Field Assessment of the Performance of a Ballasted Rail Track with and without Geosynthetics

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Abstract: Understanding the complex mechanisms of stress transfer and strain accumulation in layers of track substructure under repeated wheel loading is essential to predict the desirable track maintenance cycle as well as the design of the new track. Various finite element and analytical techniques have been developed in the past to understand the behavior of composite track layers subjected to repeated wheel loads. The mechanical behavior of ballast is influenced by several factors, including the track confining pressure, type of aggregates, and the number of loading cycles. A field trial was conducted on an instrumented track at Bulli, New South Wales, Australia, with the specific aims of studying the benefits of a geocomposite installed at the ballast-capping interface, and to evaluate the performance of moderately graded recycled ballast in comparison to traditionally very uniform fresh ballast. It was found that recycled ballast can be effectively reused if reinforced with a geocomposite. It was also found that geocomposite can effectively reduce vertical and lateral strains of the ballast with obvious implications for improved track stability and reduced maintenance costs.

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Introduction

The accurate prediction of a typical rail track maintenance cycle needs an understanding of the complex mechanisms of track deterioration. To date, most of the design methods are based on conservative estimates of settlements and stress transfer between the track layers. Due to complexities in the behavior of the composite track system consisting of rail, sleeper, ballast, and subballast under repeated traffic loads, the track design techniques are still far from advanced. Recent studies by Indraratna and Salim (2005), Lackenby et al. (2007), Indraratna et al. (2005, 2008), McDowell and Harireche (2002), and Lu and McDowell (2008) reported on the particle deformation (permanent and resilient) and degradation of ballast layer under cyclic loading. Also, studies conducted by Rowe and Jones (2000), Ashpiz et al. (2002), Raymond (2002), and Indraratna and Salim (2003) proved that geosynthetics can improve track performance by reducing the track deformation and degradation. In order to understand the stress-distribution and strain accumulation in various layers of the track substructure under repeated wheel loads, a field trial was conducted on a section of railway track in the town of Bulli. The objectives of this instrumented field trial were to study the benefits of a geocomposite layer installed at the ballast-capping interface, and in addition, to examine the performance of moderately graded recycled ballast in comparison to traditionally very uniform fresh ballast. The University of Wollongong provided the technical specifications for the design of the instrumented track to RailCorp, Sydney who sponsored the research project.

The track was constructed between two turnouts at Bulli along the New South Coast. The total length of the instrumented track section was 60 m and was divided into four sections, each of 15 m length. Fresh and recycled ballast were used at Sections 1 and 4, respectively, without inclusion of a geocomposite layer, while Sections 2 and 3 were built by placing a geocomposite layer at the base of the fresh and recycled ballast, respectively. The settlement pegs and displacement transducers were installed at the center of each section, whereas pressure cells were installed at Locations 1C and 1D in Section 1, as shown in Fig. 1(a). Figs. 1(b) and c) show the schematic diagram of a ballasted track bed with and without the inclusion of a geocomposite layer. Concrete sleepers were used in the test track.

The overall track bed thickness was 450 mm including a ballast layer of 300 mm and a capping layer of 150 mm in thickness. The particle size, gradation, and other index properties of fresh ballast used at the Bulli site were in accordance with the technical specification TS 3402 (Rail Infrastructure Corporation of NSW 2001a) which represents sharp angular coarse aggregates of crushed volcanic basalt (latite). Recycled ballast was collected from spoil stockpiles of a recycled plant commissioned by RailCorp at their Chullora yard near Sydney. The finest fraction (less...
than 9.5 mm was removed by screening (i.e., \( d_{\text{min}} = 9.5 \text{ mm} \); see Table 1). The capping material was comprised of sand-gravel mixture. The particle size distribution of fresh ballast, recycled ballast, and the capping (subballast) materials are shown in Fig. 2. Table 1 shows the grain size characteristics of fresh ballast, recycled ballast, and the capping materials used in the Bulli instrumented track (Indraratna and Salim 2005; Ionescu 2004).

### Site Geology and Track Construction

The site investigation was carried out to investigate the condition of subgrade and comprised of 8 test pits and 8 cone penetrometer tests. Test pits were excavated using a Bobcat backhoe excavator to a maximum depth of 860 mm below the sleeper and the subgrade encountered was silty clay with shale cobbles and gravels. The longitudinal section of the track showing subsurface profile is shown in Fig. 3(a). Cone penetrometer testing (sometimes referred as a Dutch cone) was carried out using electrical friction cone penetrometer (EFCP). The high values of cone resistance \( q_c \) and friction ratio \( R_f \) obtained in EFCP tests as evident in Figs. 3(b and c) revealed that the subgrade soil was stiff, over-consolidated, and of sufficient strength to support the train loads (Robertson 1990). Bedrock was found at a depth of 2.3 m below the excavation level at center of Section 4 and based on other EFCP test results, it was anticipated that its depth gradually increased toward Section 1. The bedrock was highly weathered sandstone having weak to medium strength (Choudhury 2006).

Track reconditioning was required due to the inhomogeneity of the soil conditions along the track. This warranted a minimum

### Table 1. Grain-Size Characteristics of Ballast and Capping Materials [Adapted from Indraratna and Salim (2005); Ionescu (2004)]

<table>
<thead>
<tr>
<th>Material</th>
<th>Particle shape</th>
<th>( d_{\text{max}} ) (mm)</th>
<th>( d_{\text{min}} ) (mm)</th>
<th>( d_{10} ) (mm)</th>
<th>( d_{50} ) (mm)</th>
<th>( d_{60} ) (mm)</th>
<th>( C_u )</th>
<th>( C_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh ballast</td>
<td>Highly angular</td>
<td>75.0</td>
<td>19.0</td>
<td>24.1</td>
<td>29.1</td>
<td>35.0</td>
<td>36.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Recycled ballast</td>
<td>Semiangular</td>
<td>75.0</td>
<td>9.5</td>
<td>23.1</td>
<td>31.5</td>
<td>38.0</td>
<td>41.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Capping</td>
<td>Angular to rounded</td>
<td>19.0</td>
<td>0.05</td>
<td>0.07</td>
<td>0.17</td>
<td>0.26</td>
<td>0.35</td>
<td>5.0</td>
</tr>
</tbody>
</table>
450 mm depth of excavation below the sleeper (300 mm ballast and 150 mm capping layer) and proof rolling at the exposed surface, and involved excavation near Section 4 [Fig. 3(a)]. The 150 mm thick capping layer was placed in compliance with Australian standards (Rail Infrastructure Corporation of NSW 2001b) with cross fall of 1 V:30 H. Then a 300 mm thick ballast layer was placed on the top of capping layer.

Cubical triaxial tests reported by Indraratna and Salim (2005) indicated that a geocomposite layer (geogrid bonded with nonwoven geotextiles) produced much better stabilization of recycled ballast compared to standard geogrids and also prevented the fouling of ballast by migration of the subgrade and capping materials. As described by Rowe and Jones (2000), geocomposites can provide reinforcement to the ballast layer, as well as filtration and separation functions simultaneously. The combination of reinforcement by the geogrid itself and the filtration and separation functions provided by the bonded nonwoven geotextile significantly decreases the lateral spreading and fouling of ballast. In areas of saturated soft subgrade soils where the groundwater table is near the surface, the nonwoven geotextile prevents the fines moving up from the capping and subgrade layers fouling the ballast. Therefore, in the present study, it was decided to use a geocomposite inclusion to study its favorable effects on the performance of both fresh and recycled ballast. A bioriented geogrid was placed over the nonwoven polypropylene geotextile to serve as the geocomposite layer, which was installed at the ballast-capping interface. The technical specifications of geosynthetic material used at the site can be found elsewhere (Indraratna and Salim 2005).

Details of Instrumentation

To accurately measure the deformations and cyclic stresses in the track, robust and high precision instruments were used at the site. The details of these instruments are given below.

Settlement Pegs and Displacement Transducers

To measure vertical and horizontal deformations of ballast, settlement pegs and displacement transducers were installed in different track sections. The settlement pegs consisted of $100 \times 100 \times 6$ mm$^3$ stainless steel base plates attached to a 10 mm diameter stainless steel rods with length matching for burial in track layers. The use of displacement transducers is an established practice for measuring vertical displacements (e.g., Grabe and Clayton 2003). In this field trial, special purpose displacement transducers were used to measure the transient horizontal track movements. These potentiometric transducers were protected inside 2.5 m long stainless steel housing, which consisted of two tubes that can slide

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Fig. 3. (a) Longitudinal section of instrumented track at Bulli [adapted from Choudhury (2006)]; (b) EFCP test record at center of Section 2 [adapted from Choudhury (2006)]; and (c) EFCP test record at center of Section 4 [adapted from Choudhury (2006)].
over each other with $100 \times 100$ mm$^2$ end caps as anchors while providing protection from moisture ingress and damage under harsh track conditions. The typical arrangement of settlement pegs and displacement transducers is shown in Fig. 4(a). The settlement pegs were installed at sleeper-ballast and ballast-capping interface at all sections. To measure the settlement of subgrade soil, settlement pegs were also installed at the capping-subgrade interface in Section 1. The settlement pegs were also placed under the rail and beneath the edge of sleeper to study the variation of deformation along the track section. Displacement transducers were installed both at the sleeper-ballast and ballast-capping interfaces to measure the horizontal track deformations. Data loggers were connected to displacement transducers to obtain a continuous record of permanent track deformations.

**Pressure Cells**

The pressure cells used in the present study were rapid-response hydraulic earth pressure cells with grooved thick active faces based on semiconductor type transducers. Selig (1964, 1980), Weiler and Kulhawy (1982), Dunnicliff (1988), Clayton and Bica (1993), and Richards et al. (2007) have reported several factors, including the aspect ratio and size of cell, placement effects, corrosion, and temperature affecting measurements. In accordance, relatively thin but robust pressure cells made of stainless steel (thickness of 12 mm, diameter of 230 mm) were adopted. They were installed by excavating beneath the sleeper up to the bottom edge of the capping layer and then backfilled at the appropriate levels, with care taken to avoid any damage during placement and subsequent material compaction. The cells were designed for minimum sensitivity to temperature (temperature range of $-20$ to $+80^\circ$C). In-house calibration was carried out by the manufacturer, and the cell output at zero pressure was recorded before installation and load application.

The vertical and horizontal stresses developed in the track bed under repeated wheel loads were measured by pressure cells. They were placed in a staggered pattern, as shown in Fig. 4(b). While vertical stresses were measured at three different levels, i.e., sleeper-ballast, ballast-capping, and capping-subgrade interfaces, horizontal stresses were measured only at two levels, i.e., sleeper-ballast and ballast-capping interfaces mainly due to budget limitations. Pressure cells were installed under the rail and at the bottom edge of sleeper near each interface. A total of 20 pressure cells were installed to record the vertical and horizontal stresses.

Electric cables were run through flexible conduits along the ballast shoulder and under the track at the central location, and connected to an automated data logger in a control box mounted on a signal box adjacent to the track.

**Data Collection**

The settlement pegs were surveyed immediately after installation and again after 2 days, then at weekly intervals for 3 weeks, monthly intervals for the next 3 months, 3-month intervals for the next 9 months, and a final survey after 17 months. The measurements were carried out using simple survey techniques recording the change in the reduced level of the surface of each layer with time. The recording of horizontal deformations from data loggers was initially conducted on an hourly basis and later transferred to a daily record in the monitoring history. The data was downloaded from the data logger manually on a daily basis.

To record the maximum values of pressure transmitted from the sleeper through the ballast, pressure cells were connected directly to the data logger and triggering was carried out manually for each train. A maximum of eight cells could be connected to the data logger, which could operate at a frequency of 40 Hz. While these results appear to be successful, it is clear that the maximum value of pressure transmitted from the sleeper was not always recorded. At a speed of 60 km/h, a wheel will travel at 0.4 m in 1/40th of a second, and therefore it could not be ascertained that the wheel would be over the instrumented sleeper at the time of recording. Therefore, the maximum values recorded for each train were taken as the best estimate of the maximum dynamic pressure from the wheel load.

**Results and Discussion**

The vertical and horizontal deformations were measured against time in the field. In order to establish a suitable correlation with other research methodologies, an appropriate scale of “number of load cycles” is selected in addition to the “time” scale. A relation between million gross tons (MGT) of rail traffic annually and number of cycles ($N$) could be used to determine number of load cycles (Selig and Waters 1994)

$$C_m = \frac{10^6}{(A_r \times N_m)}$$

where $C_m=$number of load cycles/MGT; $A_r=$axle load in tons; and $N_m=$number of axles/load cycle.

Considering the annual traffic tonnage of 60 MGT and four axles per load cycle, an axle load of 25 t gives 600,000 load cycles per MGT. Therefore results are plotted against both the time and number of load cycles as discussed below.

**Vertical Deformation of Ballast Layer Both under Rail and Edge of the Sleeper**

The vertical deformation of ballast layer both under the rail position ($S_{vr}$) and edge of sleeper position ($S_{ve}$) are obtained by de-
ducting the vertical displacements of sleeper-ballast and ballast-capping interfaces. The vertical strains ($e_{vr}$, $e_{v}$) of the ballast layer are obtained by dividing the vertical deformations ($S_{vr}$, $S_{v}$) of the ballast layer by the initial layer thickness. The vertical deformations ($S_{vr}$, $S_{v}$) and vertical strains ($e_{vr}$, $e_{v}$) thus obtained are plotted against the time ($t$) and number of load cycles ($N$), as shown in Figs. 5(a and b). It is observed that the vertical deformations ($S_{vr}$, $S_{v}$) of the ballast layer are highly nonlinear under cyclic loading [similar to Jeffs and Marich (1987), Ionescu et al. (1998), Indraratna and Salim (2005), and Lackenby et al. (2007)]. A rapid increase in vertical deformations ($S_{vr}$, $S_{v}$) is observed during first 120,000 load cycles, beyond which deformations ($S_{vr}$, $S_{v}$) show marginal increase.

It is evident from Fig. 5(a) that fresh ballast exhibits greater vertical deformation under the edge of sleeper ($S_{v}$) compared to that under the rail ($S_{vr}$) for increasing number of loading cycles. A similar trend is observed for recycled ballast, as shown in Fig. 5(b). Only at the sleeper edge position, the magnitude, and rate of vertical deformations of the recycled ballast almost match with those of fresh ballast [Figs. 5(a and b)]. This can be attributed to the reduced lateral restraint at the edge of sleeper. However, recycled ballast shows significant reduction in vertical deformation under the rail position than that of fresh ballast because of its moderately graded particle size distribution compared to the very uniform fresh ballast. Therefore, the average values of vertical deformations in the recycled ballast are always less than the fresh ballast.

The geocomposite layer decreases the vertical deformations ($S_{v}$) of fresh and recycled ballast. Nevertheless recycled ballast-geocomposite assembly shows increased vertical deformation under the edge of sleeper ($S_{v}$) when compared with fresh ballast-geocomposite assembly. One possible reason for this may be the lower global interface friction mobilized between the geocomposite layer and the semianular or semirounded particles of recycled ballast. The property of angularity enables better interlocking between the ballast particles and the geogrid to improve the global interface friction, which is less pronounced in the semirounded particles of recycled ballast.

**Average Vertical and Lateral Deformations of Ballast Layer**

To investigate the overall performance of the ballast layer, the average vertical deformation ($S_{v}$) and average vertical strain ($e_{v}$) are considered by taking the mean of measurements taken under the rail ($S_{vr}$, $e_{vr}$) and the edge of sleeper ($S_{v}$, $e_{v}$) at each interface. The ($S_{v}$) and ($e_{v}$) are plotted against the time ($t$) and number of load cycles ($N$) in Fig. 6(a). The geocomposite inclusion reduces ($S_{v}$) and ($e_{v}$) for both fresh and recycled ballast at a large number of cycles. Also, Fig. 6(a) shows that the ($S_{v}$) and ($e_{v}$) in the recycled ballast are less than the fresh ballast. The recycled ballast performed well, and this is because it was moderately graded than the relatively very uniform fresh ballast. The better performance of selected recycled ballast (if placed as a moderately graded or well-graded mix) can also benefit from less breakage as they are often less angular thereby preventing corner breakage due to high contact stresses. Under a typical railway track environment, considerable stress concentrations occur at the corners of sharp angular fresh ballast particles, leading to corner breakage (Indraratna et al. 2005; Lackenby et al. 2007; Hossain et al. 2007). The well-graded ballast has a smaller void ratio (higher density) and has a higher shear strength compared to uniformly graded ballast (Marsh 1967; Jeffs and Tew 1991). Studies by Raymond and Dyaljee (1979) as well as Selig and Waters (1994) have reported that a more well-graded distribution decreases the track settlement. Therefore, the moderately graded recycled ballast used in this study is expected to produce a higher placement density, and a reduced settlement compared to fresh ballast.

Results of cyclic triaxial tests conducted by Indraratna et al. (2004) also confirmed that ballast breakage also decreases as the value of $C_{p}$ increases. This is because the ballast samples with a higher $C_{p}$ provides a denser packing with a greater coordination number, thus providing a higher shear strength and decreased settlement. They have reported that even a modest change in the $C_{p}$ substantially affects the deformation and the breakage of ballast. Therefore, it is not surprising that the recycled ballast gives less displacements due to its higher $C_{p}$ value compared to fresh ballast, even though the individual recycled ballast particles are more rounded ($\varphi=43^\circ-54^\circ$) compared to the relatively angular fresh ballast ($\varphi=46^\circ-69^\circ$).

Fig. 6(b) shows the average lateral deformation ($S_{l}$) of ballast (i.e., determined from the mean of measurements at sleeper-
ballast and ballast-capping interfaces) plotted against the time \((t)\) and number of load cycles \((N)\). The average lateral strain of ballast layer \((\epsilon_3)_{\text{avg}}\) is obtained by dividing the average lateral deformation \((S_h)_{\text{avg}}\) by the initial lateral dimension (considered as 2.5 m) of the ballast layer. The ballast layer exhibits an increase in average lateral deformation \(S_h\) and \((\epsilon_3)_{\text{avg}}\) compared to fresh ballast. The moderately graded gradation of recycled ballast produces smaller lateral strains. The inclusion of geocomposite in fresh ballast decreases \((S_h)_{\text{avg}}\) and \((\epsilon_3)_{\text{avg}}\) significantly; however, inclusion of the same in the recycled ballast shows a negligible effect on \((S_h)_{\text{avg}}\) and \((\epsilon_3)_{\text{avg}}\). This is due to highly frictional, angular particles of fresh ballast which develop increased global interface friction with the geocomposite layer in the lateral direction, thus resisting lateral movement to a greater extent (Indraratna and Salim 2005).

More significantly, the recycled ballast stabilized with the geocomposite layer exhibits \((S_h)_{\text{avg}}\) and \((\epsilon_3)_{\text{avg}}\) less than those of unreinforced fresh ballast (i.e., without geosynthetics). This has a significant bearing on the maintenance of rail tracks. The reduction in the lateral movement of ballast decreases the need for additional layers of crib and shoulder ballast during maintenance. However, questions related to the potential reduction in track drainage due to use of a considerably more well-graded recycled ballast needs to be addressed for much higher values of \(C_u\). Also, highly well-graded ballast can become more prone to segregation during long distance transportation (vibration) reported earlier by Chrismer (1985). In this study, the moderately graded recycled ballast has a value of \(C_u\) of 1.8 compared to 1.5 of more uniform fresh ballast, and this increase of \(C_u\) is not large enough to cause segregation during transport or to reduce permeability to any significant extent. Also, in the absence of fouling (screening removed particles finer than 9.5 mm), reduced permeability was not a concern.
Average Shear and Volumetric Strain of Ballast Layer

The average shear strain $(e_v)_\text{avg}$ and average volumetric strain $(e_s)_\text{avg}$ of the ballast layer can be determined by (Timoshenko and Goodier 1970)

\[(e_v)_\text{avg} = \frac{\sqrt{3}}{3} \left( \frac{1}{2} [(e_1)_\text{avg} - (e_2)_\text{avg}]^2 + [(e_2)_\text{avg} - (e_3)_\text{avg}]^2 + [(e_3)_\text{avg} - (e_1)_\text{avg}]^2 \right) \]

\[(e_s)_\text{avg} = (e_1)_\text{avg} + (e_2)_\text{avg} + (e_3)_\text{avg} \]

Since longitudinal strain measurement were not carried out at the site due to time and budget restrictions, plane strain conditions are assumed (average intermediate principal strain acting parallel to rail, $(e_s)_\text{avg}=0$) to determine average shear strain $(e_v)_\text{avg}$ and average volumetric strain $(e_s)_\text{avg}$. Figs. 7(a and b) show the variation of $(e_v)_\text{avg}$ and $(e_s)_\text{avg}$ against time $(t)$ and number of load cycles $(N)$. These results clearly show that geocomposite layer reduces $(e_v)_\text{avg}$ and $(e_s)_\text{avg}$ in both fresh and recycled ballast layer. The fresh ballast-geocomposite assembly performs well in terms of least values of $(e_v)_\text{avg}$ and $(e_s)_\text{avg}$ compared to other cases. It is also observed from Fig. 7(b) that the ballast layer in all sections exhibits volume decrease (i.e., compression) with increase in number of load cycles. The recycled ballast exhibits $(e_v)_\text{avg}$ and $(e_s)_\text{avg}$ quite lower than those of fresh ballast. This is due to the selection of moderately graded recycled ballast in comparison to traditionally very uniform fresh ballast as discussed earlier.

Vertical Deformation of Subgrade Soil Both under the Rail and Edge of Sleeper

The vertical deformation of the subgrade soil was measured both under rail $(S_vr)$ and edge of sleeper $(S_vh)$ at Section 1 as described earlier and reported in Fig. 8. The large dynamic stresses induced by regular rail traffic within the period of measurement may induce appreciable subgrade deformation. It is evident that the subgrade soil shows more deformation under the rail $(S_vr)$ than that under the edge of sleeper $(S_vh)$. The subsurface investigations revealed that there was no groundwater table within the first couple of meters beneath the surface. The resilient modulus $(M_R)$ is correlated as $15q_c$ where, $q_c$ is the cone resistance (Choudhury 2006). The subgrade deformations measured at Section 1 were deducted to obtain the vertical deformation of ballast layer at that section. For other sections, subgrade deformations obtained based on EFCP test results were deducted to obtain the vertical deformations of ballast layer.

In Situ Stresses across Different Layers

Fig. 9(a) shows that the maximum vertical cyclic stresses $(\sigma_{vr},\sigma_{vh})$ and maximum horizontal cyclic stress $(\sigma_{hr},\sigma_{hs})$ recorded in the Section 1 due to the passage of train at 60 km/h (20.5 t axle load) both under the rail and edge of sleeper position. It is observed that $(\sigma_{vr}$ and $\sigma_{vh}$ are much higher than $\sigma_{hr}$ and $\sigma_{hs}$, thus producing large shear strains in the rail track. Under normal rail track environment, there is significant lateral movement observed in the ballast layer. It is the large vertical stress and relatively small lateral (confining) stress that cause large shear strains in the track. The corresponding ease for horizontal spreading of
ballast in the absence of sufficient confinement leads to increased vertical compression of the layer, as also confirmed by Selig and Waters (1994). Also, \( \sigma_{yv}, \sigma_{hr}, \sigma_{vs}, \) and \( \sigma_{hs} \) increase with increase in number of load cycles leading to further degradation of track bed. It is evident that \( \sigma_{yv} \) and \( \sigma_{vs} \) decrease significantly with depth, while \( \sigma_{hr} \) and \( \sigma_{hs} \) decrease only marginally with depth. If a greater internal confining pressure on track could be applied by placing a geosynthetic layer within the ballast bed itself, lateral strains of ballast would also decrease. There is an increase in the apparent friction angle due to the placement of the geosynthetic layer. The track substructure is essentially self-supporting with minimal lateral restraints and the effective confining pressure is a key parameter governing the design of railway tracks with implications on ballast movement and associated track maintenance (Lackenby et al. 2007). The study reported by Indraratna and Salim (2005) has clearly highlighted the increase in the track confinement as a result of placing the geosynthetic layer.

Fig. 9(b) shows the maximum cyclic stresses \( (\sigma_{yv}, \sigma_{hr}, \sigma_{vs}, \sigma_{hs}) \) recorded in Section 1 due to the passage of a coal train with 100 T wagons (25 t axle load), where the stresses are measured both under the rail and edge of sleeper. As expected, maximum cyclic stresses \( (\sigma_{yv}, \sigma_{hr}, \sigma_{vs}, \sigma_{hs}) \) measured in the ballast and capping layer are higher due to a coal freight train than those attributed to a passenger train. It is anticipated that the greater axle load of the coal train imposes higher \( \sigma_{yv}, \sigma_{hr}, \sigma_{vs}, \) and \( \sigma_{hs} \), resulting in greater deformation and degradation of ballast, implying the need for earlier track maintenance.

Fig. 10 shows the maximum vertical cyclic stresses \( (\sigma_{yv}) \) plotted with time \( (t) \), measured under the rail due to the passage of a coal train. It demonstrates that while most of the maximum vertical cyclic stresses \( (\sigma_{yv}) \) range up to 230 kPa, one peak is observed at 415 kPa, which was later found out to correspond with the arrival of a wheel-flat. High impact loads can be generated by wheel imperfections and therefore their influence needs to be carefully assessed and accounted for in the design of ballasted track bed and corresponding track maintenance schedules.

### Comparison of Current Results with Previous Literature

The maximum vertical cyclic stresses \( (\sigma_{yv}) \) measured beneath the rail in the Bulli track are compared with results of analytical models and field studies reported in the literature, as shown in Fig. 11. Rose et al. (2004) conducted trials at Transportation Technology Centre Inc., and also used the software KENTRACK to validate the field data (Huang et al. 1984a,b; Rose et al. 2003). They used a slightly different track bed configuration viz. 304.8 mm ballast layer underlain by 101.6 mm hot mix asphalt layer and a wheel load of 200 kN (40 t axle load). A wheel load of 145 kN, a ballast depth of 380 mm, and a subballast depth of 150 mm were considered in MULTA (three-dimensional equations of linear elasticity for multilayered systems), PSA (Fourier

![Fig. 10. Vertical maximum cyclic stresses \( (\sigma_{yv}) \) transmitted to the ballast layer underneath the rail by coal train with wagons (100 t) with a wheel irregularity](image)

![Fig. 11. Comparison of vertical maximum cyclic stresses \( (\sigma_{yv}) \) measured under the rail at Bulli with analytical predictions](image)
series for linear elastic behavior of materials), and ILLI-TRACK (finite-element method employing nonlinear elastic material behavior), as further elaborated by Adegoke et al. (1979). In addition, GEOTRACK (modified version of MULTA) was used with a wheel load of 146 kN and a ballast depth of 300 mm (Selig and Waters 1994), while the Bulli field trial was based on 125 kN wheel load (i.e., 25 t axle load). While the writers recognize the limitations of a direct comparison, due to these variations in input parameters, an acceptable match could be found with the results of this study, the field data and analytical predictions.

Figs. 12(a and b) show comparison of average vertical strains \( (e_1)_{avg} \) observed in the ballast layer at Bulli instrumented track with laboratory results reported by Indraratna and Salim (2005) using prismatic triaxial apparatus. Indraratna and Salim (2005) applied small lateral stresses \( (\sigma_2=10 \text{ kPa}, \sigma_3=7 \text{ kPa}) \) to simulate field confinement and a maximum cyclic principal stress \( (\sigma_1)_{max,cyc} \) of 460 kPa corresponding to an axle load of 25 t and at a frequency of 15 Hz (Esveld 2001; Jeffs and Tew 1991). In the field trial reported here, 25 t axle load and frequency of 8.25 Hz may be considered as the best estimates corresponding to an average train speed of 60 km/h and assumed distance between wheels of common rolling stock bogies as 2.02 m. It is evident from Figs. 12(a and b) that the nature of variation of average vertical strains \( (e_1)_{avg} \) observed in the cyclic triaxial tests is in acceptable agreement with those measured at the Bulli test track. The average vertical strains \( (e_1)_{avg} \) measured at Bulli track for recycled ballast are less than those measured for fresh ballast, while the reverse trend is observed in the cyclic triaxial tests [Fig. 12(a)]. This is because, the grain size characteristics of the recycled ballast in the cyclic triaxial tests was similar to those of fresh ballast and as stated earlier, the recycled ballast in the field was moderately graded. The average vertical strains \( (e_1)_{avg} \) measured in recycled ballast-geocomposite assembly are higher than those reported by Indraratna and Salim (2005). Nevertheless, the trend in \( (e_1)_{avg} \) is similar [Fig. 12(b)]. The large prismatic triaxial apparatus can accommodate specimens: 800 mm long, 600 mm wide, and 600 mm high. Therefore, the sample size ratio (i.e., size of testing chamber divided by the maximum particle dimension) generally exceeded 10 in all directions. It has been argued that as the sample size ratio exceeds 6–7 in triaxial compression, the size effects become negligible (Indraratna et al. 1993, 1998). However, the presence of the rigid boundary conditions in the triaxial apparatus may be the possible reason for the variation in results.

Conclusions

The field trial conducted at town of Bulli highlights the performance of different layers of the track exposed to repeated wheel loads. As expected, the performance of layers of the track differs from adjacent sections where material properties are different. Under the sleepers edge, the compression of both fresh and recycled ballast is more due to reduced lateral constraints.

The recycled ballast produce less settlements and strains compared to the fresh ballast. This is due to moderately graded composition of recycled ballast used here in contrast to the very uniform fresh ballast. Test results demonstrate the potential benefits of using geocomposite in track to reduce vertical and lateral deformations. The geocomposite reduces the lateral strains of fresh ballast significantly, thus minimizing the lateral spread of ballast thereby eliminating the need for additional layers of crib and shoulder ballast during maintenance. Also, recycled ballast when used with a geocomposite layer is found to perform as well as fresh ballast without a geocomposite, with obvious implication on reduced maintenance costs. This study also shows that the inclusion of a geosynthetic layer at ballast-capping interface may also serve as an alternative method of increasing internal confining pressure.

The measurement of in situ stresses indicates that maximum vertical cyclic stress decreases significantly with the increase in depth while, the maximum horizontal cyclic stress decreases only marginally with depth. The geosynthetic layer increases both the friction interlock and the confining pressure. In rail track environments, the confining pressure is of major concern. Therefore, the need for increasing the track confinement (e.g., adding geosynthetic layer within the ballast layer itself) is further justified to improve track stability. Another important finding of this study is that wheel imperfections such as wheel-flat can increase the vertical maximum cyclic stress significantly, causing further ballast degradation. Work is currently being conducted to assess the influence of high impact loads from wheel irregularities on ballast behavior.
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Notation

The following symbols are used in this paper:

- $A_t$ = axle load (t);
- $C_c$ = coefficient of curvature;
- $C_m$ = number of load cycles/million gross tons;
- $C_u$ = coefficient of uniformity;
- $d_{\text{max}}$ = maximum particle size (mm);
- $d_{\text{min}}$ = minimum particle size (mm);
- $d_{50}$ = median particle size (mm);
- $M_R$ = resilient modulus (MPa);
- $N$ = number of load cycles;
- $N_a$ = number of axes/load cycle;
- $q_c$ = cone resistance (MPa);
- $(S_h)_{\text{avg}}$ = average lateral deformation of ballast layer (mm);
- $S_{ov}$ = vertical deformation of ballast layer under the rail (mm);
- $S_{us}$ = vertical deformation of ballast layer under edge of sleeper (mm);
- $(S_v)_{\text{avg}}$ = average vertical deformation of ballast layer (mm);
- $t$ = time (months);
- $\varepsilon_{ov}$ = vertical strain in ballast layer under the rail;
- $\varepsilon_{us}$ = vertical strain in ballast layer under edge of sleeper;
- $(\varepsilon)_{\text{avg}}$ = average shear strain;
- $(\varepsilon_v)_{\text{avg}}$ = average volumetric strain;
- $(\varepsilon_s)_{\text{avg}}$ = average vertical strain (major principal strain) in ballast layer;
- $(\varepsilon_2)_{\text{avg}}$ = average intermediate principal strain in ballast layer;
- $(\varepsilon_3)_{\text{avg}}$ = average lateral strain (minor principal strain) in ballast layer;
- $\sigma_{hr}$ = maximum horizontal cyclic stress under the rail (kPa);
- $\sigma_{hs}$ = maximum horizontal cyclic stress under edge of sleeper (kPa);
- $\sigma_{ov}$ = maximum vertical cyclic stress under the rail (kPa);
- $\sigma_{us}$ = maximum vertical cyclic stress under edge of sleeper (kPa);
- $(\sigma_1)_{\text{max,cyc}}$ = maximum cyclic principal stress (kPa);
- $\sigma_2$ = intermediate principal stress (kPa) (parallel to the rails); and
- $\sigma_3$ = minor principal stress (kPa) (parallel to the sleeper).

References


