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Abstract

The ballasted railroads form an integral part of the modern transportation infrastructure in Australia. However, they are subjected to large stresses especially on mixed traffic lines, where heavy freight trains are operated. Under such adverse operational conditions, ballast progressively degrades contributing to overall track deformations and frequent maintenance. Maintaining geometry of ballast embankments is necessary to improve safety and efficiency of railway operations. The use of artificial inclusions (geosynthetics and shock mats) as well as recycled (discarded) ballast in track can be economically viable options. In order to gain more insight, the CGRE has conducted extensive field trials on two rail lines in Bulli and Singleton in New South Wales supported by Sydney Trains and Australian Rail Track Corporation, respectively. In these studies, different types of geosynthetics (geogrid, geotextile and geocomposite) and shock mats were installed beneath the ballast layer constructed on varying subgrade conditions. Relative advantages of different geogrids were studied. Traffic induced stresses, ballast breakage, transient and permanent deformations were routinely monitored using precise instrumentation schemes. This paper discusses the details of track construction, instrumentation, monitoring processes and results of these field studies.

Keywords

shock, mats, railroads, ballasted, geosynthetics, assessment, field

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Field Assessment of Ballasted Railroads using Geosynthetics and Shock Mats

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Abstract
The ballasted railroads form an integral part of the modern transportation infrastructure in Australia. However, they are subjected to large stresses especially on mixed traffic lines, where heavy freight trains are operated. Under such adverse operational conditions, ballast progressively degrades contributing to overall track deformations and frequent maintenance. Maintaining geometry of ballast embankments is necessary to improve safety and efficiency of railway operations. The use of artificial inclusions (geosynthetics and shock mats) as well as recycled (discarded) ballast in track can be economically viable options. In order to gain more insight, the CGRE has conducted extensive field trials on two rail lines in Bulli and Singleton in New South Wales supported by Sydney Trains and Australian Rail Track Corporation, respectively. In these studies, different types of geosynthetics (geogrid, geotextile and geocomposite) and shock mats were installed beneath the ballast layer constructed on varying subgrade conditions. Relative advantages of different geogrids were studied. Traffic induced stresses, ballast breakage, transient and permanent deformations were routinely monitored using precise instrumentation schemes. This paper discusses the details of track construction, instrumentation, monitoring processes and results of these field studies.

Keywords: ballast, field monitoring, deformation, geosynthetics, shock mats

1 Introduction

Ballasted railroads offer one of the largest and reliable fright transportation systems in the world. In order to keep pace with population and economic growth, it has become crucial to increase the axle load and speed of trains, improve its efficiency with concomitant gains in national productivity. The structure of railroad is divided into two categories viz. superstructure and substructure. The

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substructure consists of the ballast, subballast and subgrade while the superstructure consists of the rail, fastening systems and sleepers or ties (Selig and Waters, 1994). Although components of superstructure are mainly elastic and undergo very minimal deformations, the granular substructure layers such as ballast and subballast often exhibit large deformations under the application of high cyclic stresses exerted by increasingly heavier and faster trains (Sun et al., 2014). These problems aggregate for tracks laid on stiff track foundation such as hard rock terrain or concrete bridge deck where large dynamic loads are encountered (Jenkins et al., 1974, Nimbalkar et al., 2012). This in turn, leads to rapid fragmentation of ballast aggregates affecting vertical as well as lateral stability of track.

In addition, the ballast layer becomes fouled due to infiltration of subgrade clay fines (Indraratna et al., 2013a) and migration of coal spillage from wagons (Indraratna et al., 2014a). While the ballast breakage is the most important source of fouling (about 76% of total fouling, see Selig and Waters, 1994), other important sources include infiltration from coal and clay. Using two-dimensional reinforcements [i.e. geogrid, geotextile, geocomposite (combination of geogrid and geotextile)] helps to reduce the track settlement as confirmed through model-scale laboratory studies (Horníček et al., 2010, Indraratna et al., 2013b, Qian et al., 2015) and full-scale field trials (Indraratna et al., 2010a, 2014b,c,d). A three-dimensional cellular geosynthetics (geocell) can provide much better lateral confinement to subballast compared to planar reinforcement (Indraratna et al., 2015). Since the last decade, use of shock mats has become prominent due to several benefits including reduced ballast degradation to improve stability of track substructure, thereby increasing its service life (Indraratna et al., 2014e), as well as reduced vibration and noise, thus improving vertical elasticity of the track structure (Auersch, 2015).

Comprehensive field investigations are very rare as they can be very time consuming (atleast 2 years) and costly (several million dollars) often demanding extensive resources in terms of staff, material and instruments. However, an optimum approach combining results of large-scale laboratory testing with the data obtained from full-scale instrumented field monitoring is crucial for accurately modeling track deformation and degradation. In view of this, extensive field trials were conducted on sections of instrumented railroad track at Bulli and Singleton, New South Wales (NSW), Australia supported by Sydney Trains and Australian Rail Track Corporation, respectively. This paper describes the results of these two unique full-scale field trials to quantify the geotechnical behaviour of ballasted railroad under repeated trains loads and improvements associated with use of synthetic inclusions.

2 Geotechnical Behavior of Ballast

Railroad ballast is a selected granular material (medium to coarse gravel aggregates varying from 10 to 60 mm in size) placed below sleepers (ties) to support and restrain the track structure. It is usually composed of highly angular crushed rock fragments originating from high quality igneous or metamorphic parent rock. It is the main load bearing layer having the load distribution characteristics largely dependent on the combination of physical properties (i.e. particle size, shape, angularity, hardness, toughness and surface texture) and mechanical properties (shear strength, deformation, ballast breakage, in-situ compaction, high resistance to weathering) (Selig and Waters, 1994).

2.1 Assessment of Ballast Breakage

The ballast degradation is a complex mechanism that usually initiates with the breakage of asperities, followed by complete crushing under further loading. The degradation affects size as well as shape of particles while reducing the interparticle friction and interlock. Indraratna et al. (2005) introduced Ballast Breakage Index (*BBI*) to quantify the amount of ballast degradation, and it is based on the change in particle size distribution (*PSD*) curves, as shown in Fig. 1(a). An increase in amount of particle breakage shifts the *PSD* curve further towards the smaller particles size region on a conventional *PSD* plot. The value of *BBI* can be determined by using the simple non-dimensional ratio termed as $BBI = A/(A+B)$. The parameter *A* is defined as the area between initial *PSD* and final *PSD*. *B* is the potential breakage which is defined as the area between the arbitrary boundary of maximum breakage and the final *PSD*.

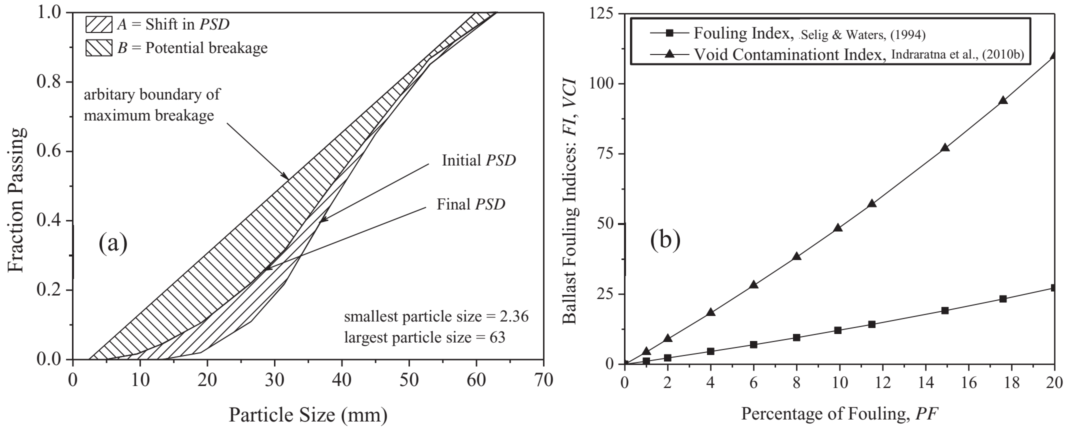

Figure 1: Evaluation of (a) BBI (data sourced from Indraratna et al., 2005), (b) VCI (data sourced from Tennakoon et al., 2012).

2.2 Assessment of Ballast Fouling

Fouling material is defined as the material passing the 9.5 mm sieve (Selig and Waters, 1994). The fouling index (*FI*) is defined as the summation of $P_{4.75}$ and $P_{0.075}$, where, $P_{4.75}$ and $P_{0.075}$ are percentages by mass of material passing the 4.75 mm and 0.075 mm sieve, respectively. A more appropriate volume based parameter defined as Void Contaminant Index (VCI) can be used as a reliable estimate of fouling. It incorporates effects of void ratio, specific gravity and gradation of fouling material and ballast and is defined as (Indraratna et al., 2014a, 2010b, Tennakoon et al., 2012). As shown in Fig. 1(b), VCI can capture the amount of fouling more accurately compared to other mass based indices, because later do not consider the correct volume of fouling in a real track environment.

3 Field Study on Instrumented Track at Bulli

The experimental track section was located between two turnouts in Bulli along South Coast Track owned and operated by Sydney Trains (formerly RailCorp), NSW. Train-induced stresses, vertical and lateral track deformations were monitored by the Centre for Geomechanics and Railway Engineering (CGRE) during this study.

3.1 Track Construction

The subgrade consisted of a stiff overconsolidated silty clay with shale cobbles and gravels, and the bedrock was highly weathered sandstone (Indraratna et al., 2010a). The total length of the instrumented track section was 60 m. It was divided into four sections, each 15 m in length. The schematic presentation of sections is provided by Indraratna and Nimbalkar (2015). The thicknesses of the ballast and subballast layer were 300 mm and 150 mm, respectively. Fresh and recycled ballast without geocomposite were used at Sections 1 and 4, while the other two sections were built by placing a geocomposite layer at the ballast-subballast interface. The geocomposite layers consisted of biaxial geogrids (aperture size = 40 × 27 mm, peak tensile strength = 30 kN/m) placed over the nonwoven polypropylene geotextile (mass per unit area = 140 g/m^2, thickness = 2 mm) layers. Further detailed information on technical specifications of various materials used during construction is reported elsewhere (Indraratna et al., 2010a). Vertical and lateral deformations of railroad were measured by settlement pegs and electronic displacement transducers, respectively. Although, the use of displacement transducers to measure vertical displacements is quite established practice, they were used to record lateral displacements in this field study. The settlement pegs and displacement transducers were installed at the sleeper-ballast and ballast-subballast interfaces, respectively. Pressure cells were also installed at these interfaces to record stresses in track substructure. More details on instrumentation schemes are presented elsewhere (Indraratna et al., 2010a, Indraratna and Nimbalkar, 2015).

3.2 Track Measurements

In the field, vertical and horizontal deformations were measured against time. A relationship between the annual rail traffic in million gross tons (*MGT*) and axle load (A_t) was therefore needed to determine the number of load cycles (N) (Selig and Waters, 1994). This relation is expressed as $N_\mathrm{t} = 10^6/(A_\mathrm{t} \times N_\mathrm{c})$, where N_t, A_t and N_c are number of load cycles per MGT, axle load in tons and number of axles per load cycle. Using this relation, for traffic tonnage of 60 MGT per year and four axles per load cycle, an axle load of 25 tons gives 600,000 load cycles per MGT. A simple survey technique was adopted to record the change in the reduced level of tip of settlement peg. Pressure cells and lateral displacement transducers were connected to the computer controlled data acquisition system. The data logger could operate at a maximum frequency of 40 Hz.

3.3 Ballast Deformations

The deformation of ballast was determined by subtracting the settlement of the ballast-capping interface from that at the sleeper-ballast interface. Figure 2 shows the variation of average deformations for both fresh and recycled ballast against the number of load cycles (N). The results indicate that both fresh and recycled ballast showed increased deformations as number of load cycles increased. Compared to fresh ballast, the recycled ballast exhibited less vertical and lateral deformations. This could be attributed to its moderately graded PSD (C_u = 1.8) compared to the very uniform PSD (C_u = 1.5) of fresh ballast. Aggregates of recycled ballast underwent less breakage because they were less angular. This in turn prevented corner breakage resulting from high contact stresses. The results also indicate that geocomposite reinforcement reduced vertical (S_v) and lateral (S_l) deformation of fresh ballast by 33 % and 49 % respectively (Figs. 2a, 2b). It also reduced vertical (S_v) and lateral (S_l) deformation of recycled ballast by 9 % and 11 % respectively (Figs. 2a, 2b). Lateral deformation is one of the most important indices and the geocomposite reinforcement was able to curtail it effectively, resulting into much improved lateral stability.

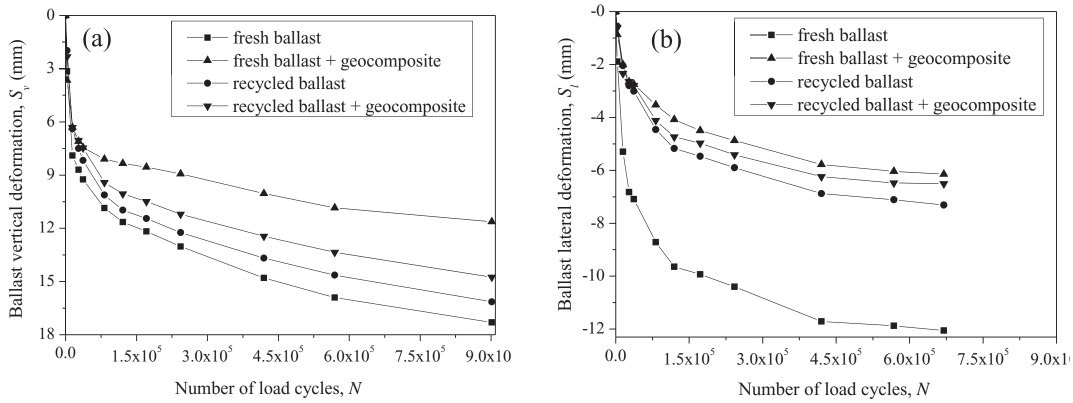

Figure 2: Average deformations of the ballast layer: (a) vertical (S_v); (b) lateral (S_l) (data sourced from Indraratna et al., 2010a).

3.4 Traffic Induced Stresses

Figure 3(a) shows the peak cyclic vertical (σ_v) and lateral (σ_l) stresses recorded at Section 1 (i.e. fresh ballast without geocomposite) due to the passage of a coal train with an axle load of 25 tons. The stresses were measured under the rail. The peak cyclic vertical stress (σ_v) was reduced by 73 % and 82 % at the depth of 300 mm and 450 mm, respectively. It was also evident that σ_l decreased only marginally with depth, thus implying the need of artificial inclusions for additional restraints. Due to time constraints and funding limitations, pressure cells were not installed at multiple locations elsewhere, thus rendering difficulty in direct comparison across these Sections.

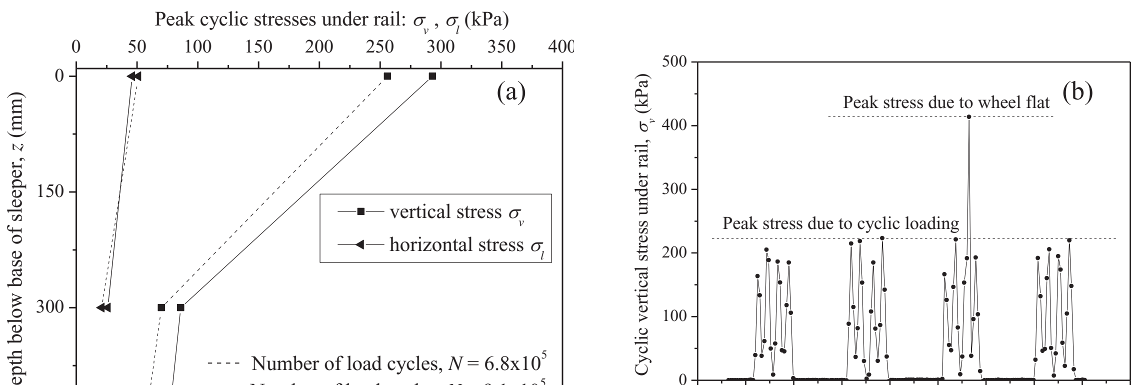

Figure 3: Cyclic stresses induced by coal train with wagons (100 tons): (a) variation of stresses with depth, (b) additional stress due to wheel flat (data sourced from Indraratna et al., 2010a).

While most of the peak cyclic vertical stresses (σ_v) were up to 230 kPa, one value of σ_v, which was later found to be associated with a wheel flat, reached 415 kPa. This proved that much larger stresses are exerted by wheel imperfections. The resulting particle breakage could be mitigated by shock mat as discussed in Singleton study.

4 Field Study on Instrumented Track at Singleton

To investigate an 'in-situ' performance of different types of geosynthetics and shock mat to improve overall track stability, an extensive field study was undertaken on instrumented track sections near Singleton, NSW. This track owned and operated by Australian Rail Track Corporation (ARTC) was in-land about 80 km away from the south coast.

4.1 Track Construction

A part of track was located on a massive sedimentary outcrop of medium- to high-strength siltstone rock, while another part was founded on a flood plain (Nimbalkar and Indraratna, 2016). The flood plain consisted of a layer of an alluvial deposit of silty clay 7-10 m thick, underlain by heterogeneous layers of medium-dense sand and silty clay that was 7-9 m thick. Medium-strength siltstone was found beneath the layer of silty clay. A reinforced concrete bridge supported by a piled foundation was also part of this track. In summary, three types of subgrades were encountered including the relatively soft alluvial silty clay deposit, the intermediate cut siltstone, and the reinforced concrete bridge deck. Eight experimental sections were constructed on these three types of subgrades. The track substructure consisted of 300 mm thick ballast underlain by 150 mm thick layer of subballast. A structural-fill layer with a minimum of 500 mm thickness was placed above the subgrade. Three biaxial geogrids and one geocomposite (biaxial geogrid + nonwoven geotextile) were installed at below the ballast layer. A layer of geogrid 1 (aperture size = 44 × 44 mm, peak tensile strength = 36 kN/m), geogrid 2 (aperture size = 65 × 65 mm, peak tensile strength = 30 kN/m) and geogrid 3 (aperture size = 40 × 40 mm, peak tensile strength = 30 kN/m) were installed at Sections 1, 2 and 3, respectively. A geocomposite layer consisting of biaxial geogrid (aperture size = 31 × 31 mm, peak tensile strength = 40 kN/m) and nonwoven polypropylene geotextile (mass per unit area = 150 g/m^2, thickness = 2.9 mm) was installed at Section 4 while geogrid 3 was also installed at Section 5. No geosynthetic layer was installed at Section A and C for comparison purpose. Section B consisted of the reinforced concrete bridge where a layer of shock mat was placed above the concrete deck. More detailed information on properties of geosynthetics and shock mats employed in this study is given elsewhere (Nimbalkar and Indraratna, 2016). Settlement pegs were installed to measure ballast deformations in a similar way discussed previously. In addition, transient deformations of the ballast layer were measured by linear variable displacement transducers (LVDTs) mounted on a custom made frame. More details on instrumentation schemes and layout of Sections are presented by Indraratna and Nimbalkar (2015).

4.2 Track Measurements

As discussed in Section 3.2, ballast deformations were plotted against number of load cycles, in lieu of the time scale adopted in the field. All the data were obtained from the aforementioned instruments at a frequency of 2 kHz.

4.3 Permanent Deformations of Ballast

The vertical deformation (S_v) of the ballast is plotted against number of load cycles (N) in Fig. 4(a) and 4(b) for soft embankment and hard rock, respectively. These results indicated that the relationship between S_v and N was non-linear for all Sections. The rate of increase of S_v diminished as the number of load cycles increased. S_v of the reinforced sections were 10-32% smaller than those without reinforcement. This pattern was similar to that observed in the laboratory (Indraratna et al., 2012, Indraratna and Nimbalkar, 2013), and it could be attributed mainly to particle-grid interlock. The results also indicated that S_v were larger when the subgrade becomes weaker. It was apparent that the geogrid reinforcement was much effective to reduce deformations of track located on softer subgrades.

4.4 Transient Deformations of Ballast

It was observed that the passage of train with an axle load of 30 tons travelling at 40 km/h resulted in a vertical deformation (S_{tv}) between 1.5 to 3 mm, resulting in an average vertical strain (ε_{tv}) of 0.5 - 1 %. The transient lateral deformations of ballast (S_{tl}) measured on the shoulder were all expansive and between 0.5 to 0.3 mm. This resulted in an average lateral strain (ε_{tl}) of 0.05 to 0.02 %. The lateral strains were larger near the crest and smaller near the toe of ballast. The average transient strains of track sections with reinforcement (i.e. Sections 1-4, 5) were about 15 % smaller than those without reinforcement (i.e. Section A, C). The vertical stresses (σ_v) due to the passage of trains with an axle load of 30 tons travelling at about 40 km/h were about 280 kPa at Section B (mat-deck interface) and between 30 to 40 kPa at Sections 1, 6, A, and C (ballast-subballast interface). Vertical stresses at the sleeper-ballast interface of the latter were between 170 to 190 kPa. Thus the traffic-induced stresses were larger for a stiff subgrade.

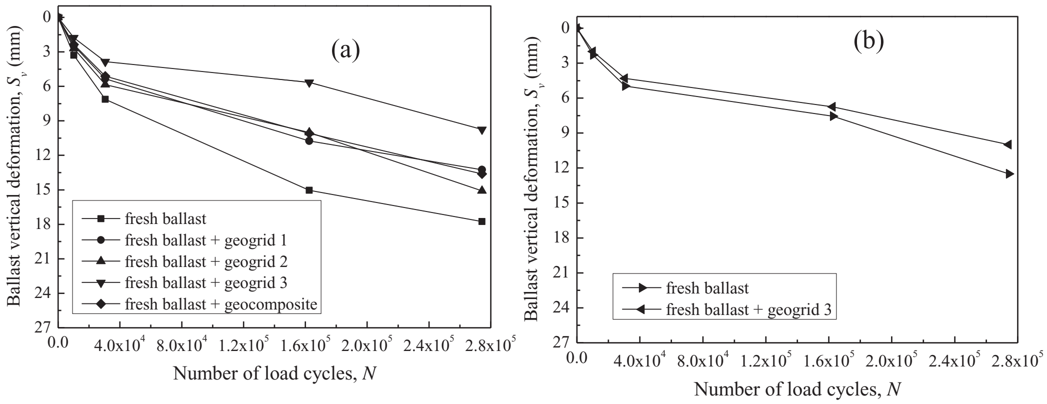

Figure 4: Vertical deformation of ballast for (a) soft embankment; (b) hard rock (data sourced from Indraratna et al., 2014d)

4.5 Ballast Fouling and Breakage

Ballast samples were recovered from beneath the sleeper as this location was considered to be most appropriate (Indraratna et al., 2010, Indraratna and Nimbalkar, 2013). Visual inspection of the samples revealed the presence of crushed rock fragments which most likely resulted from particle breakage. The value of *VCI* was less than 4-6 % indicating very minimal fouling level prevalent at the time when these measurements were obtained. Particle breakage was quantified in terms of *BBI* and its values are given in Table 1. As expected, *BBI* was highest at the top, while undergoing significant reduction with depth. Largest values of *BBI* obtained at hard rock verified that particle breakage was influenced by the type of subgrade.

Sr. No.	subgrade	Ballast breakage index (*BBI*) for		
		Top layer	Middle layer	Bottom layer
1	alluvial silty clay (Section A)	0.17	0.08	0.06
2	concrete bridge deck (Section B)	0.06	0.03	0.02
3	Siltstone (Section C)	0.21	0.11	0.09

Table 1: Assessment of ballast breakage (data sourced from Indraratna et al., (2014b)

The ballast breakage index (*BBI*) for Section *B* was the least. This is because, larger confinement from the barriers of concrete bridge most likely resulted in a significantly smaller value of *BBI* (Indraratna et al., 2014d, 2016, Sun et al., 2015). These results also suggest the effectiveness of shock mats in reducing particle degradation when placed above a concrete deck.

5 Conclusions

This paper discussed the results of a comprehensive field monitoring program undertaken at Bulli and Singleton in NSW, Australia, to study the ability of various geosynthetics and shock mats to reduce track deformations. In these studies, different types of geosynthetics (geogrid, geotextile and geocomposite) and shock mats were installed beneath the ballast layer constructed on varying subgrade conditions. The findings from the Bulli Study verified that the discarded ballast aggregates could be reused in track construction. The placement of geocomposite in track was able to reduce the lateral deformation of fresh ballast by about 49 % and recycled ballast by 11 %. In the ballasted bed, the vertical stresses decreased significantly (@73 %), while lateral stresses showed a marginal reduction. The results of the Singleton Study showed that geogrids were more effective in curtailing deformation on soft subgrade. Shock mats were effective when placed above bridge. Transient deformations of the ballast layer also reduced by 15 % when a geosynthetic layer was used. The placement of shock mat also helped to mitigate degradation. Better understanding of such 'in-situ' track performance greatly assists in safe and reliable design of ballasted railroads.

Nomenclature

A_t is the axle load of train
BBI is the ballast breakage index
e_b is void ratio of clean ballast
e_f is void ratio of fouling material
$G_{s,b}$ is the specific gravity of the ballast
$G_{s,f}$ is the specific gravity of the fouling material
M_b is the dry mass of the fresh ballast
M_f is the dry mass of the fouling material
PF is the percentage of fouling
PSD is the particle size distribution
MGT is the million gross tons
N is the number of load cycles
S_{tv}, S_{tl} are transient vertical and lateral deformations of ballast, respectively
ε_{tv}, ε_{tl} are average vertical and lateral strain of ballast, respectively
VCI is the void contaminant index
V_T is the total volume of fouled ballast

V_{cf} is the volume of fouling material
σ'_3 is the effective confining pressure
σ_v, σ_l are peak cyclic vertical and lateral stresses, respectively

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