The paper was published in the proceedings of the 12th Australia New Zealand Conference on Geomechanics and was edited by Graham Ramsey. The conference was held in Wellington, New Zealand, 22-25 February 2015.

# Recent advances in railroad infrastructure and track performance - Australian experience

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## ABSTRACT

As trains become longer, heavier and quicker, ballast shows signs of distress and degradation, leading to deterioration of the track geometry. Appropriate stabilisation techniques using artificial inclusions such as polymeric geosynthetics and energy-absorbing shock mats are needed to improve track stability and longevity. Large-scale laboratory tests at University of Wollongong revealed that the geogrids with an optimum aperture governed the effectiveness of the reinforcement mechanism. The use of shock mats was influenced by their placement position and the type of subgrade (e.g. estuarine soil, rock etc.). In these studies, different types of geosynthetics and shock mats were placed beneath the ballast embankment constructed on varying subgrade conditions. Traffic induced stresses, ballast breakage, transient and permanent deformations of the substructure were routinely monitored using precise instrumentation schemes. The findings from the Bulli Study verified that the discarded aggregates could be reused in track construction, if reinforced with geogrids with appropriate apertures. The results of the Singleton Study also showed that geogrids could significantly reduce track deformation especially when subgrade was soft. In contrast, shock mats were more effective in reducing ballast degradation when placed above a concrete deck (i.e. rail bridges).

*Keywords:* ballast, geosynthetics, shock mats, deformation, degradation

## 1 INTRODUCTION

The ballasted rail track is one of the most demanded and widely used modes of urban and freight transportation in Australia. In order to support track superstructure, the use of a ballast layer is prioritized for several reasons, including economy (availability and abundance), rapid drainage, high bearing capacity and resiliency to the repeated wheel loads. However, recent use of longer and heavier freight wagons and faster passenger trains has led to excessive deformation and degradation in ballast, leading to deterioration of the track geometry (Indraratna et al. 2011a, Le Pen and Powrie 2011). The rail industry spends hundreds of millions of dollars in ballast cleaning and replacement. The use of polymeric geosynthetics (geogrids, geotextiles, geocomposites) and shock mats (under-ballast mats and under-sleeper pads) can improve the stability and longevity of track reducing maintenance costs.

Geosynthetics have been widely and successfully used in new tracks and in track rehabilitation schemes for almost three decades. The use of geosynthetics can improve track confinement, and separation between the ballast and subballast under cyclic loading. Geogrids can reduce the lateral spreading of ballast, as well as its degradation (Selig and Waters 1994, Indraratna and Salim 2003, McDowell et al. 2006, Indraratna and Nimbalkar 2013, Indraratna et al. 2014a,b). A layer of geocomposite stabilises recycled ballast, and also prevents the ballast from being fouled due to fines migrating from the underlying layers of subballast and subgrade (Indraratna et al. 2010a,b, 2012, 2014c,d).

The wheel and rail irregularities cause severe repeated impact loads. Two types of peak forces are observed during impact loading, namely, an instantaneous sharp peak ($P_1$) with very high frequency, and a gradual peak ($P_2$) of smaller magnitude with relatively lower frequency (Jenkins et al. 1974). $P_1$ occurs when a vibration mode between the wheel and rail is excited, while $P_2$ occurs when the coupled wheel-rail vibrates in phase on the ballast (Rochard and Schmid 2004). The $P_2$ force leads to an increased magnitude of sleeper-ballast contact stress and rapid ballast degradation. Installing shock mats in rail tracks can attenuate the $P_2$ force and mitigate ballast breakage substantially (Nimbalkar et al. 2012).

However, only a few studies have assessed the relative merits of geosynthetics and shock mats under in situ track conditions (e.g. Rose et al. 2004, Li et al. 2010, Indraratna et al. 2010a, 2014a). In order to gain more insight into performance verification of these artificial inclusions, comprehensive field trials were carried out on two rail lines in Bulli and Singleton in New South Wales supported by Sydney Trains (previously, RailCorp) and Australian Rail Track Corporation (ARTC), respectively. The effectiveness of geosynthetics and shock mats were also assessed in controlled laboratory environment under cyclic and impact loads, respectively. This paper discusses the details of instrumentation, monitoring processes and results of these field studies along with the findings of large-scale laboratory tests at the University of Wollongong.

## 2 SELECTION OF SUITABLE GEOGRIDS

### 2.1 Laboratory Testing

In order to investigate the effect of the geogrid aperture on the ballast-geogrid interface strength, a series of laboratory tests were conducted using large-scale direct shear apparatus (Figure 1). It consists of two square boxes (upper immovable box with dimensions of 300 × 300 × 100 mm and lower movable box with 300 × 300 × 90 mm in size). Fresh latite basalt with a mean particle size ($d_{50}$ = 35 mm) and uniformity coefficient ($C_u$ = 1.87) in accordance with industry recommended particle size distribution (PSD) (AS 2758.7, 1996) and seven geogrids with aperture sizes (A) ranging from 21 to 88 mm were considered. Their physical characteristics and technical specifications are given elsewhere (Indraratna et al. 2011b). Ballast sample was compacted in three layers to achieve the desired field density ($\rho$) of 1550 kg/m$^3$. A geogrid was placed at the interface of the upper and lower sections of the shear box. Tests were conducted at normal pressures of about 26, 38, 52, and 61 kPa, using a strain rate of about $10^{-4}$ /min. All tests were conducted to a maximum strain of 12 %.

*Figure 1. Large-scale direct shear apparatus at University of Wollongong*

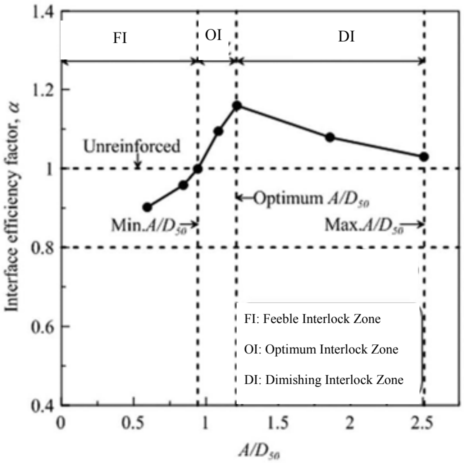

*Figure 2. Variation of interface efficient factor ($\alpha$) with $A/D_{50}$ ratio (data sourced from Indraratna et al., 2011b)*

### 2.2 Results and discussion

An improved behaviour of the ballast-geogrid interface could be determined in terms of the interface efficiency factor ($\alpha$) which is defined as the ratio of the shear strength of the interface to the shear strength of the ballast. A normalised aperture ratio is defined as the ratio of the geogrid aperture size (A) to the mean particle size of ballast ($D_{50}$). Figure 2 shows the variation of $\alpha$ with $A/D_{50}$ ratio. It is shown that $\alpha$ showed an increasing trend until it attained a maximum value of 1.16 at $A/D_{50}$ of 1.21, and then decreased as $A/D_{50}$ approached 2.5. Based on this variation of $\alpha$, the ratio $A/D_{50}$ was classified into three distinct zones: (i) Feeble Interlock (FI) zone, (ii) Optimum Interlock (OI) zone and (iii) Diminishing Interlock (DI) zone. In the FI zone, the particle-grid interlock was weaker than the inter-particle interaction achieved without geogrid, because, the particle-grid interlock was only attributed to smaller particles (<$0.95D_{50}$) compared to the particle-particle interlock with respect to all sizes. An insignificant particle breakage occurred during shearing, which suggests that the interface failure originated from a loss of particle-grid interlock.

In the OI zone, the interlocking of relatively larger particles occurred, which contributed to values of $\alpha$ exceeding unity. The value of $\alpha$ attained a maximum of 1.16 at an optimum $A/D_{50}$ ratio of about 1.20. Significant amount of particle breakage was observed at the interface, which resulted in the interface failure. In the DI zone, the values of $\alpha$ were greater than unity, but the degree of interlocking decreased rapidly, leading to a reduction in $\alpha$ with an increasing $A/D_{50}$ ratio. The minimum and maximum size apertures of geogrid required to achieve maximum efficiency were $0.95D_{50}$ and $2.50D_{50}$, respectively. For all practical purposes, the optimum aperture of geogrid could be considered as $1.15\text{-}1.3D_{50}$.

## 3 USE OF SHOCK MATS FOR MITIGATING BALLAST BREAKAGE

### 3.1 Laboratory Testing

In order to evaluate the effects of impact loads and mitigation of ballast degradation using shock mats, a series of laboratory tests were carried out using large scale drop-weight impact testing equipment (Figure 3). The impact testing equipment consists of a free-fall hammer of 5.81 kN weight that can be dropped from a maximum height of 6 m. An isolated concrete foundation (5 × 3 × 2.5 m) was designed to withstand a significantly higher fundamental frequency than the equipment to eliminate surrounding noise and ground motion. A thin layer of compacted sand was used to simulate a typical 'weak' subgrade. The 10 mm thick shock mat used in the study was made of recycled rubber granulates of 1-3 mm size particles, bounded by a polyurethane elastomer compound.

*Figure 3. Drop weight impact testing equipment at UOW*

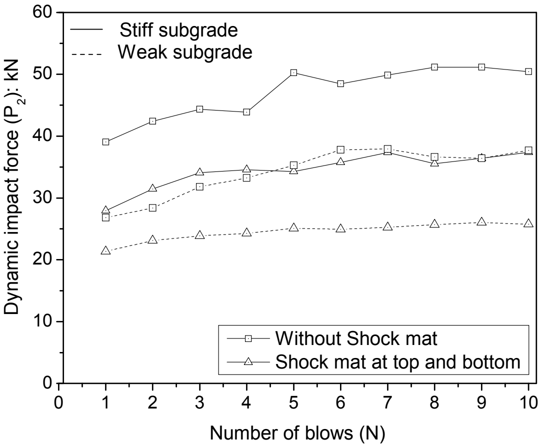

*Figure 4. Variation of impact force ($P_2$) with number of blows (data sourced from Nimbalkar et al. 2012).*

The ballast specimens ($d_{50}$ = 35 mm, $C_u$ = 1.6) were compacted in several layers to simulate the field densities of heavy haul tracks. The drop hammer was raised mechanically to the required height and then swiftly released by an electronic system to simulate impact representative of a typical 'wheel-flat' condition.

### 3.2 Results and discussion

Two distinct force peaks ($P_1$ and $P_2$) were observed during impact loading which was in agreement with a previous study by Jenkins et al. (1974). Figure 4 shows variation of $P_2$ force peak against number of impact blows. $P_2$ force showed a gradual increase with an increased number of blows. This was because the ballast underwent densification due to reorientation and rearrangement of aggregates. A rapid increase of $P_2$ occurred at the initial stages of impact loading, but became almost insignificant thereafter. The stabilisation of ballast after a certain number of impact blows resulted into development of constant $P_2$. Even without a shock mat, a ballast layer on a weak subgrade led to a decreased magnitude of $P_2$ compared to a stiffer subgrade.

Particle degradation severely affects the strength and deformation of ballast (Selig and Waters 1994, Indraratna et al. 2005, Anderson and Fair 2008, Indraratna and Nimbalkar 2011, Nimbalkar and Indraratna 2014). The breakage was measured using the parameter, Ballast Breakage Index (BBI), proposed by Indraratna et al. (2005). After each test, ballast sample was sieved to obtain BBI. The BBI values are presented in Table 1.

*Table 1: Ballast breakage under impact loading (Indraratna et al. 2011b).*

| Test No. | Base type | Shock Mat Details | *BBI* |
|---|---|---|---|
| 1 | Stiff | Without shock mat | 0.170 |
| 2 | Stiff | Shock mat at top of ballast (under sleeper pad) | 0.145 |
| 3 | Stiff | Shock mat at bottom of ballast (under ballast mat) | 0.130 |
| 4 | Weak | Without shock mat | 0.080 |
| 5 | Weak | Shock mat at top of ballast (under sleeper pad) | 0.055 |
| 6 | Weak | Shock mat at bottom of ballast (under ballast mat) | 0.056 |

An application of just 10 impact blows caused considerable ballast breakage (i.e. BBI = 17%) when a stiff subgrade was used (Table 1). However when a shock mat was placed above the ballast bed (i.e. under sleeper pad), BBI was reduced by 14.7% for a stiff subgrade and about 23.5% for a relatively weak subgrade. Also, when a shock mat was placed below the ballast (i.e. under ballast mat), BBI was reduced by 31.3% for a stiff subgrade and about 30% for a relatively weak subgrade. In summary, effectiveness of shock mats was influenced by their placement position and the type of subgrade.

## 4 APPLICATIONS OF GEOGRID FOR TRACK STABILISATION: FIELD ASSESSMENT

In order to investigate train induced stresses and associated track deformation, as well as the advantages of using geosynthetics, a field trial was undertaken on a section of instrumented track at Bulli, NSW (Indraratna et al. 2010a).

### 4.1 Track construction

The field trial was carried out on a section of instrumented track located between two turnouts at Bulli, part of RailCorp's South Coast Track. The total length of the instrumented track section was 60 m, which was divided into four equal sections. Fresh and recycled ballast were used at Sections 1 and 4, while the other two sections were built by placing a geocomposite layer between the ballast and subballast (Figure 5). The PSDs of fresh ballast ($d_{50}$ = 35 m, $C_u$ = 1.5) and recycled ballast ($d_{50}$ = 38 m, $C_u$ = 1.8) were in accordance with the Industrial Standard (AS 2758.7, 1996; TS 3402, 2001). The technical specifications of the geocomposite layer are given in Indraratna et al. (2014d).

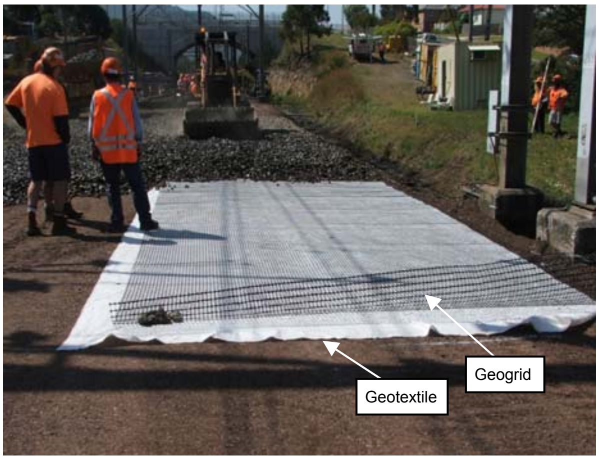

*Figure 5. Installation of geocomposite under the ballast at Bulli, NSW*

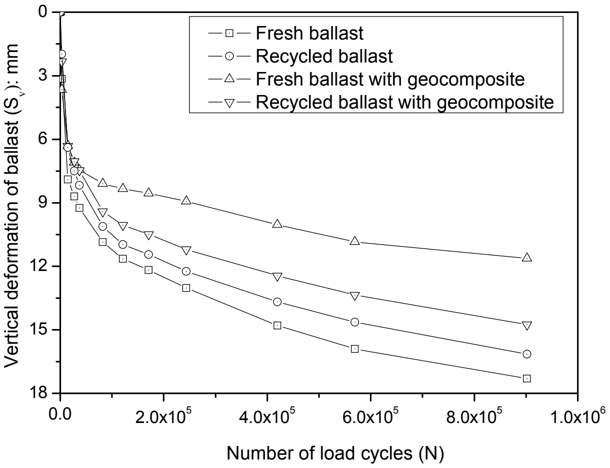

*Figure 6. Average vertical deformations of the ballast layer plotted against number of load cycles (data sourced from Indraratna et al. 2010a)*

The performance of each section of track under the repeated loads of moving trains was monitored using sophisticated instrumentation. The vertical and horizontal stresses induced in the track substructure due to repeated wheel loads were measured by pressure cells. Vertical deformations of the track at different sections were measured by settlement pegs. Lateral deformations were measured by electronic displacement transducers connected to a data acquisition system. Pressure cells were installed at the sleeper-ballast, ballast-subballast and subballast-subgrade interfaces. The settlement pegs and displacement transducers were installed at the sleeper-ballast and ballast-subballast interfaces, respectively.

## 4.2 Ballast deformation

Under repeated loading, the ballast layer undergoes compression in the vertical direction and expands in the two orthogonal lateral directions. The time-dependent vertical deformations were measured in the field. A relationship between the annual traffic tonnage (million gross ton, MGT) and axle load (ton) was used to determine the number of load cycles (Selig and Waters 1994). The ballast deformation ($S_v$) was determined by subtracting the displacements of the ballast-capping interface from those at the sleeper-ballast interface, and it is plotted against the number of load cycles (N) in Figure 6. The vertical deformation is highly non-linear under cyclic loading and the similar trend is observed also in the laboratory (Indraratna et al. 2005, 2012, Indraratna and Nimbalkar 2013). Its non-linear variation against the number of load cycles is best described by a semi-logarithmic relationship (Indraratna et al. 2011a):

$$S_v = a + b\left(\ln N\right) \tag{1}$$

where, a and b are two empirical constants, depending on the type of ballast, type of geosynthetics used, and the initial placement density. The recycled ballast showed less deformations because of its moderately graded PSD compared to the very uniform fresh ballast. Recycled ballast often has less breakage because the individual aggregates are less angular which prevents corner breakage resulting from high contact stresses. The results presented in Figure 6 indicate that a geocomposite can reduce vertical deformation of fresh ballast by 33% and that of recycled ballast by 9%. The aperture of the geogrid (A = 40 × 27 mm) was adequate to offer a strong interlock with fresh ballast ($d_{50}$ = 35 m) than with recycled ballast ($d_{50}$ = 38 m). Thus, the results of the field trial demonstrated the potential benefits of using a geocomposite at the base of the ballast layer in track, and the use of moderately graded recycled ballast with favourable implications on cost savings.

## 4.3 Stresses in ballast

The stresses were measured under the rail and at the edge of the sleeper. Figure 7 shows the maximum cyclic vertical ($\sigma_v$) recorded at Section 1 (i.e. fresh ballast) due to the passage of a coal train with 25 tons axle load. It is evident that $\sigma_v$ decreases significantly with depth.

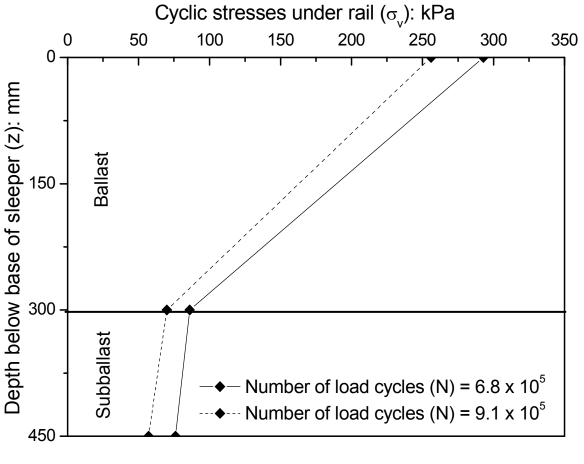

*Figure 7. Cyclic stresses induced by coal train with 25 tons axle load (data sourced from Indraratna et al., 2010a).*

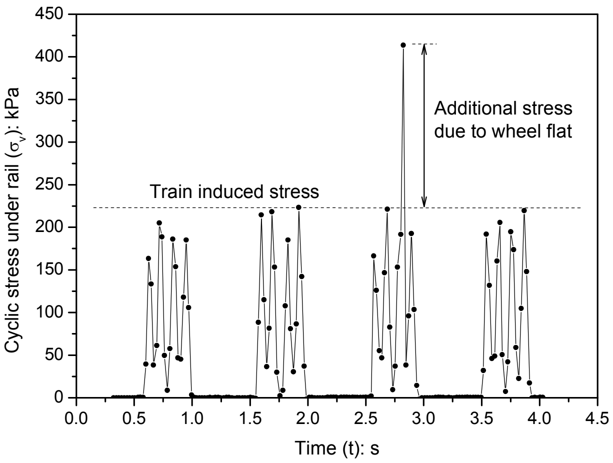

*Figure 8. Cyclic stresses induced by coal train with 25 tons axle load (data sourced from Indraratna et al., 2010a).*

Figure 8 shows transient records of vertical stresses induced at sleeper-ballast interface due to the passage of a coal train with 25 tons axle load. This transient data was collected by operating the data acquisition system in high frequency mode. While most of the peak stresses ranged up to 230 kPa, one peak stress reached 415 kPa, which was associated with a wheel flat. This proved that large dynamic impact loads can be generated by wheel imperfections. The shock mats can be used for mitigating damage induced by impact loads. The 'in-field' performance of these artificial inclusions are described in the following section.

## 5 APPLICATIONS OF GEOGRID AND SHOCKMAT FOR TRACK STABILISATION: FIELD ASSESSMENT

To investigate the performance of different types of inclusions to improve overall track stability, an extensive study was undertaken on instrumented track sections near Singleton, NSW.

### 5.1 Track construction

Eight experimental sections were constructed on subgrades viz. (i) the relatively soft general fill and alluvial silty clay deposit, (ii) the stiff reinforced concrete bridge deck, and (iii) the intermediate siltstone. The track substructure consisted of a 300 mm thick ballast ($d_{50}$ = 36 mm, $C_u$ = 1.6) underlain by a 150 mm thick layer of subballast. A structural fill with a minimum of 500 mm thickness was placed below the subballast. Three commercially available geogrids and one geocomposite were installed at the ballast-subballast interface (Figure 9). A layer of shock mat was installed between the ballast and bridge deck to minimise any degradation of the ballast. Pressure cells and settlement pegs were installed at the sleeper-ballast and ballast-subballast interfaces. Technical specifications of various instruments, geosynthetics and shock mat used at the site can be found in Indraratna et al. (2014a,d).

*Figure 9. Installation of geogrid under the ballast at Singleton, NSW*

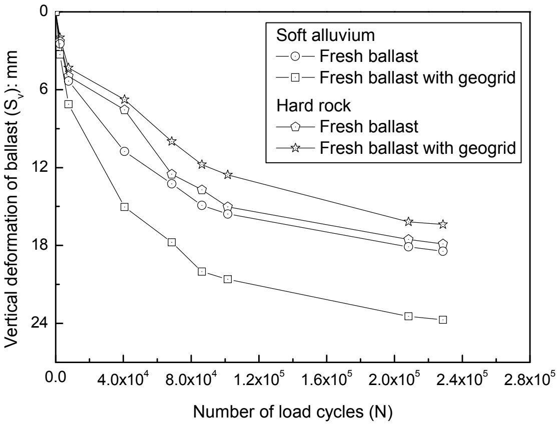

*Figure 10. Average vertical deformations of the ballast layer plotted against number of load cycles (data sourced from Indraratna et al., 2014a)*

### 5.2 Ballast deformation

The variation of ballast deformations ($S_v$) against number of load cycles is shown in Figure 10. The vertical deformation of the ballast is highly nonlinear under cyclic loading, and is in agreement with the laboratory data (Section 3) and field trial (Section 4) discussed earlier. The vertical deformations of ballast with reinforcement were generally smaller (10-32%) than those without reinforcement. This observation is mainly attributed to interlocking between the ballast particles and geogrid, thus indicating larger track confinement as discussed previously. When the results for different subgrades are compared, ballast deformations were found to be largest at the soft alluvial deposit. When the results for sections with similar geogrids were compared, it was observed that the effectiveness of a geogrid to reduce track settlement became higher for softer subgrades. This observation is in agreement with the study by Ashmawy and Bourdeau (1995).

### 5.3 Ballast breakage

Samples were recovered from load bearing ballast beneath the rail seat. Visual inspection revealed that fouling of the ballast layer due to spillage of coal from passing trains and 'slurry pumping' of the fines from the underlying subgrade had not taken place at this relatively new track. Particle breakage was quantified in terms of BBI and its values are shown in Table 2.As expected, the ballast breakage was highest at the top and reduced with depth. The variations in the BBI with depth were found quite similar to those observed in stresses and displacements of load bearing ballast layer. Largest values of BBI at hard rock revealed that particle breakage was influenced by the type of subgrade. The ballast degradation phenomenon was more pronounced for stiff subgrade than that for the relatively soft or weak subgrade. This is in agreement with the laboratory study reported in Section 3.

*Table 2: Assessment of ballast breakage (data sourced from Indraratna et al. 2014b)*

| Sr. No. | subgrade | BBI | | |
|---|---|---|---|---|
| | | top | middle | bottom |
| 1 | alluvial silty clay | 0.17 | 0.08 | 0.06 |
| 2 | concrete bridge deck | 0.06 | 0.03 | 0.02 |
| 3 | siltstone | 0.21 | 0.11 | 0.09 |

Although the track at concrete bridge deck was much stiffer than that at soft alluvial deposit, larger confinement from the barriers of bridge most likely resulted in a significantly smaller value of BBI. These results may also suggest the effectiveness of under-ballast mats in reducing particle degradation when placed above the concrete deck. However, more data from a similar bridge without any shock mat inclusion is vital for further validation.

## 6 CONCLUSIONS

This paper presented recent advances in railway infrastructure and their implications on track performance and stability. The effects of ballast degradation and benefits of geosynthetics (geogrid, geotextile, geocomposite) and shock mats (under sleeper pads, under ballast mats) for improved track performance were analysed through laboratory studies and field trials. The use of large-scale shear apparatus, drop-weight impact testing equipment and precise instrumentation schemes adopted at instrumented sections of rail track near Sydney in Australia has advanced the state of the art knowledge in railroad transportation geomechanics.

The large-scale direct shear tests revealed that normalised aperture ratio ($A/D_{50}$) had a profound influence on the interface efficiency factor ($\alpha$). An optimum aperture size of geogrid was found to be $1.20D_{50}$ which was able to derive maximum shear strength of ballast-grid interface. The minimum aperture required to attain the beneficial effects of geogrids was $0.95D_{50}$. The large-scale impact tests showed that the shock mat was able to reduce particle breakage as well as attenuate impact force. The use of shock mat was influenced by its placement position and the type of subgrade. The impact caused considerable ballast breakage (BBI = 17%) in case of stiff subgrade. Due to the use of an under-sleeper pad, particle breakage was reduced by 14.7% using a stiff subgrade and by 23.5% for a weak subgrade, while the inclusion of an under-ballast mat, particle breakage was reduced by 31.3% for a stiff subgrade and by 30% for a weak subgrade.

The findings of the Bulli field study demonstrated that the recycled ballast could be reused in track construction, if stabilised using geocomposite reinforcement. The geocomposite was able to minimise the deformation and degradation of rail tracks. The results of the Singleton field study showed that geogrids with an optimum aperture size could significantly reduce ballast deformation by improving the interlock between the particles. The effectiveness of geosynthetics appeared to increase, as the subgrade became softer. Results of large scale laboratory tests and field trials demonstrated the benefits of using geosynthetics and shock mats for improved performance and stability of track substructure.

## 7 ACKNOWLEDGEMENTS

The authors wish to thank the Australian Research Council (ARC) Centre of Excellence in Geotechnical Science and Engineering, CRC for Rail Innovation, Sydney Trains (previously, RailCorp), Australian Rail Track Corporation (ARTC), and Aurizon (previously, Queensland Rail National) for their continuous support during various phases of this research. The assistance of Mr David Christie (formerly Senior Geotechnical Consultant, RailCorp), Mr Tim Neville (ARTC), Mr Michael Martin (Aurizon), and Mr Sandy Pfeiffer (RailCorp) is gratefully acknowledged. A significant portion of the contents reported here are described in more detail in a number of scholarly articles listed below. Kind permission has been obtained to reproduce some of these contents in this paper.

# 8 REFERENCES

Anderson, W. F., and Fair, P. (2008). “Behaviour of railroad ballast under monotonic and cyclic loading.” Journal of Geotechnical and Geoenvironmental Engineering ASCE, 134 (3), 316-327.

Ashmawy, A. K., and Bourdeau, P. L. (1995). “Geosynthetic-reinforced soils under repeated loading: a review and comparative design study.” Geosynthetics International, 2 (4), 643-678.

AS 2758.7 (1996). “Aggregates and rock for engineering purposes; Part 7: Railway ballast.” Australian Standard, NSW, Australia.

Indraratna, B., Hussaini, S. K. K., and Vinod, J. S. (2011b). “On the shear behavior of ballast-geosynthetic interfaces.” ASTM Geotechnical Testing Journal, 35 (2), 1-8.

Indraratna, B., Lackenby, J., and Christie, D. (2005). “Effect of confining pressure on the gradation of ballast under cyclic loading.” Geotechnique, 55 (4), 325-328.

Indraratna B, and Nimbalkar S. (2011). “Implications of ballast breakage on ballasted railway track based on numerical modeling.” Proceedings of 13th International Conference of the International Association for Computer Methods and Advances in Geomechanics, Khalili, N and Oeser, M (eds), Melbourne Australia: 1085-1092.

Indraratna, B., and Nimbalkar, S. (2013). “Stress-strain degradation response of railway ballast stabilized with geosynthetics.” Journal of Geotechnical and Geoenvironmental Engineering ASCE, 139 (5), 684-700.

Indraratna B., Nimbalkar S., Christie D., Rujikiatkamjorn C., and Vinod J. S. (2010a). “Field assessment of the performance of a ballasted rail track with and without geosynthetics.” Journal of Geotechnical and Geoenvironmental Engineering ASCE, 136 (7), 907-917.

Indraratna, B., Nimbalkar, S., and Neville, T. (2014a). “Performance assessment of reinforced ballasted rail track.” Proceedings of the Institution of Civil Engineers – Ground Improvement, 167 (1), 24-34.

Indraratna, B., Nimbalkar, S., and Rujikiatkamjorn, C. (2012). “Track stabilisation with geosynthetics and geodrains, and performance verification through field monitoring and numerical modeling.” International Journal of Railway Technology, 1 (1), 195-219.

Indraratna, B., Nimbalkar, S., and Rujikiatkamjorn, C. (2014b). “Enhancement of rail track performance through utilisation of geosynthetic inclusions”, Geotechnical Engineering Journal of the SEAGS & AGSSEA, 45 (1), 17-27.

Indraratna, B., Nimbalkar, S., and Rujikiatkamjorn, C. (2014c). “Modernisation of rail tracks for higher speeds and greater freight”, International Journal of Railway Technology, 2 (3), 1-20.

Indraratna, B., Nimbalkar, S., and Rujikiatkamjorn, C. (2014d). “From Theory to Practice in Track Geomechanics - Australian Perspective for Synthetic Inclusions.” Transportation Geotechnics Journal - Special issue on ‘Rail Geomechanics - From Theory to Practice’, doi: http://dx.doi.org/10.1016/j.trgeo.2014.07.004.

Indraratna, B., Nimbalkar, S., and Tennakoon, N. (2010b). “The behaviour of ballasted track foundations: track drainage and geosynthetic reinforcement” GeoFlorida 2010, ASCE Annual GI Conference, Florida, USA.

Indraratna B., and Salim W. (2003). “Deformation and degradation mechanics of recycled ballast- stabilised with geosynthetics. Soils and Foundations, 43 (4), 35-46.

Indraratna, B., Salim, W., and Rujikiatkamjorn, C. (2011a). “Advanced rail geotechnology - ballasted track.” CRC Press, Taylor & Francis Group, London, UK.

Jenkins, H. M., Stephenson, J. E., Clayton, G. A., Morland, J. W., and Lyon, D. (1974). “The effect of track and vehicle parameters on wheel/rail vertical dynamic forces.” Railway Engineering Journal, 3, 2-16.

Le Pen, L. M., and Powrie, W. (2011). “Contribution of base, crib and shoulder ballast to the lateral sliding resistance of railway track: a geotechnical perspective.” Proceedings of Institution of Mechanical Engineers Part F: Journal of Rail & Rapid Transit, 225 (2), 113-128.

Li, D., Otter, D., and Carr, G. (2010). “Railway bridge approaches under heavy axle load traffic: problems, causes, and remedies.” Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit, 224 (5), 383-390.

McDowell G. R., Harireche O., Konietzky H., Brown, S. F., and Thom, N. H. (2006). “Discrete element modelling of geogrid-reinforced aggregates.” Proceedings of the Institution of Civil Engineers – Geotechnical Engineering, 159 (1), 35-48.

Nimbalkar, S., and Indraratna, B. (2014). “Numerical and analytical modeling of particle degradation.” Proceedings of 14th International Conference of the International Association for Computer Methods and Advances in Geomechanics, Kyoto Japan, Accepted, in press.

Nimbalkar, S., Indraratna, B., Dash, S. K., and Christie, D. (2012). “Improved performance of railway ballast under impact loads using shock mats.” Journal of Geotechnical and Geoenvironmental Engineering ASCE, 138 (3), 281-294.

Rochard, B. P., and Schmidt, F. (2004). “Benefits of lower-mass trains for high speed rail operations.” Proceedings of the Institution of Civil Engineers – Transportation Engineering, 157 (1), 51-64.

Rose, J., Su, B., and Twehues, F. (2004). “Comparisons of railroad track and substructure computer model predictive stress values and in-situ stress measurements.” Proceedings of the Annual Conference and Exposition, American Railway Engineering and Maintenance-of-Way Association, USA.

Selig, E. T., and Waters, J. M. (1994). “Track Geotechnology and Substructure Management.” Thomas Telford, UK.

T. S. 3402. (2001). “Specification for Supply of Aggregates for Ballast.” Rail Infrastructure Corporation of NSW, Sydney, Australia.