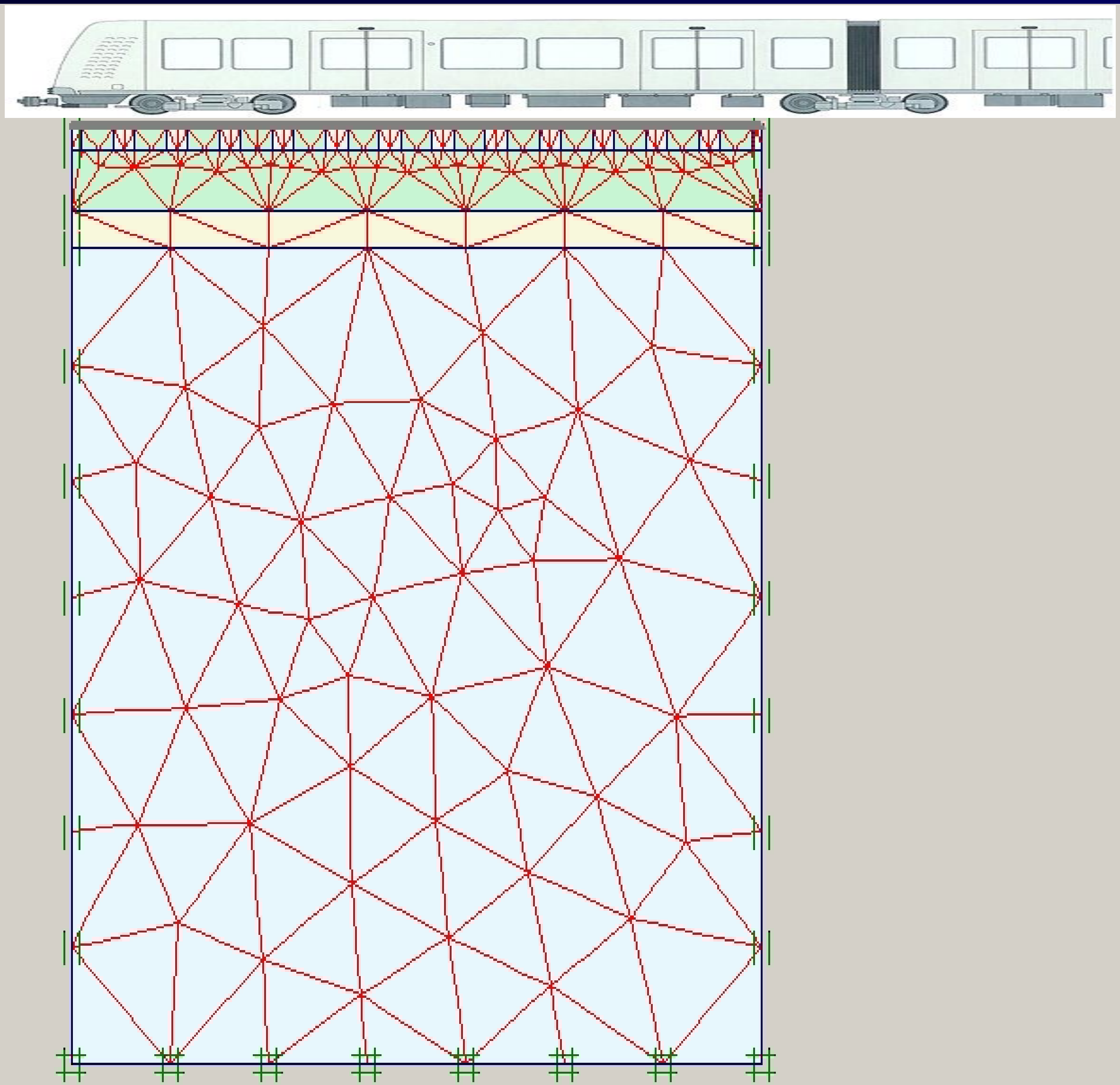


Track transverse section deformation



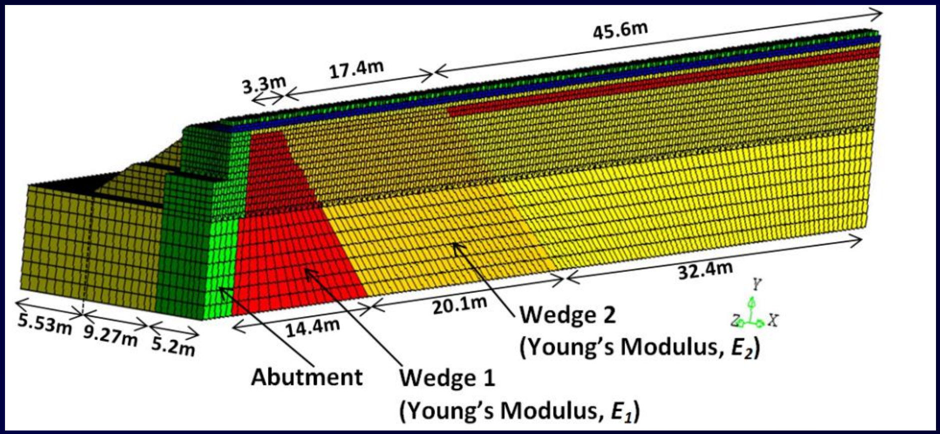
Deformed mesh
(Step 0)

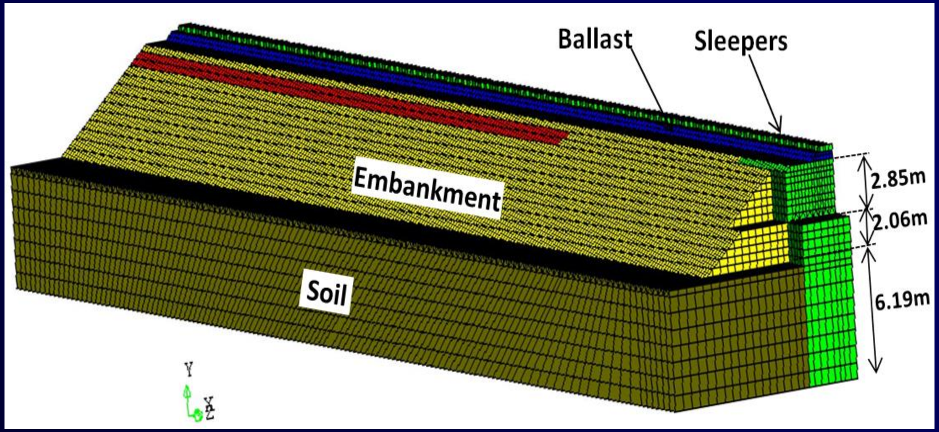
Track longitudinal section deformation

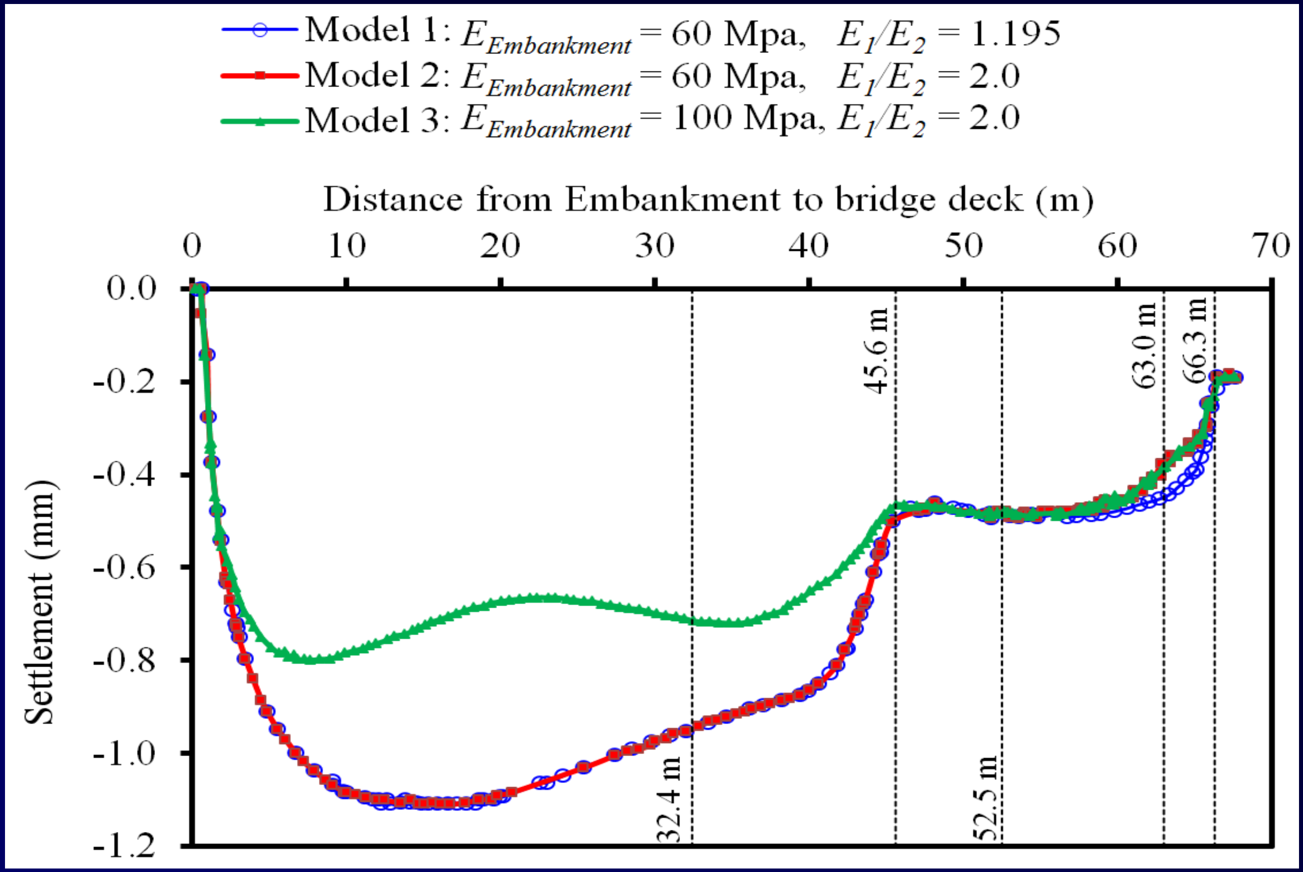


Deformed mesh
(Step 0)

FEM modelling of Transition Zones





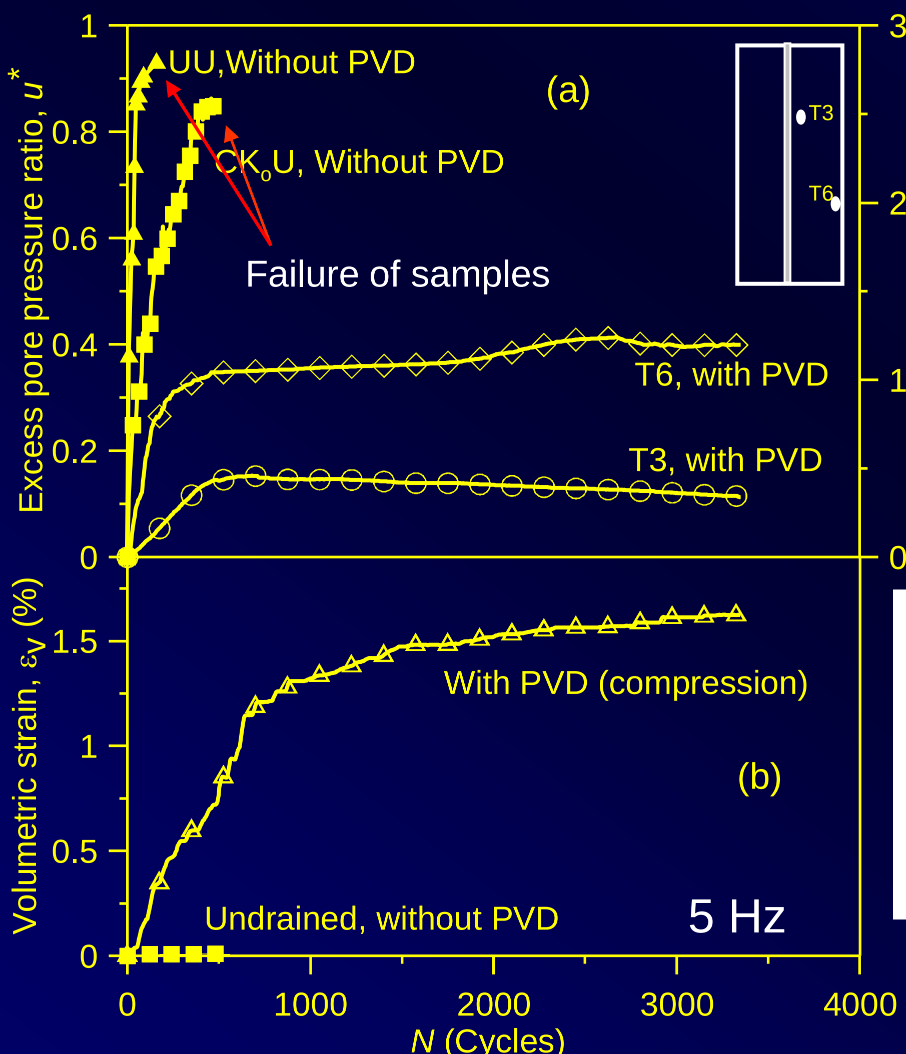


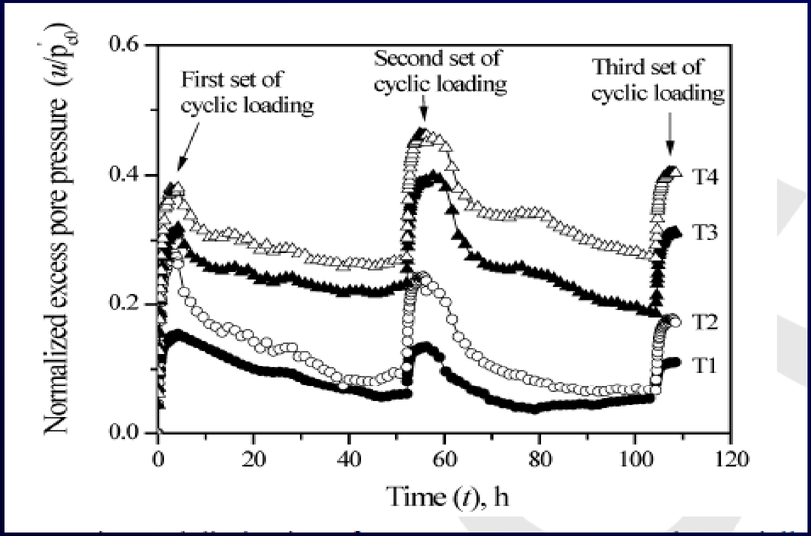
Performance assessment and numerical solutions for transition zones – approaching bridge deck

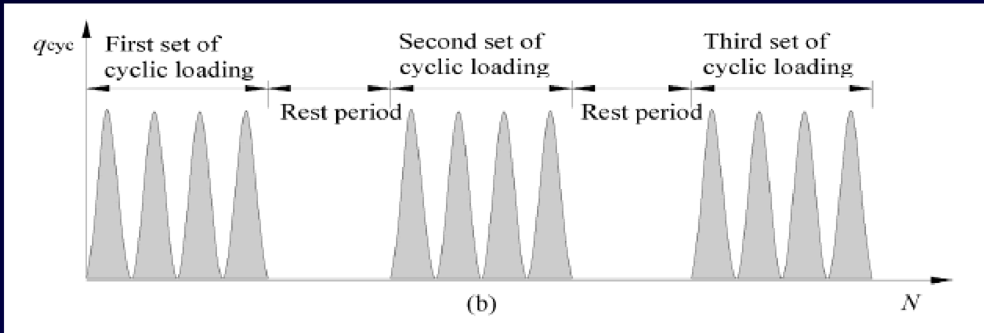
Seara and Correia (2010), Semana de Engenharia Escola de Engenharia da Universidade do Minho.

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



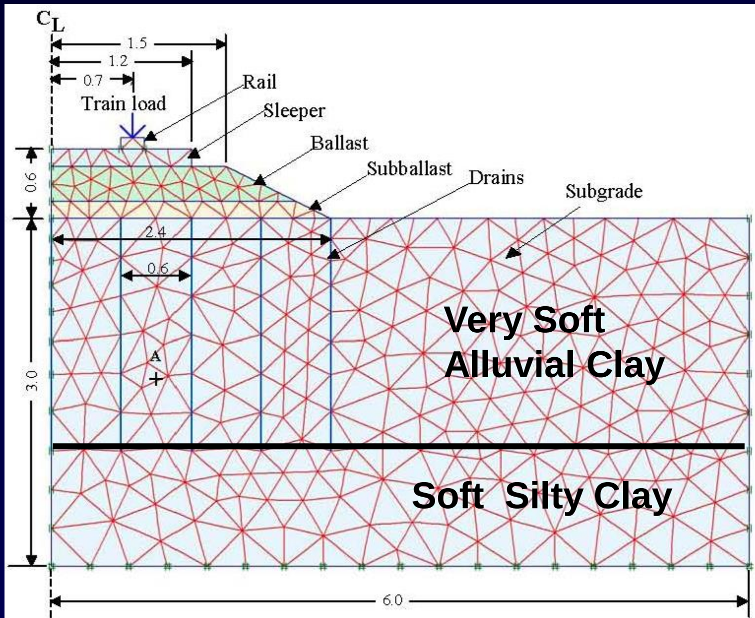


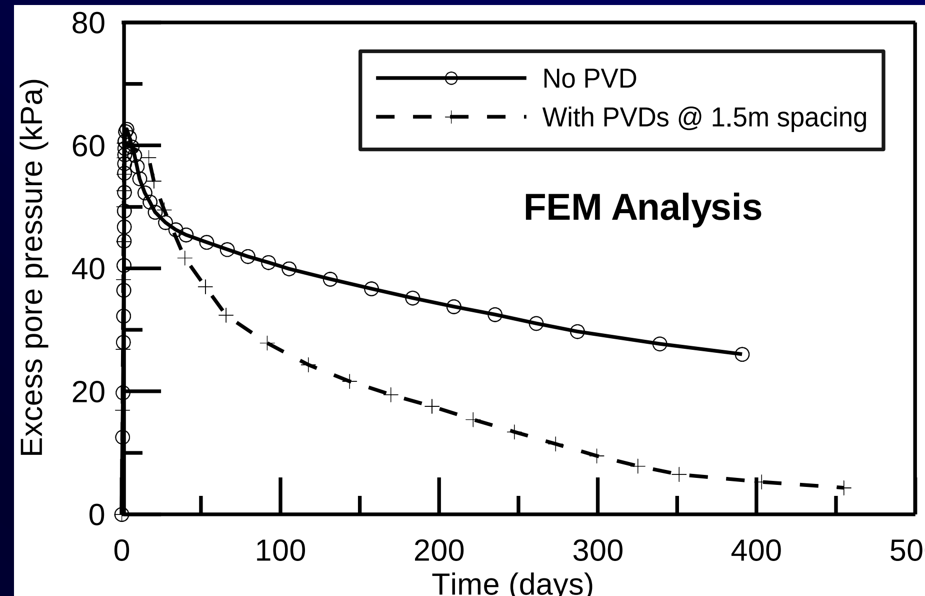


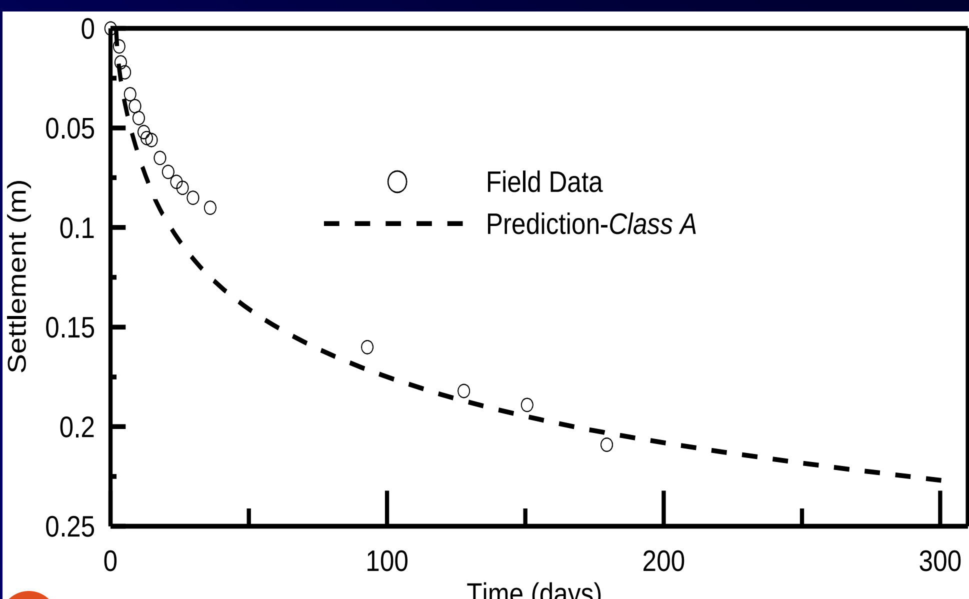
Specimens without PVD fail very quickly as the excess pore pressure rises rapidly!

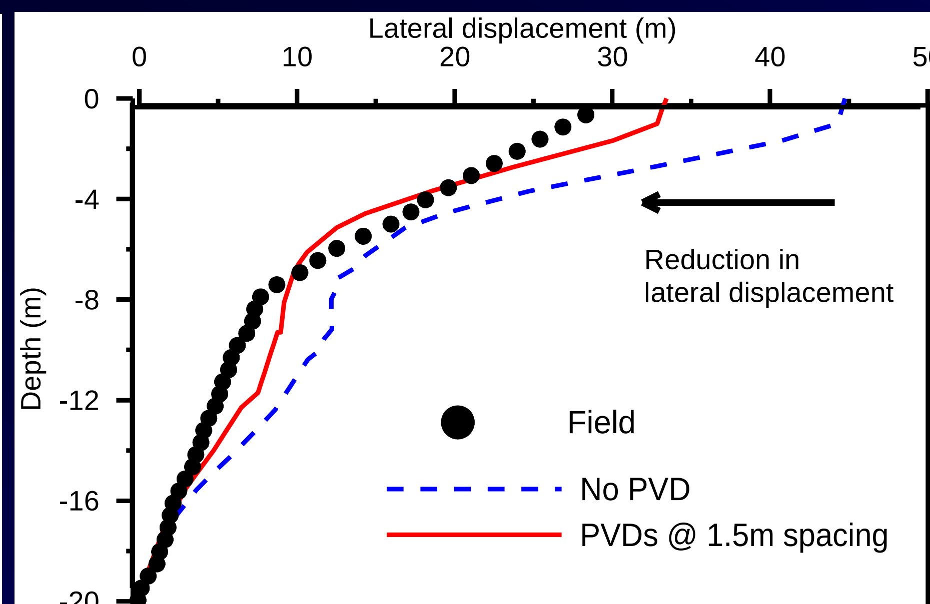
Short PVD Applications to Rail Embankment at Sandgate and FEM Analysis

Class A Prediction (Indraratna et al, ASCE, JGGE, 2010)



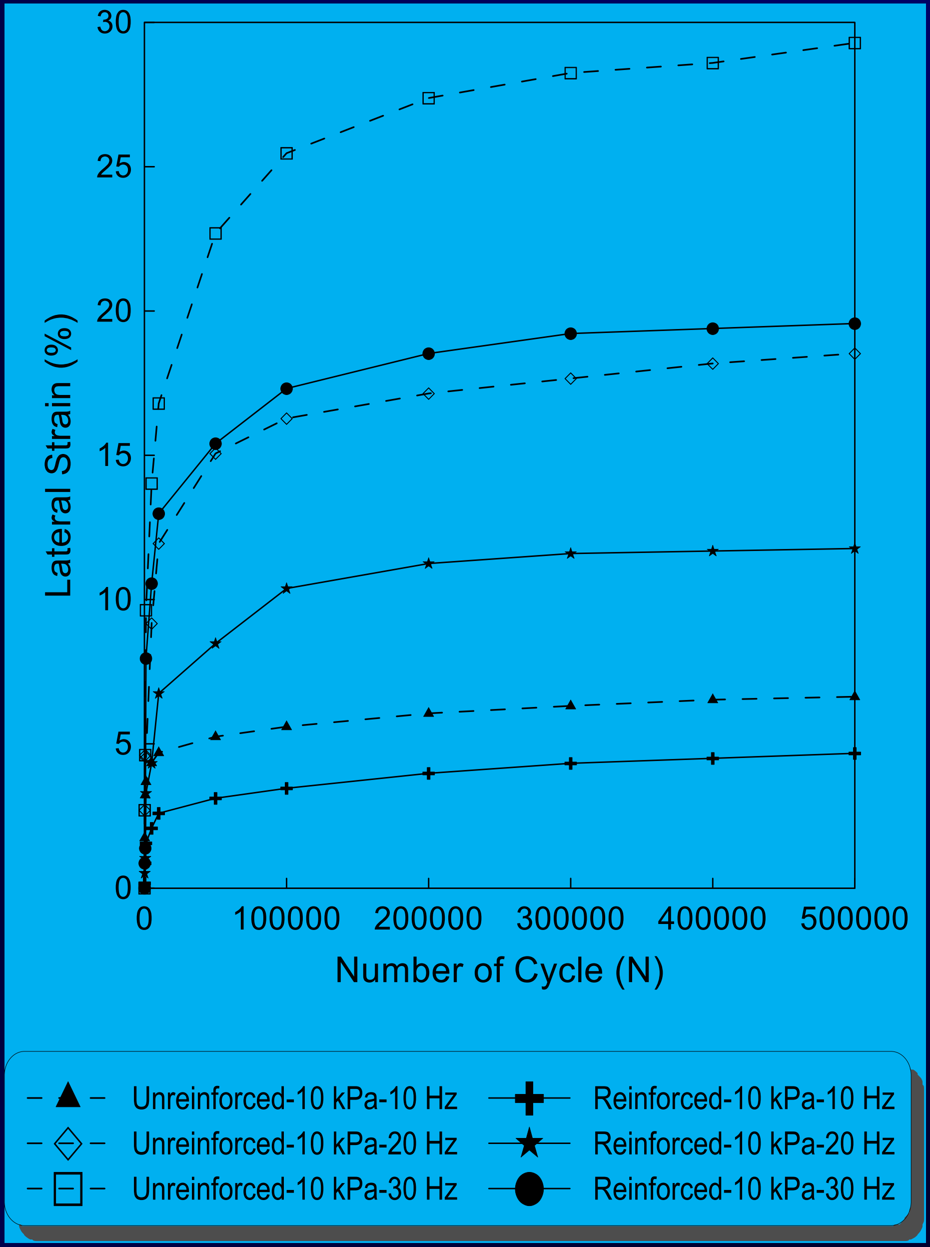






Geocell stabilisation of capping layer to minimise mud pumping

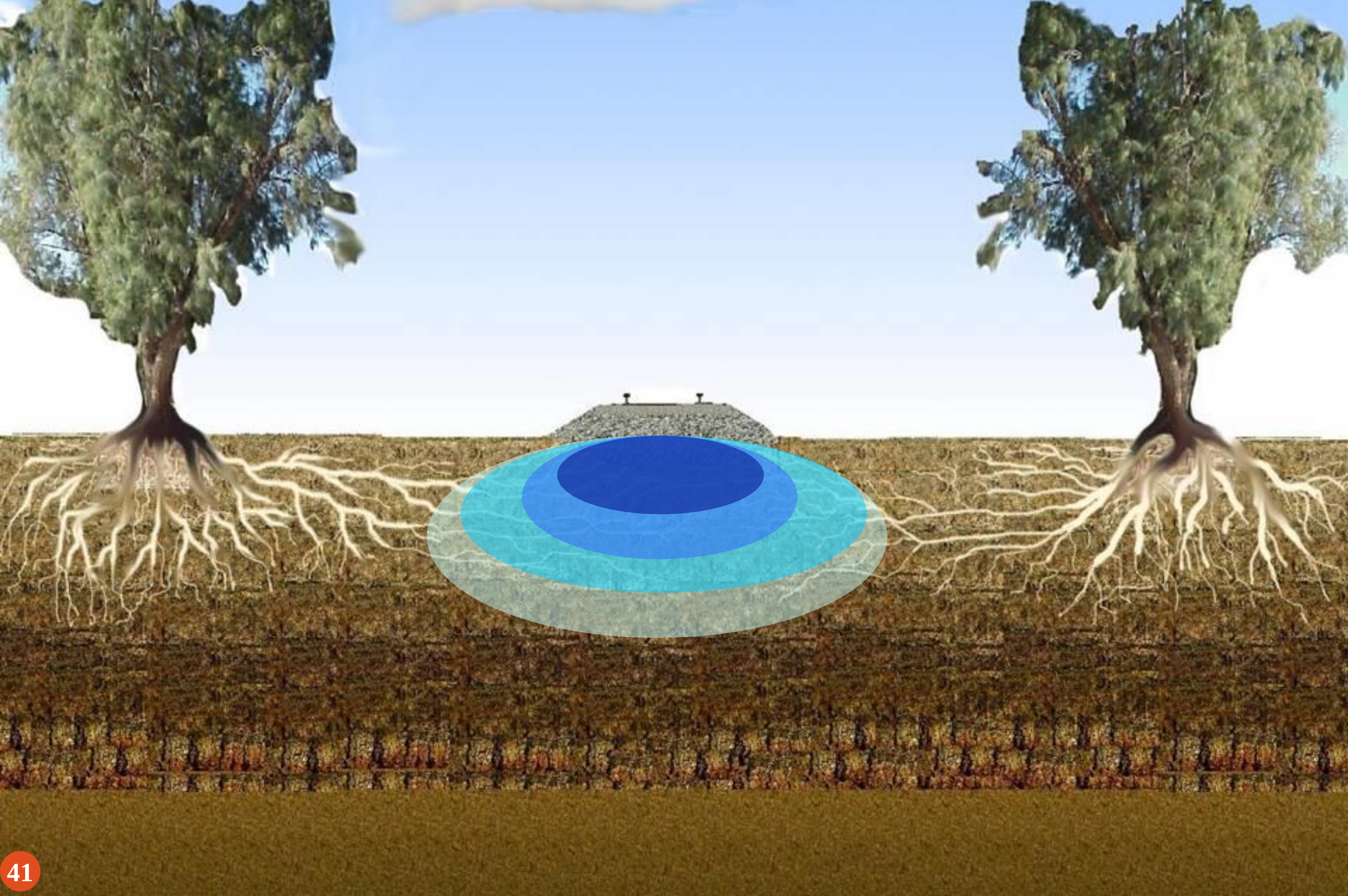
Indraratna et al. (2015). JGGE, ASCE, Vol. 141(1), 1-16



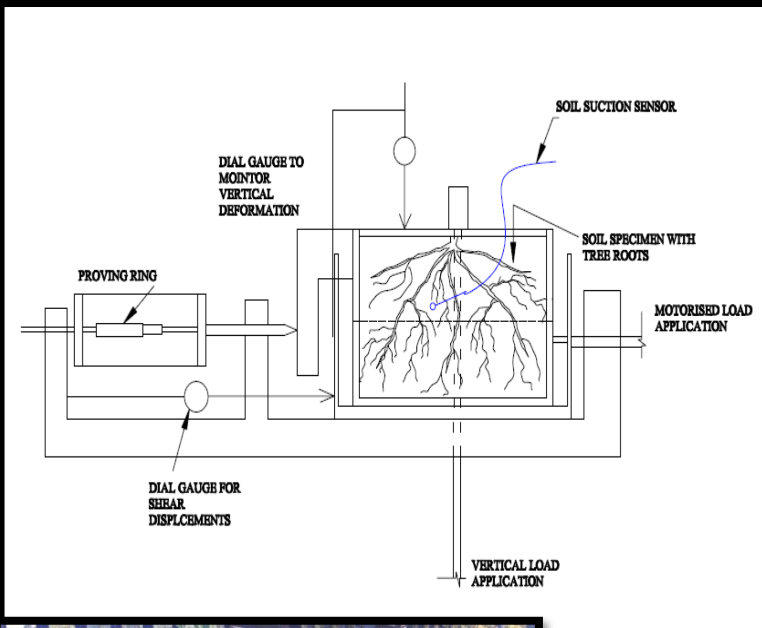
Geocells provide confinement to the capping layer and prevent lateral spreading

Interaction of Trees and Ground for Stabilising Rail Corridors

Indraratna et al. (2006), ICE Proceedings, Vol. 159, 77-90

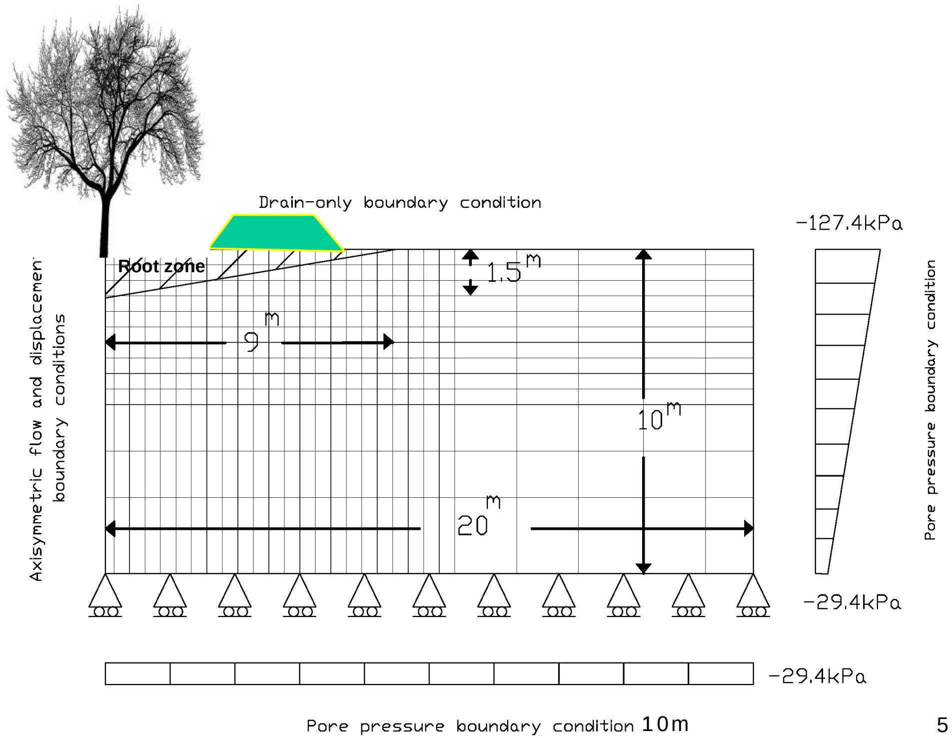


Laboratory and Field Measurements: Role of Soil Suction



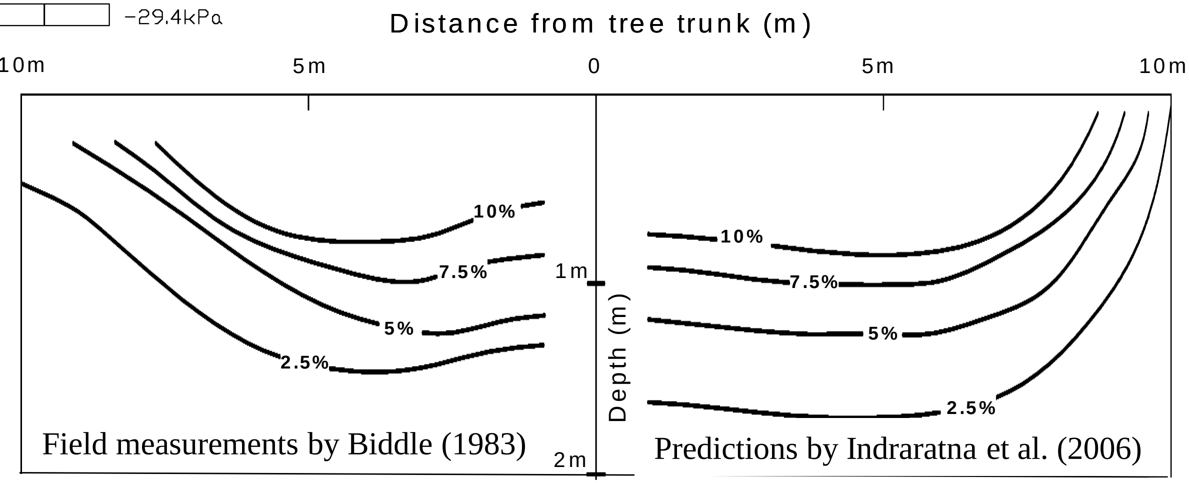
Computational Tree Root Model Validation

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

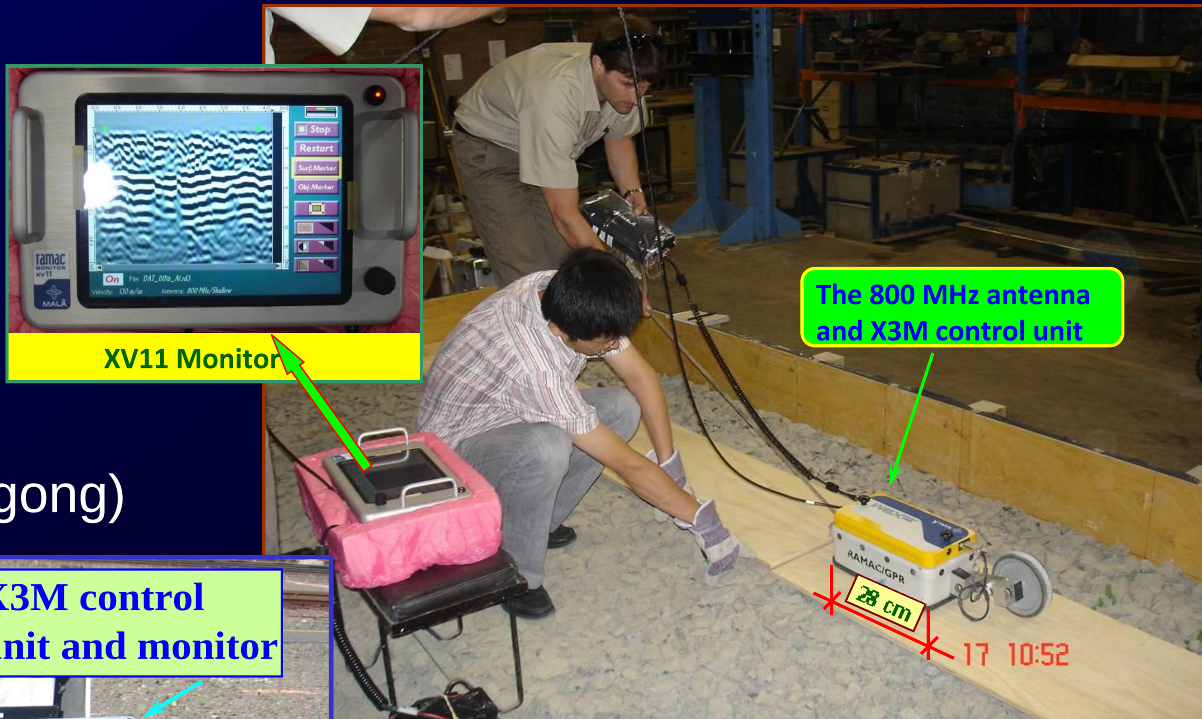


FEM modeling of a single native tree

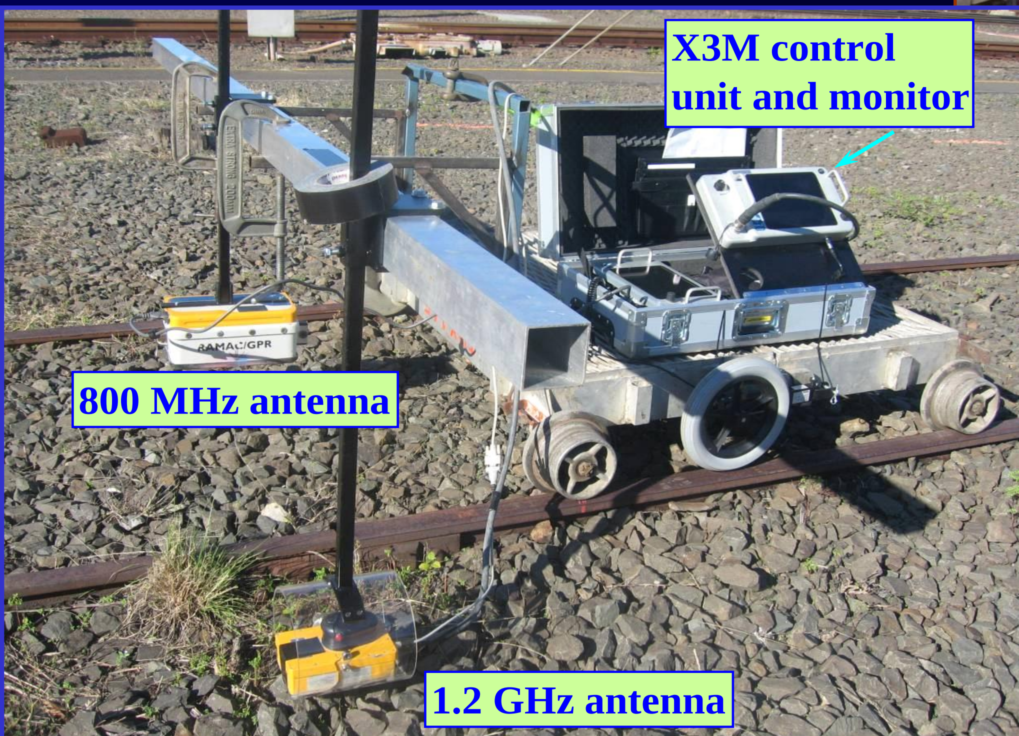
Contours of volumetric soil moisture content reduction (%) in the vicinity of a lime tree



Track Condition Monitoring - Ground Penetration Radar (GPR)

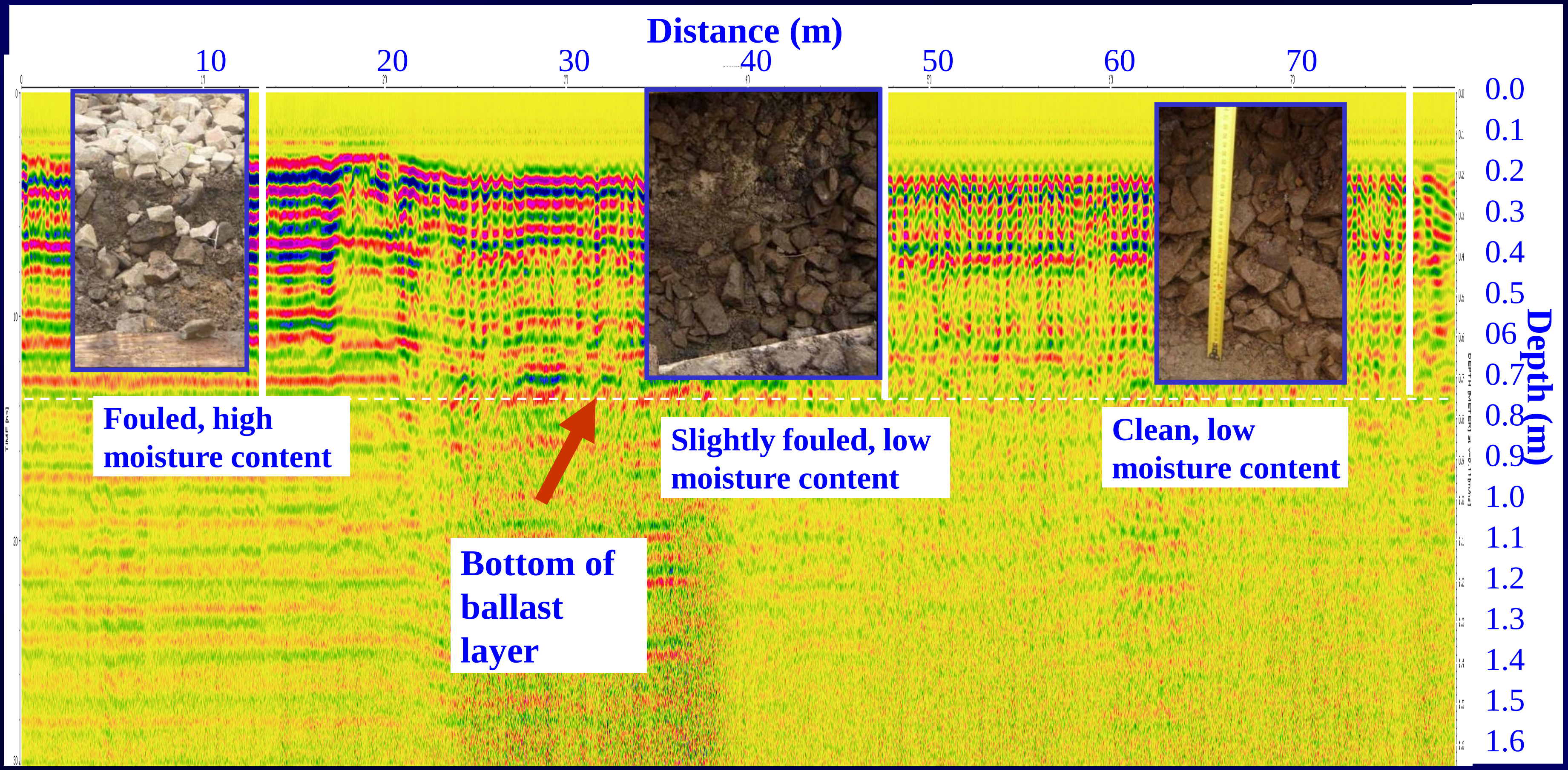


Lab testing (Uni. of Wollongong)



Field testing (Wollongong)

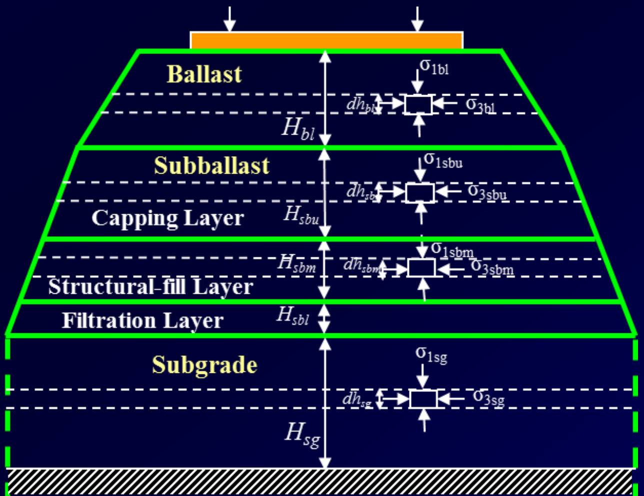
GPR Lab and Field Testing

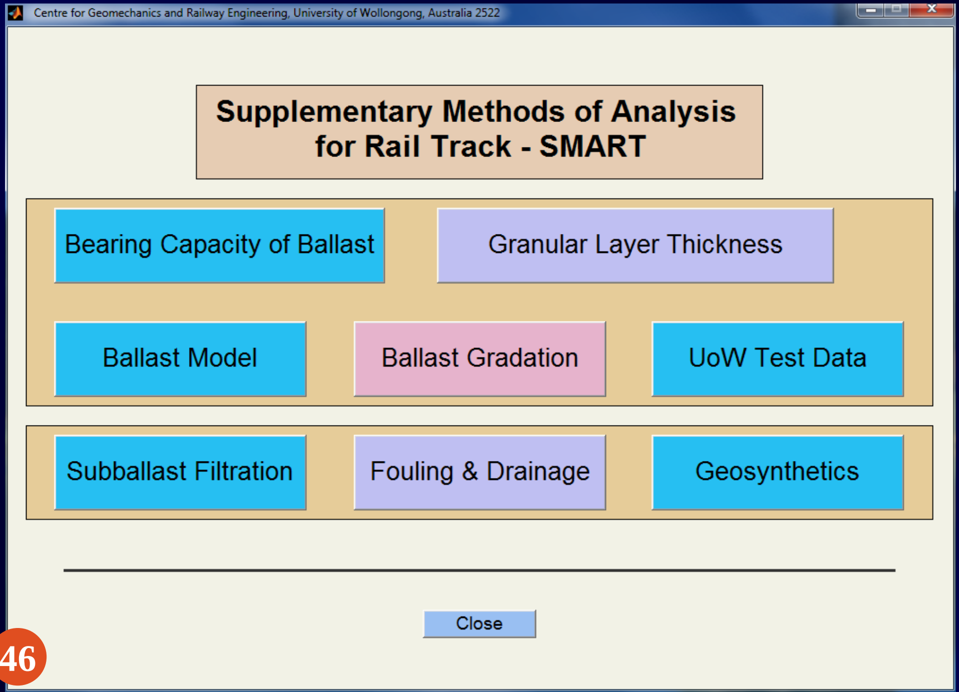


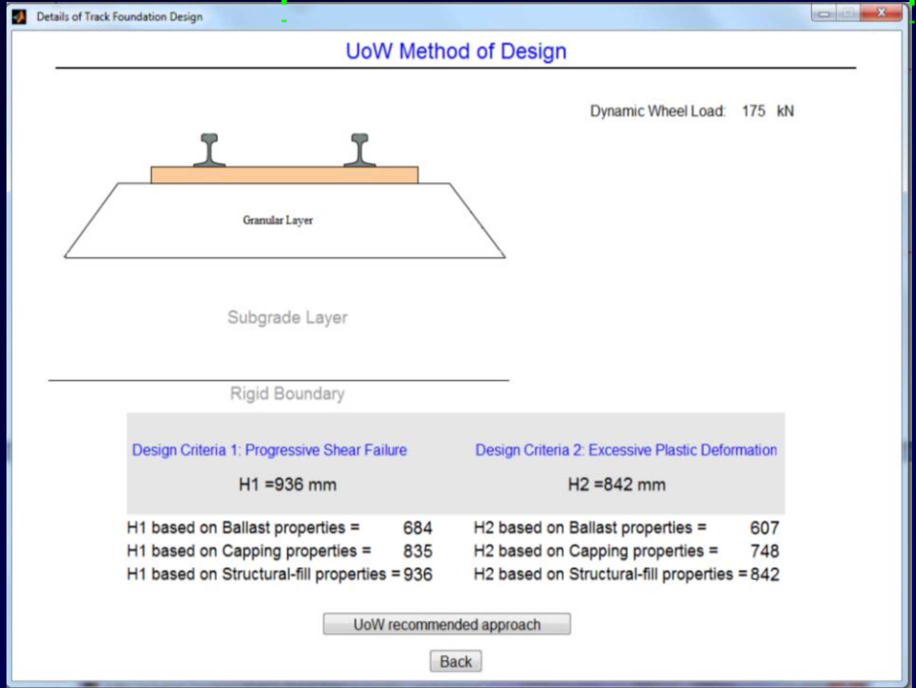
New Design Procedures – UoW Method
(Supplementary Method of Analysis of Rail Track – *SMART*)

Key features:

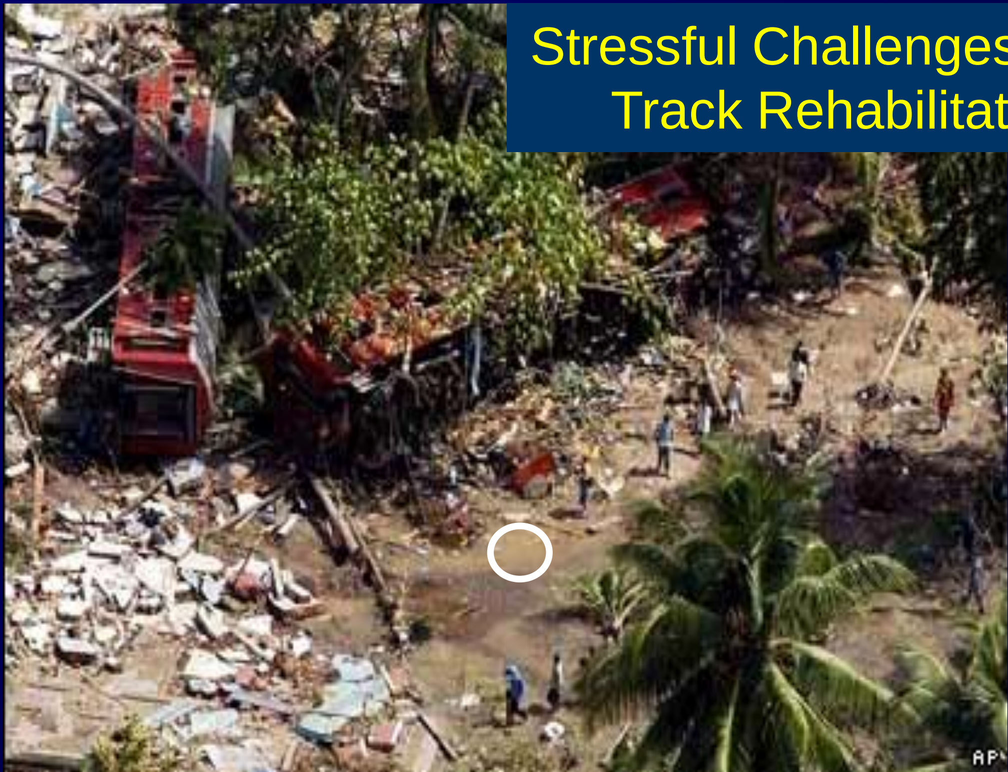
- a set of MATLAB subroutines: design and analysis of track based on research outcomes;
- a collection of performance-based methods for formation-track analysis.
- stand-alone computer application: user-friendly interfaces for data input and output.

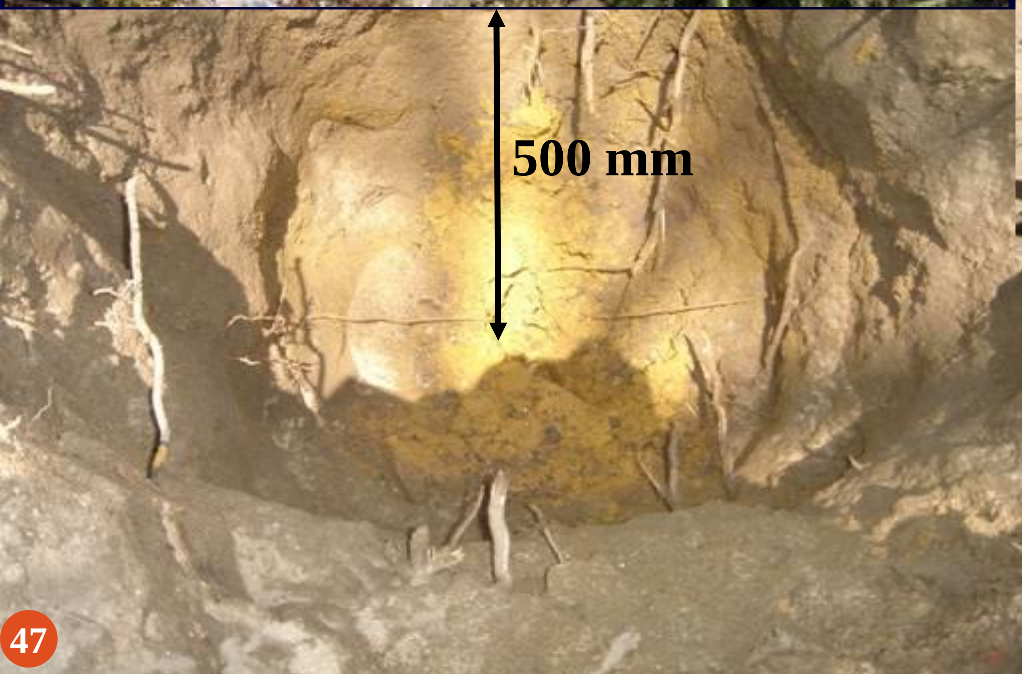






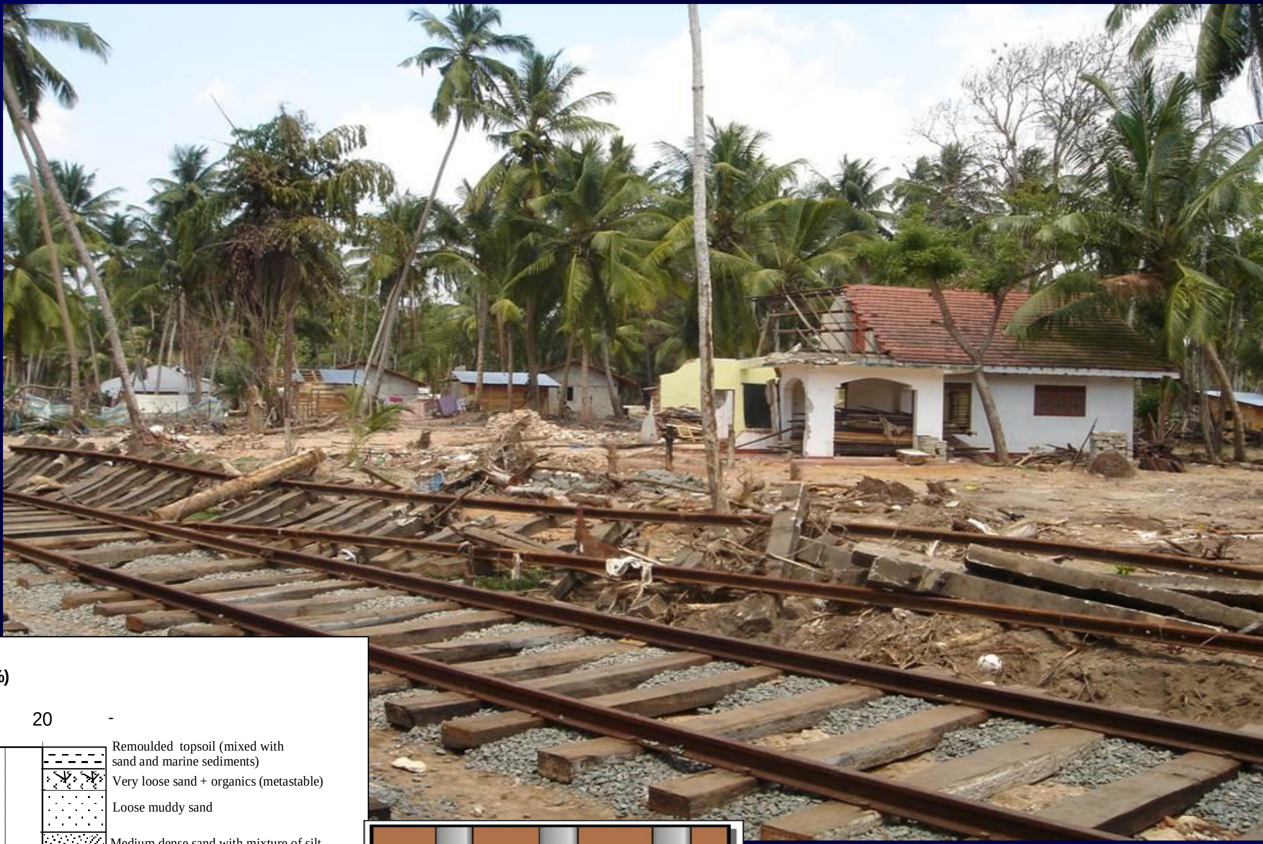
Stressful Challenges in Disaster areas: Post-Tsunami Rail Track Rehabilitation in Sri Lanka (Jan-March 2005)

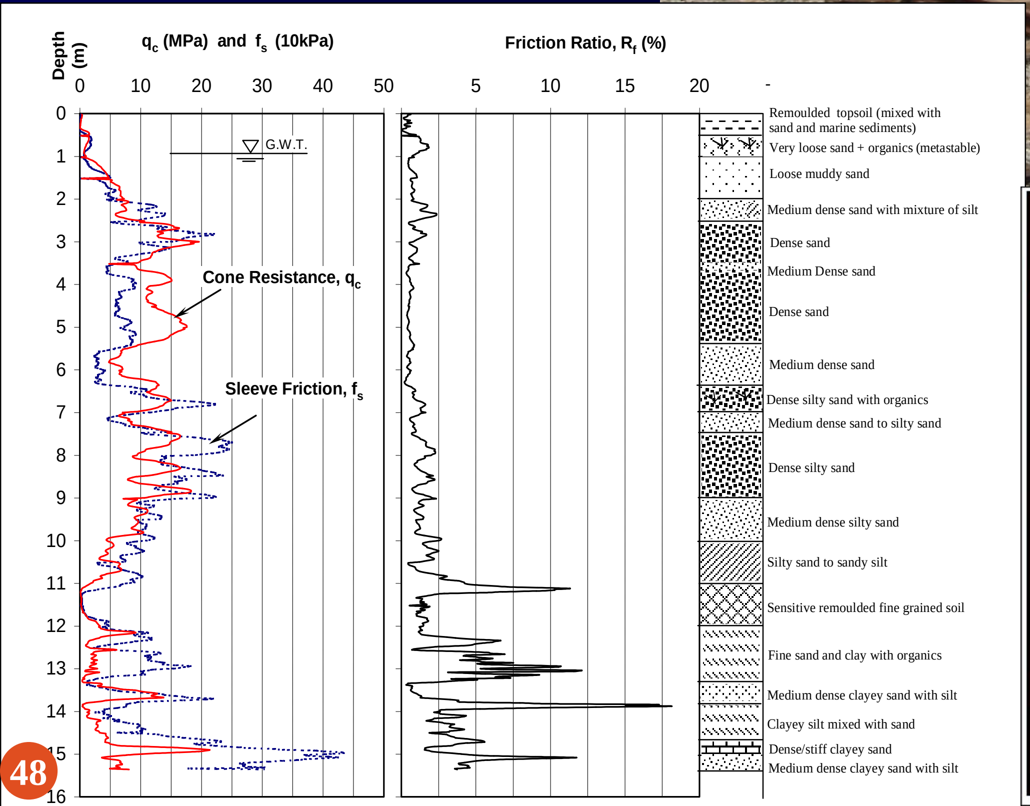


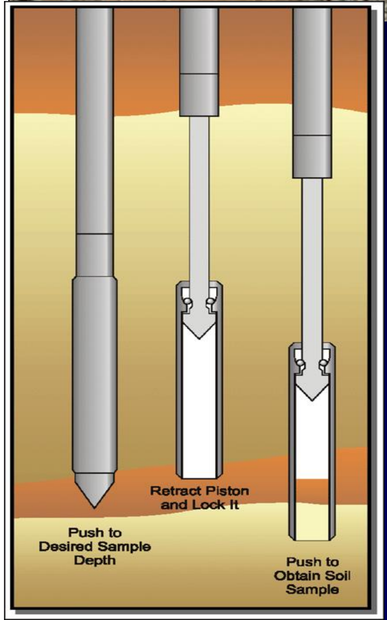


Cone Penetration Test and Trial Pit
Mixed metastable sands with fine sediments (organic) at shallow depths followed by undisturbed coarser sand at greater depths

Ground condition assessment using cone penetration test (CPT)







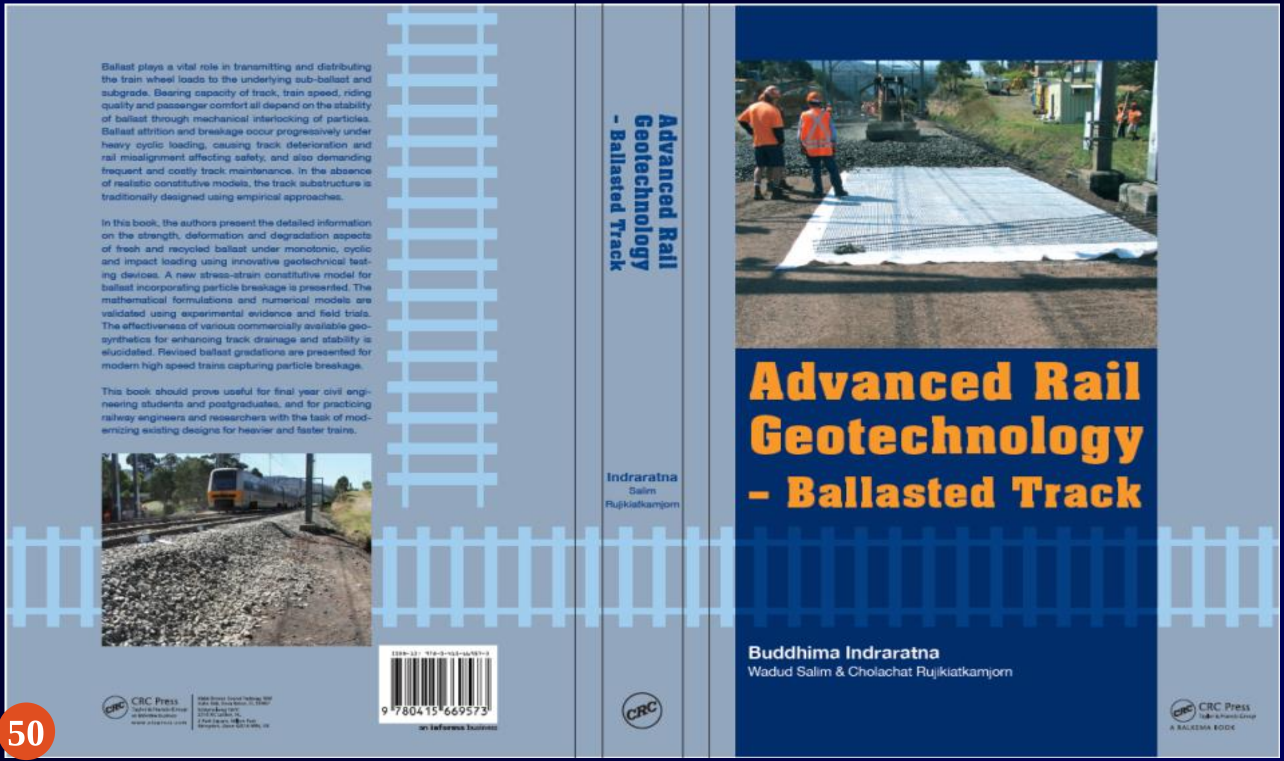
Observe the coconut palm trees !

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



Thank You!