Performance Assessment of Synthetic Shock Mats and Grids in the Improvement of Ballasted Tracks

Évaluation de la performance des nappes synthétiques à effet d'amortissement et des géogrilles dans l'amélioration des plates-formes ferroviaires ballastées

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ABSTRACT: In Australia, railways offer the most prominent transportation mode in terms of traffic tonnage serving the needs of bulk freight and passenger movement. Ballast is an essential constituent of conventional rail infrastructure governing track stability and performance. However, in recent times, higher traffic induced stresses due to dramatically increased train speeds and heavier axle loads have caused excessive plastic deformations and degradation of ballast. This seriously hampers safety and efficiency of express tracks, for instance, enforcing speed restrictions and effecting more frequent track maintenance. Installing layers of synthetic materials such geogrids and rubber pads (shock mats) in rail tracks can significantly reduce ballast degradation. Field trials were conducted on rail track sections in the towns of Bulli (near Wollongong City) and Singleton (near Newcastle) to measure track deformations associated with cyclic stresses and impact loads. This paper describes the results of large-scale laboratory testing as well as the observations from full-scale instrumented field trials characterising the behaviour of rail ballast improved by shock mats and synthetic grids.

RÉSUMÉ : En Australie, les chemins de fer offrent le mode de transport plus important en terme de tonnage de trafic apte à répondre aux besoins de transport de passagers et de fret en vrac. Le ballast est un constituant essentiel de l'infrastructure ferroviaire conventionnelle régissant les performances et la stabilité de la voie. Toutefois, dans les temps récents, les contraintes plus fortes induites par un trafic se faisant à vitesse de plus en plus élevée et avec des charges à l'essieu plus importantes provoquent des déformations plastiques excessives et la dégradation du ballast. Cela entrave sérieusement la sécurité et l'efficacité des voies expresses en nécessitant, par exemple, des restrictions de vitesse et un entretien des voies plus fréquent. L'installation de couches de matériaux géosynthétiques tels que les géogrilles et les nappes de caoutchouc dans les plates-formes ferroviaires peuvent réduire de façon significative la dégradation du ballast. Des essais en place ont donc été réalisés sur des sections de plates-formes ferroviaires dans les villes de Bulli (près de Wollongong) et Singleton (près de Newcastle) afin de mesurer les déformations de la voie associées à des charges cycliques et d'impacts. Cette communication présente les résultats des essais en laboratoire à grande échelle ainsi que des observations résultant des essais en place grandeur nature instrumentés, caractérisant le comportement du ballast ferroviaire amélioré par les renforcements en grilles géosynthétiques.

KEYWORDS: ballast, degradation, field trial, geosynthetics, impact loads, shock mats.

1 INTRODUCTION

The rail track structure consists of rail, sleeper (crossties), ballast, sub-ballast (capping and structural-fill) and subgrade. Ballast is one of important track components and is used as the primary means of distributing of the wheel loads to underlying layers, and for holding the track in proper alignment, cross level and grade. The ballast assembly undergoes irrecoverable deformations due to particle breakage and cyclic densification. The breakage of ballast particles due to wheel loading can occur due to: (a) the particle splitting, (b) breakage of angular projections and (c) grinding of small-scale asperities (Raymond and Diyaljee 1979). In Australia, most breakage of latite ballast is primarily attributed to the presence of highly angular corners of quarried aggregates (Lackenby et al. 2007).

Several previous studies focused on the laboratory testing of the soil-geogrid interfaces (Tang et al. 2008, Liu et al. 2009) and the ballast-geogrid interfaces (Raymond 2002, Indraratna and Salim 2003, Brown et al. 2007, Indraratna et al. 2010a,b). In order to reduce ballast degradation, the use of geosynthetic grids has been recommended (Selig and Waters 1994, Indraratna et al. 2006, 2007, Indraratna and Nimbalkar 2012). The geosynthetic grids hinder the lateral movement of ballast due to frictional interlock among aggregates. The grid-particle interlock in turn increases the track stability and prolongs the maintenance period. Wheel-rail irregularities such as wheel flats produce high levels of impact loading (Indraratna et al. 2010). This impact load induces high frequency vibration of the track components (Jenkins et al. 1974, Indraratna et al. 2011a,b,c). It has been proven that excessive impact loads aggravate ballast degradation (Indraratna et al. 2012a,b, Nimbalkar et al. 2012). A field trial was conducted on sections of an instrumented rail track in the town of Bulli (near Wollongong) and Singleton (near Newcastle) to study the effectiveness of geosynthetic grids and shock mats. This paper describes the large-scale laboratory studies and full-scale field trials.

2 USE OF SHOCK MATS IN MITIGATING BREAKAGE

In order to evaluate the effectiveness of shock mats, a large scale drop-weight impact testing equipment was used.

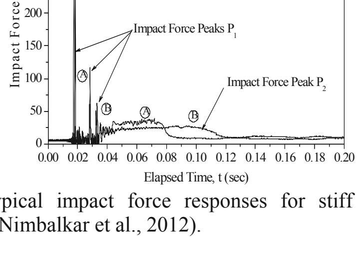

Figure 1. Typical impact force responses for stiff subgrade (data sourced from Nimbalkar et al., 2012).

2.1 *Test setup and procedure*

A steel plate of 300 mm diameter and 50 mm thickness was used to represent a hard base such as the deck of a bridge, or hard rock. A thick sand layer of 100mm thickness was used to simulate a typical 'weak' subgrade. The drop hammer was raised mechanically to the required height and then released by an electronic quick release system. After 10 blows, an attenuation of strains in the ballast layer was reached.

2.2 *Single impact loading*

The impact load-time history under a single impact load is shown in Figure 1. Two distinct types of peak forces were seen during impact loading: (a) an instantaneous sharp peak with very high frequency P_1, and (b) a gradual peak of smaller magnitude with a relatively smaller frequency P_2 (Jenkins et al. 1974). It was also evident that multiple P_1 type peaks followed by the distinct P_2 type peak often occurred. The multiple P_1 peaks occurred when the drop hammer was not restrained vertically, so consequently it rebounded after the first impact and impacted the specimen again.

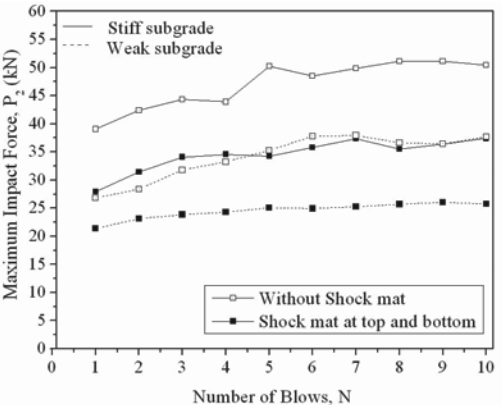

Figure 2. Variation of impact force with number of blows (data sourced from Nimbalkar et al. 2012).

2.3 *Multiple impact loading*

Figure 2 shows the variation of P_2 force peak with repeated hammer blows (N). The P_2 force showed a gradual increase with the increased number of blows due to the densification of ballast. A dense aggregate matrix offers a higher inertial resistance which leads to an increased value of P_2. Even without a shock mat, a ballast bed on a weak subgrade leads to a decreased magnitude of impact force compared to a stiffer subgrade.

2.4 *Particle breakage*

After each test, the ballast sample was sieved to obtain the ballast breakage index (BBI) as shown in Table 1. The particle breakage encountered under 10 impact blows was significantly higher than that under both static and cyclic loads (Indraratna et al. 1998, 2005, Lackenby et al. 2007, Indraratna and Nimbalkar 2011).

The higher breakage of ballast particles can be attributed to the considerable non-uniform stress concentrations occurring at the corners of the sharp angular particles of fresh ballast under high impact stresses. When a shock mat was placed above and below the ballast bed, particle breakage was reduced by approximately 47% for a stiff subgrade, and approximately 65% for a weak subgrade. This implies that the weak subgrade itself acts as a flexible cushion.

Table 1. Ballast breakage under impact loading (Indraratna et al., 2011a).

Base type	Test Details	*BBI*
Stiff	Without shock mat	0.170
Stiff	Shock mat at top and bottom of ballast	0.091
Weak	Without shock mat	0.080
Weak	Shock mat at top and bottom of ballast	0.028

3 USE OF GEOSYNTHETICS FOR STABILISING A BALLASTED TRACK: BULLI CASE STUDY

In order to investigate deformations of a multi-layer rail track caused by train traffic, and the associated benefits of using geosynthetics in fresh and recycled ballast, a field trial was carried out on a fully instrumented track in the town of Bulli north of Wollongong City [Indraratna et al. 2009, 2010]. The proposed site was located between two turnouts.

3.1 *Site geology and track construction*

A site investigation comprising 8 test pits and 8 Cone Penetrometer tests was carried out to assess the condition of the sub-surface soil profiles. The subgrade consisted of a stiff over consolidated silty clay that showed high values of cone resistance (q_c) and friction ratio (R_f) (Robertson 1990, Choudhury 2006).

The instrumented section of track was 60 m long and it was divided into four equal sections. The layers of ballast and subballast (capping) were 300 mm and 150 mm, respectively. Fresh and recycled ballast without a geocomposite layer were used in two sections, while in the other two sections, fresh and recycled ballast was used with a layer of geocomposite at the ballast-subballast interface. The physical and technical specifications of the fresh ballast, recycled ballast and geosynthetic material used at this site have been reported elsewhere (Indraratna et al. 2011a, 2012a).

3.2 *Track instrumentation*

The vertical and horizontal stresses induced in the track bed were measured by pressure cells. Vertical deformations of the track were measured by settlement pegs, and lateral deformations were measured by electronic displacement transducers. The settlement pegs and displacement transducers were installed at the sleeper-ballast and ballast-subballast interfaces, respectively, as shown in Figure 3.

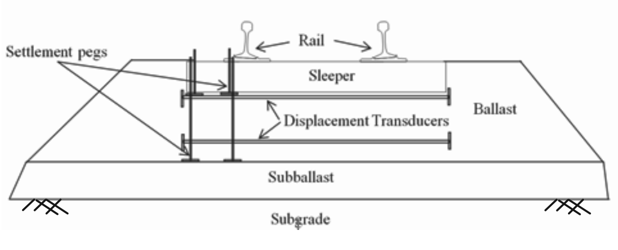

Figure 3. Installation of settlement pegs and displacement transducers at Bulli site (data sourced from Indraratna et al. 2012b)

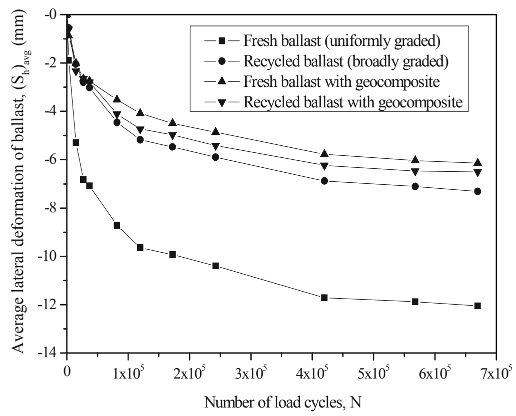

Figure 4. In-situ response of the ballast layer: lateral deformations (data sourced from Indraratna et al. 2010).

3.3 *Lateral ballast deformations*

Average lateral deformations of ballast are plotted against the number of load cycles (*N*) in Figure 4. The recycled ballast with moderately graded particle size distribution (C_u = 1.8) showed less lateral deformations compared to the very uniform fresh ballast (C_u = 1.5). Recycled ballast often shows less breakage because the individual particles are more rounded which prevents high angular corner breakage caused by high stress concentrations. The results presented in Figure 4 indicate that the geocomposite reduced lateral deformation of fresh ballast by about 49 % and that of recycled ballast by 11 %. The apertures of the geogrid offered strong mechanical interlocking with the ballast. The capacity of the ballast to distribute loads was improved by the placement of the geocomposite, which substantially reduced settlement under high repeated loading.

4 USE OF GEOSYNTHETICS FOR STABILISING A BALLASTED TRACK: SINGLETON CASE STUDY

To investigate the performance of different types of geosynthetics for improving the overall track stability under in situ conditions, an extensive study was also undertaken on an instrumented track sections in Singleton, near the City of Newcastle.

4.1 *Site geology and track construction*

Nine experimental sections were included in the trial track while it was under construction, on three different types of sub-grades, including (i) the relatively soft general fill and alluvial silty clay deposit (Sections 1-4 and Section *A*), (ii) the intermediate cut siltstone (Sections 5 and *C*), and (iii) the stiff reinforced concrete bridge deck supported by a piled abutment (Section B), as shown in Table 2. Further details of track construction and material specifications can be found in Indraratna et al. (2012c).

Table2. Reinforcement at experimental sections using geogrids, geocompolistes, and shock mats.

Section	Location	Reinforcement
A	234.75	-
1	234.66	Geogrid 1
2	234.40	Geogrid 2
3	234.22	Geogrid 3
4	234.12	Geocomposite
B	232.01	Shock mat
C	228.50	-
5	228.44	Geogrid 3

4.2 *Track instrumentation*

The strain gauges were installed in groups, 200 mm apart, and on the top and bottom sides of the grids in both longitudinal and transverse directions (Figure 5). The strain gauges were of a post-yield type suitable to measure strains in the range of 0.1 to 15%. Two pressure cells were installed at Sections 1, 5, *A* and *C*. At these locations, one pressure cell was installed at the sleeper-ballast and another at the ballast-sub-ballast interface. At Section *B*, three pressure cells were installed at the synthetic mat-deck interface. Settlement pegs were also installed at the sleeper-ballast and ballast-sub-ballast interfaces to measure the vertical deformations of the ballast layer.

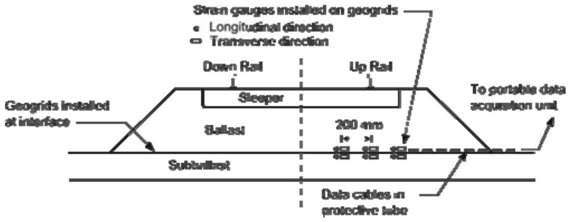

Figure 5. Details of track instrumentation using strain gauges.

4.3 *Vertical ballast deformations*

The settlements (s_v) and vertical strains (ε_v) of the ballast layer after 2.3 × 10^5 load cycles are reported in Table 3. The vertical settlements of sections with reinforcement are generally smaller than those without reinforcement. This observation is mainly attributed to the effective interlocking between the ballast particles and grids, thus inducing increased track confinement as explained earlier. When sections *a*, *b*, and *c* are compared, the results indicate that s_v and ε_v are larger when the subgrade stiffness becomes smaller, i.e. S_v is smallest on the concrete bridge deck and largest at the alluvial deposit.

Table 3. Vertical deformation and strain of ballast after 2.3×10^5 load cycles.

	Instrumented section details							
	1	2	3	4	5	A	B	C
S_v (mm)	16.3	21.2	14.8	16.0	16.3	23.8	8.8	17.8
ε_v (%)	5.4	7.1	4.9	5.3	5.4	7.9	2.9	5.9

It is also observed that the geogrid is more effective in terms of reducing track settlement for relatively weak subgrades. Similar observations have been reported by Ashmawy and Bourdeau (1995) thorough full scale testing. The geogrid at Section 3 performed better, although the tensile strength did not differ much with the other types. This is attributed to the optimum aperture size (40 mm) which would enable better interlocking between the ballast particles and the geogrid.

4.4 *Strains accumulation in geogrids & geocomposites*

Accumulated longitudinal (ε_l) and transverse (ε_t) strains after 2.3 × 10^5 load cycles are given in Table 4. The transverse strains were generally larger than the longitudinal strains, and this is attributed to the ease of lateral spreading of the ballast layer upon loading. It was also observed that ε_l and ε_t were mainly influenced by the subgrade deformations. The strains of geogrid at Section 4 were relatively large although its higher stiffness could have resulted in smaller strains. This is because, the thicker general fill underwent large lateral deformations shortly after the track was commissioned. Induced transient strains in both longitudinal and transverse directions due to the passage of trains (axial load of 30 tons) travelling at 40 km/h were of magnitude in the order of 0.14-0.17 %.

Table 4. Accumulated longitudinal and transverse strain in geogrid and geocomposite after 2.3×10^5 load cycles.

	Instrumented section details				
	1	2	3	4	5
ε_l (%)	0.80	0.78	0.61	0.60	0.62
ε_t (%)	0.85	1.50	0.80	1.80	0.85

5 CONCLUSIONS AND RECOMMENDATIONS

The effects of geosynthetic reinforcement and shock mats on the performance of ballasted rail tracks were discussed in this paper. The use of shock mats was beneficial in terms of reduced ballast breakage and attenuated impact forces. A few impact blows were observed to have caused considerable ballast breakage (*BBI* = 17%). Due to the placement of shock mats, *BBI* could be reduced by approximately 47% over a stiff subgrade and by approximately 65% over a weak subgrade.

The performance of instrumented ballasted tracks at Bulli and Singleton was evaluated, in which different types of geosynthetics were examined. The results of the Bulli field study indicated that the use of geocomposites as reinforcing elements for recycled ballast proved to be a feasible and economically attractive alternative. The results of the Singleton study revealed that the effectiveness of geogrids is greater for relatively weak subgrades. The accumulated strains in the geogrids were influenced by the subgrade deformation, while the induced transient strains were mainly affected by the geogrid stiffness. An in-depth understanding of the geogrid and shock mat stabilised performance would allow for safer and more effective ballasted track design and construction in the future, especially for increased trains speeds where high cyclic loading together with impact is almost inevitable.

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