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A laboratory investigation to assess the functioning of railway ballast with and without geogrids

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Disciplines

Engineering | Science and Technology Studies

Publication Details

Hussaini, S., Indraratna, B. & Vinod, J. S. (2016). A laboratory investigation to assess the functioning of railway ballast with and without geogrids. *Transportation Geotechnics*, 6 45-54.

A LABORATORY INVESTIGATION TO ASSESS THE FUNCTIONING OF RAILWAY BALLAST WITH AND WITHOUT GEOGRIDS

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No. of Words: 6254
No. of Tables: 4
No. of Figures: 7

Keywords: geogrid, lateral spreading of ballast, FBG sensing system, ballast breakage index, cyclic loading.

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Abstract

Understanding the complex load transfer mechanism and the subsequent accumulation of deformation in ballast and subballast layers under repeated wheel loading is essential to design resilient rail tracks. Large-scale cyclic tests have been conducted on railroad ballast instrumented with optical based fiber Bragg grating (FBG) sensors, LVDTs, pressure plates and the settlement pegs to explore the role of geogrid and its interaction with ballast in improving the track performance. Latite basalt and geogrids with different aperture sizes were used for the investigations. The laboratory experimental results indicate that the geogrid inclusions enhance track performance by arresting the lateral spreading of ballast and thereby significantly reducing the extent of its vertical settlement. In contrast, the reinforcement of ballast with geogrid has only a marginal effect on reducing the settlement in the subballast layer. The results also show that geogrid minimises the amount of particle breakage, the effectiveness of which is governed by its placement position, with lowest breakage occurring when the geogrid is placed at a location 130 mm above the subballast. In addition, geogrids also reduce the extent of vertical stress in the subgrade soil. The laboratory test results establish beyond doubt the effectiveness of FBG sensing system in capturing the ballast movement under cyclic loading.

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Introduction

The emergent requirement for better and efficient rail transport system both in terms of increased freight capacity and greater train speeds inherently place additional stresses on ballast. The repeated application of stress arising due to the passage of trains degrades and fouls the ballast which directly contributes to differential track settlement and track misalignment, thereby affecting the track stability and safety. In addition, the low in-situ confining pressure (i.e. 10-30 kPa) prompts the lateral spreading of ballast that further deteriorates the track condition (Baessler and Rucker 2003; Selig and Waters 1994). The recent study conducted by Dash and Shivadas (2012) also highlighted the lateral flow of ballast as one of the serious track problems. The practical implications of these track

problems are to either impose speed restrictions on the affected track segments or to repair the concerned portions by replacing the ballast. However, the imposition of speed restrictions contradicts the very idea of introducing high-speed trains, and hence is not an acceptable solution. Moreover, repairing the tracks that involves ballast replacement and correcting the track alignment is a costly exercise that consumes millions of dollars every year worldwide. In this view, it is necessary to stabilise the ballasted rail tracks by means of geosynthetics so that they can carry high-speed trains without experiencing any major problem.

In the recent past, several studies have described the cyclic behaviour of geosynthetic-reinforced ballast using the large-scale testing facilities (e.g. Bathurst and Raymond 1987; Raymond and Bathurst 1987; Nancey et al. 2002; Indraratna et al. 2006; Indraratna et al. 2012). Raymond and Bathurst (1987) commented that inclusion of a biaxial geogrid within the ballast layer lead to a decrease in permanent vertical deformations of up to 50% after 100,000 load cycles. Moreover, the number of load cycles required to cause a permanent vertical deformation of 50 mm increased by a factor of ten (10) when a geogrid was used. Bathurst and Raymond (1987) concluded that the effect of reinforcement in reducing the permanent deformations of ballast is more pronounced in the case of tracks laid on soils with a relatively low California Bearing Ratio (CBR) values. Similarly, Matharu (1994) has reported reductions in settlement when a geogrid was used in ballasted rail track. The field studies carried by Indraratna et al. (2010) also confirmed the effectiveness of geosynthetics in augmenting the track performance. The geogrid reinforcement of ballast also reduces the extent of particle breakage (Indraratna et al. 2006, and Fernandes et al. 2008).

The aforementioned benefits of geogrid predominantly stem from the interlocking of ballast particles within the geogrid apertures. Therefore, any improvement in the deformation and degradation characteristics of ballast depends on the degree of ballast-geogrid interaction. Moreover, the effect of geogrid due to its planar geometry is expected to reduce with distance away from its placement location. Further, the internal deformations in ballast that occur as a result of train induced vibrations are yet to be studied in detail. Therefore, the current study was carried out on geogrid-reinforced ballast using the large-scale process simulation apparatus (LPSA) to gain insight into the interaction mechanism at ballast-geogrid interface and its implications on the track behaviour.

Large-scale laboratory tests on ballast with and without geogrids

Large-scale process simulation apparatus (LPSA)

The laboratory tests were conducted using a large-scale process simulation apparatus (LPSA) (Indraratna et al. 2013). It can simulate a section of track with plan dimensions of 800 mm long by 600 mm wide. The middle segment of one of the shorter side walls comprises of five independently movable plates (600 mm x 64 mm x 25.5 mm) assembled vertically with a small gap of 1mm between each plate to allow their free lateral movement upon loading (Figure 1a). The shorter dimension of the box (i.e. 600 mm) represents the centre-to-centre spacing between the sleepers while its longer dimension (i.e. 800 mm) represents the width of the loaded track (Indraratna et al. 2013). Test chambers of similar or smaller dimensions (having different side wall arrangements) were also successfully used in the past by several researchers (Mc. Dowell et al. 2004a, 2004b; Chen 2013) to study the role of geogrid on ballast behaviour.

Materials used and the testing methodology adopted

The test specimen comprised of a subballast layer of 150 mm at the bottom of the test chamber overlain by a 325 mm thick layer of ballast that was compacted in three layers using a vibrating plate to achieve a target field density of 1550 kg/m³. To minimize particle breakage during vibration, a 5 mm thick rubber pad was placed underneath the vibrator. Fresh latite basalt from Bombo quarry, New South Wales, Australia was used for the laboratory investigations. The maximum and mean particle sizes (D_{max} and D_{50}) of ballast used in the study were 53 mm and 35 mm respectively. The coefficient of uniformity, C_u of ballast was 1.87. The ballast specimens conformed to AS 2758.7, and also satisfied the revised recommendations proposed by Indraratna et al. (2004) that the value of C_u should range from 1.5 to 2.6 to possess sufficient strength and permeability. The void ratio (e) of ballast samples was 0.74. On the other hand, the maximum and mean particle sizes (D_{max} and D_{50}) of subballast were 19 mm and 0.5 mm respectively. The coefficient of uniformity, C_u of subballast was 5. The particle size distribution (PSD) of both the ballast and the subballast used in this study is shown in Figure 1(b). An assembly of sleeper (700 mm long) and rail section was placed above the load-bearing ballast and the space around the sleeper was filled with crib ballast up to 150 mm thick (Figure 1a). All the samples were prepared in a similar manner except a layer of geogrid (G1 through G4: Table 1) was placed at either (a) $z = 0$ mm or (b) $z = 65$ mm, where z is the distance above the subballast-ballast interface. Settlement pegs were installed at the subballast-ballast interface and at the sleeper-ballast interface to

record the vertical settlement of ballast and subballast upon loading. A photograph of the ballast sample with settlement pegs installed in the test apparatus ready for testing is shown in Figure 2(a). A sample geogrid used in the current study is shown in Figure 2(b).

A predetermined load was applied to the rail-sleeper assembly to create a maximum vertical stress of 460 kPa on the top of ballast layer. This applied vertical stress is representative of the maximum contact stress generated due an axle load of 25 tons (Indraratna et al. 2011). Further, in accordance with the in-situ confining pressure of 10-30 kPa (Indraratna et al. 2010&2011), a lateral pressure of 10 kPa (imitating the effect of shoulder ballast along with its slope) was applied using server-controlled static actuators onto the side wall comprising of five movable plates. Le Pen (2008), and Le Pen and Powrie (2011) have also reported similar values of confining pressure considering the effect of the shoulder ballast. Moreover, the field studies carried out by Indraratna et al. (2010 and 2011) for a typical railway track (300 mm ballast depth), illustrated that the confining pressure of the ballast would remain almost constant along its depth. In this context, the application of lateral pressure of 10 kPa on the movable plates is realistic. The lateral movement of these movable plates was continuously recorded by means of linear variable differential transformers (LVDTs), while the other walls of the test apparatus were held fixed to simulate the real track conditions. Tests were conducted at a loading frequency of 20 Hz and up to 250000 load cycles and were halted at selected number of load cycles (i.e. $N= 1; 100; 1000; 3000; 5000; 10,000; 30,000; 50,000; 100,000$ and $200,000$) to record the readings from the settlement pegs. The ballast specimen was recovered from the test apparatus and sieved at the end of each test to evaluate the change in gradation and to quantify the breakage of particles; thereafter the used ballast was discarded. Further details on test equipment and the testing procedures can be found in Indraratna et al. (2013) and Hussaini et al. (2015a).

Instrumentation to capture internal lateral strains in ballast and those at the ballast boundary

The five independently movable plates of the LPSA apparatus allow the free lateral movement of ballast, thereby realistically simulating the ballast behavior in the laboratory. The LVDTs were attached to these five movable plates to capture the lateral strain variation along the ballast depth. While this technique can be conveniently used to measure lateral displacements at the ballast boundary, they run the risk of being damaged when placed within ballast. Therefore, there is a need to use a thin and flexible sensing system that can record the

internal displacements in ballast while maintaining the ballast properties unchanged. The optical-Fiber Bragg Grating sensors (FBGs) due to their high accuracy, reliability and flexibility may be used for achieving this objective. Moreover, the polyamide coating to the optical fiber is anticipated to provide resistance against the grinding motion of particles, thus minimizing the risk of damage to the optical fibres when used in ballast. This is in sharp contrast to the conventional strain gauges that are vulnerable to damage both during the specimen placement and the actual testing (Rowe and Gnanendran 1994). In comparison to the conventional electric strain gauges, the use of optical-FBG sensors have a number of obvious advantages such as (a) their ability to accurately capture the strains owing to their high sensitivity and resolution, fast response and (b) their immunity to electromagnetic and electrical signals (Zhu 2009; Mihailov 2012).

In the recent past, the FBG sensing system was successfully used in the structural health monitoring (Liehr et al. 2008; Guo et al. 2011) and in monitoring the slope stability (Dijcker et al. 2011; Nöther et al. 2012). In railway engineering, it was used to monitor the strains induced in rails, and for estimating the weight and speed of trains (Lee et al. 2004; Yoon et al. 2011). A unique characteristic of optical sensing technology is that the FBG strains can be monitored, without any alterations in them, even from about 50-100 km away from the location of sensors (Tam et al. 2007; Fernandez-Vallejo et al. 2011). Therefore, to measure the variation of internal lateral strain along the ballast depth, a sensing sheet was made by attaching four optical fibers with each containing one FBG (having a sensor length of 10 mm) to a thin and flexible polymeric sheet (Figure 1a). Figure 2(c) depicts the optical fiber with a FBG sensor embedded in it. The optical fibers were glued within the grooves of the polymeric sheet (475 mm long, 100 mm wide and 2 mm thick) by means of Cyanoacrylate adhesive, and were left undisturbed for some time for the adhesive to form a bond between fiber and the sheet. The sensing sheet was installed in the test chamber 400 mm away from the movable side wall (i.e. at mid-length of the sleeper) and just adjacent to the rail, with intent to capture internal ballast movement in the immediate vicinity of the rail. The placement location of the FBGs above the subballast, as well as their wavelengths is summarized in Table 2. The FBG data was demodulated by means of a dynamic 4-channel optical sensing interrogator (Si425) and was recorded at a frequency of 1.25 Hz. An Ethernet connection was used for the automatic data communication between the interrogator and the computer (Micron Optics Inc. 2007).

Operating principle of FBG sensors

An optical fiber is a flexible fiber made of glass or plastic, designed to guide light along its length by total internal reflection. Typically, FBG is formed by exposing the core of an optical fiber to an intense Ultraviolet interference to cause periodic changes of the refractive index. This grating structure results in the reflection of the light at a specific narrowband wavelength, known as the Bragg wavelength. The Bragg wavelength is a function of the refractive index of the fiber core and the grating period, and this condition is represented by Equation 1. The operating principle of fiber Bragg grating (FBG) sensors involves monitoring of the wavelength shift in the reflected wavelength spectrum, and then converting it to strain in FBG sensor by using the relevant calibration charts (Hussaini et al. 2015b).

$$\lambda_B = 2n_e \Lambda \quad (1)$$

Where, λ_b is the Bragg wavelength of the FBG, n_e is the effective refractive index of the fiber core and Λ is the grating period.

Results and discussion

To correlate the laboratory data to the actual rail track behaviour, the number of load cycles (N) has been suitably converted to the track operation time as per Equation 2 (Selig and Waters 1994).

$$C_m = \frac{10^6}{(A_t \times N_a)} \quad (2)$$

Where C_m is the number of load cycles/MGT (million gross tons); A_t is the axle load in tons; and N_a is the number of axles/load cycle.

For an annual traffic tonnage of 25 MGT and four axles per load cycle, an axle load of 25 tons imparts 250000 load cycles per year of track operation. Based on this criterion, the 250000 load cycles considered in this current study corresponds to one year of track operation.

The lateral strains in ballast with number of load cycles (N)

The change in FBG strains ($\mu\epsilon$) with number of load cycles (N) for unreinforced and ballast reinforced with geogrid G4 (placed at $z = 0$ mm) is shown in Figure 3. The lateral

displacements in ballast as obtained from the conventional LVDTs attached to the movable plates are also shown here for the sake of comparison. Here, the data from FBG-1 (bottom sensor) and FBG-4 (topmost sensor) are compared with the movement of bottom and top plates, respectively. On the other hand, the data from FBG-2 and FBG-3 are compared with the average of movement of plates 2-3 and 3-4, respectively. Figure 3 reveals that a major portion of the FBG strains and also displacements from LVDTs develop during the initial 50000 load cycles indicating that particles tend to spread laterally during this loading regime. A similar observation with regards to strains in FBG sensors for the ballast reinforced with geogrid G3 was made by Hussaini et al. (2015b). A closer look at Figure 3 depicts that both the FBG strains and the lateral displacements from LVDTs, in a macroscopic sense, follow a similar strain evolution pattern with load cycles (N). This strain evolution pattern is also in line with that reported in the past by several researchers based on the conventional data acquisition techniques (Raymond and Bathurst 1994; Lackenby et al. 2007; Aursudkij et al. 2009). The occasional sharp rise and fall in FBG strain (Figure 3c) is consistent with the research results available in the literature (Zhu 2009; Weng and Wang 2011) and is due to the localized rearrangement of particles (e.g. sudden loss of interlock between particles) during the loading, which the FBG sensors could successfully capture owing to their high resolution. As expected, the reduction in deformations in ballast due to the geogrid inclusion is also clearly evident from both the FBG as well as the LVDT data. This clearly underscores the capability of FBG sensing system in accurately capturing the internal strains in ballast at both initial and final stages of loading. The absence of fluctuations in FBG strains in Figure 3 for a certain range of load cycles may be attributed to the lack of ballast movement in the vicinity of FBG due to strong inter-particle interlocking in a localised zone. Moreover, it is seen from Figure 3d that the effect of geogrid in imposing non-displacement boundary conditions at the ballast-geogrid interface and hence inhibiting the lateral spread of ballast exists even after 250000 load cycles (i.e. one year of track operation). Even at locations away from the geogrid (Figure 3a), the lateral displacements in ballast from both the FBG sensors and LVDTs remain fairly constant after 50000 load cycles until the end of loading. This indicates that ballast continues to possess sufficient strength and does not show any signs of fatigue induced damage, and hence can perform intended function of load distribution without any portion of it requiring replacement.

While the LVDTs could record only the overall lateral strain behaviour of ballast, the FBG sensing system owing to its higher sensitivity and resolution also succeeded in capturing the

minor variations in strain that arises because of the vibrations in ballast due to high-frequency cyclic loading (Figure 3). These sorts of minor fluctuations could in the past be captured only by DEM based numerical simulations (e.g. Ferrellec and McDowell 2010). However, the use of FBG sensors has made it possible to record the minor fluctuations from laboratory tests as well. This attribute of FBG sensing system makes it a viable alternative to accurately obtain the internal deformations in ballast, and hence can effectively be utilised in future studies to capture the effect of increasing train speed on the vibrations in ballast.

Vertical settlement of ballast and subballast layers

A total of eight settlement pegs were placed at the top of the load bearing ballast and at the subballast-ballast interface to record the vertical settlements in the subballast and ballast layers. While the readings from the bottom settlement pegs directly gives the vertical settlement of subballast layer, the difference of readings from the top and bottom layers of settlement pegs gives the total vertical settlement of ballast. The average vertical settlement of the ballast and the subballast layers for unreinforced and geogrid-reinforced ballast (G3 and G4) are shown in Figure 4a. It is evident from Figure 4a that both unreinforced and geogrid-reinforced ballast (G3 and G4) follow a similar pattern of vertical settlement with number of load cycles (N), with rapid deformations occurring within the first 50000 load cycles. The geogrid G4, owing to its favourable aperture size in comparison to D_{50} of 35 mm, performs better than G3. This is primarily attributed to the level of interaction at the ballast-geogrid interface as described earlier by Indraratna et al. (2012). The settlement pattern for ballast reinforced with other geogrids is also the same and is therefore not shown here for the sake of brevity. The settlement of ballast recorded from the current study follows a similar trend to that measured from the field by Indraratna et al. (2010). For loading beyond 50000 cycles, ballast attains a stable packing and hence the total vertical settlement remains fairly constant (Figure 4a). These observations, in a practical sense, imply that intense rearrangement of particles occurs within the first two months of track operation (for a track with annual traffic tonnage of 25 MGT) when the ballast is in the loosest state. As evident, all the ballast samples including the unreinforced one could successfully survive 250000 cycles of loading without any sudden destabilisation (Figure 4a). These findings signify that a rail track can effectively support an axle load of 25 tonnes moving at a speed of 150 km/h even for a low in-situ confining pressure of 10 kPa, albeit with higher associated deformations. The inclusion of geogrid (G4) has successfully reduced the total vertical settlements in ballast from 23.5 mm to 13.2 mm. Moreover, the number of load cycles required to cause a given

vertical settlement of about 13 mm increases from 100 in case of unreinforced ballast to 10000 and 200000 load cycles for ballast reinforced with G3 and G4 respectively. Further, the vertical settlement of both the unreinforced ballast and that reinforced with different geogrids with number of load cycles (N) is established to be governed by a logarithmic relationship as expressed in Equation 3.

$$\text{Settlement in ballast (mm)} = \alpha \times \ln(N) + \beta \quad (3)$$

Where α and β are the empirical constants; and N is the number of load cycle. The values of α and β for ballast reinforced with different geogrids are summarized in Table 3.

The vertical settlements in subballast layer also follow a trend akin to that of ballast except that it undergoes only a marginal vertical settlement of 4.33 mm (Figure 4b) in comparison to a total vertical settlement of 23.5 mm in case of unreinforced ballast. While the total maximum vertical strain in ballast is about 7.25%, the maximum vertical strain in subballast is only about 3%. This may be attributed to the reduced stresses acting at the subballast-ballast interface (as evident from Figure 7) topped up by the relatively higher density of subballast layer that eventually leaves a lesser room for particle rearrangement. Upon reinforcing the overlying ballast layer with geogrids G3 and G4, the settlement of subballast reduces to 3.01 and 2.82 mm respectively. The reinforcement of ballast with other geogrids also produced similar marginal effect on settlement of subballast, but is not shown here for the sake of brevity. It is to be clarified here that in the current study geogrid was placed either within ballast or at the base of ballast, and the subballast layer was free from any reinforcement. These experimental observations indicate that it is more beneficial to reinforce the ballast layer rather than subballast, as the latter undergoes minor deformations only.

Influence of loading on the PSD of ballast

The ballast samples were sieved after the tests to evaluate the changes in PSD because of the applied cyclic loading. The final PSD of unreinforced and geogrid-reinforced ballast (G3) is shown in Figure 5. The coefficient of uniformity (c_{uf}) of different ballast samples after the testing ranged from 1.89-1.94 in comparison to an initial c_u of 1.87 (Table 4). Their corresponding ballast breakage indices (BBI , after Indraratna et al. 2005) ranged from 4.6 to 11.0%, as reported by Indraratna et al. (2013). The generation of fines of different sizes as a result of particle breakage makes the sample well-graded, with the ones undergoing higher

particle breakage exhibiting a higher value of c_{uf} . However, the c_{uf} value of 1.94 obtained after 250000 load cycles is still less than the permissible upper limit of 2.6 to be able to possess sufficient permeability, as recommended by Indraratna et al. (2004). In other words, the particle degradation that occurs with loading (i.e. passage of trains) is not high enough on its own to cause any major permeability problem in tracks. This is further substantiated by the fact that the final void ratio (e_f) of unreinforced ballast is 0.65, which is only marginally less than its initial value of 0.74. The sample reinforced with geogrid G4 exhibits a still higher final void ratio of 0.71 (Table 4). These results certainly point out that although the breakage of particles alone does not critically affect the ballast permeability, still geogrid plays a role in maintaining the voids in ballast that are essential for the quick drainage of water in case of flash floods.

Optimum geogrid placement position to minimise particle breakage

It is well known that rearrangement of particles upon loading lead to their breakage (Indraratna et al. 2005 and Lackenby et al. 2007), the extent of which directly determines the design life of ballast. Therefore, it is essential to lessen the particle breakage to enhance the ballast life, and thereby minimise the need for frequent ballast replacements. In this context, the placement position of geogrid was altered within the test tank to study its possible effect on the particle degradation.

A significant variation in the BBI is witnessed as the placement position of geogrid is altered (Figure 6a). For instance, the geogrid G3 when placed at 0, 65, 130 and 195 mm above the subballast-ballast interface exhibits a BBI of 6.49, 4.80, 4.66 and 6.11% respectively. The reduction in BBI from 6.49 to 4.8% as the position of geogrid is changed from 0 to 65 mm above the subballast may be attributed to the better ballast-geogrid interaction, as the ballast particles now have the scope to protrude through the geogrid apertures in contrast to when placed directly over a dense and compacted layer of subballast. When the reinforcement is placed 130 mm above the subballast, the non-displacement boundary conditions imposed by geogrid extend on both sides of it thereby further reducing the extent of breakage to 4.66%. However, as the position of reinforcement is further elevated to $z=195$ mm the extent of BBI increases again to 6.11%. This is because the geogrid now gets into the zone close to the applied load wherein intense particle movement occurs which adversely affects the intensity of ballast-geogrid interaction. Figure 6(a) clearly depicts the optimum geogrid placement position to be 130 mm above the subballast to minimise the particle degradation. For

practical purposes, geogrid can be positioned at 65 mm above the subballast as the increase in breakage (*BBI*) is insignificant. For all positions of geogrid, the extent of breakage of bigger sized particles (i.e. > 37 mm) effectively governs the degree of overall ballast breakage, *BBI* (Figure 6b; after Marsal 1967). For instance, a reduction in breakage of particles of sizes > 37 mm (Figure 6b) in case of geogrid placed at 130 mm eventually leads to reduced *BBI* as well (Figure 6a). Here, ΔW_k is the difference in percentage retained before and after testing. A closer look at Figure 6(b), that shows the variation in the extent of particle breakage with respect to their sizes, reveals that the particles bigger than 37 mm experience a greater extent of breakage in comparison to smaller sizes. This is because the bigger particles generally take up the entire applied load while smaller particles only fill up the voids. Moreover, bigger particles naturally contain higher micro-cracks as well (Lade et al. 1996) that make them more vulnerable to breakage. On the other hand, particles smaller than 26.5 mm show an increase in their percentage ($-\Delta W_k$) as broken fragments from bigger particles fall in this size range.

Stress distribution along the ballast depth

Rapid-response hydraulic earth pressure cells having a diameter of 230 mm and thickness of 12 mm were placed centrally at the sleeper-ballast interface and at the subballast-ballast interface to establish the role of geogrid on the vertical stress variation along the ballast depth. This kind of pressure cells with grooved thick active faces based on semiconductor type transducers were successfully used in the past by Indraratna et al. (2010 & 2011) and Nimbalkar et al. (2014) to measure the vertical and horizontal stresses in ballast. It is seen from Figure 7 that the magnitude of applied vertical stress on ballast gets significantly reduced at the ballast-subballast interface. For instance, the stress at the ballast-subballast interface is only 220 kPa in comparison to the applied vertical stress of 460 kPa. A similar pattern of reduction in stress along the ballast depth was demonstrated earlier by Indraratna et al. (2010) based on the field studies. The primary reason behind the reduction in stress, as expected, is the dispersion of load over a wider area with depth of ballast. The energy dissipation because of the particle rearrangement and their breakage also contributes towards the stress reduction. The inclusion of geogrid G1 and G4 within the ballast helps reducing the applied stress further to about 170 and 151 kPa at the said interface, which is only about 35% of the original stress. In case of reinforced ballast, the straining of geogrid leads to a higher reduction in stress which is also supplemented by reduced extent of particle degradation and

deformations (Figures 3-5). These findings point out that geogrid reduces the subgrade stresses while still maintaining the track alignment, thereby making it an attractive solution to tackle the track problems.

Conclusions

This paper presented the results from large-scale cyclic tests carried on geogrid-reinforced ballast using the LPSA apparatus. The results from the study established the novel FBG sensing system to be effective in precisely capturing the internal lateral deformations in ballast under cyclic loading. Unlike the conventional LVDTs, the FBG sensors due to their high resolution also captured the minor fluctuations in lateral strains in ballast. The geogrid was found to be effective in inhibiting both the lateral as well as vertical deformations in ballast. For instance, the geogrid G4 reduced the lateral spreading at the subballast-ballast interface from 18 to 6.8 mm. Similarly, the total vertical settlements in ballast were successfully reduced from 23.5 mm to 13.2 mm. The settlement in both unreinforced and geogrid-reinforced ballast was shown to be governed by a logarithmic relation (Equation 3). Moreover, the vertical strain in subballast layer was observed to be only about 3% in comparison to that of about 7.25% in ballast. This observation points out that the benefits of geogrid would be higher when placed in ballast rather than subballast.

In comparison to an initial coefficient of uniformity (c_u) of 1.87, the c_u of different ballast samples after the testing ranged from 1.89 to 1.94 which was well below the critical value to impede track drainage. The test results also proved beyond doubt that geogrid curtails the extent of particle breakage (BBI). However, an optimum placement position of geogrid does exist to minimise the particle degradation, which was determined as 130 mm above the subballast. Furthermore, the data from pressure plates revealed that the applied vertical stress (i.e. sleeper-ballast contact stress) of 460 kPa got reduced to 220 kPa at the ballast-subballast interface. The inclusion of geogrid (G1 and G4) helped reducing the stress further to about 170 and 151 kPa at this interface.

It is to be noted that manufacturers produce geogrids of different aperture sizes to serve different functions for wide variety of soils (not necessarily for ballast and subballast reinforcement). Therefore, extra care needs to be exercised in selecting geogrids for railroad

applications as the smaller aperture sized geogrids will not establish proper geogrid-aggregate interlock.

Acknowledgement

This research was funded by the Cooperative Research Centre for Rail Innovation (established and supported under the Australian Government's Cooperative Research Centres program). The assistance of Technical Officers at the Centre of Geomechanics and Railway Engineering, University of Wollongong in the laboratory tests is highly appreciated. Our thanks are also due to the anonymous reviewers for their valuable comments and suggestions to improve the quality of the paper.

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Notation

A_t	axle load in tons
BBI	ballast breakage index
C_m	the number of load cycles/MGT
C_{uf}	coefficient of uniformity (after the testing)
D_{50}	mean particle size of ballast
D_{max}	maximum particle size of ballast
FBG	fiber Bragg grating
$LPSA$	large process simulation apparatus
N_a	the number of axles/load cycle
N	number of load cycles
PSD	particle size distribution
Z	distance above the subballast

e_f	void ratio
α, β	empirical constants
λ_b	Bragg wavelength
n_e	effective refractive index
A	grating period

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Table 1 Physical and technical properties of the geogrids used in the current study (after Indraratna et al. 2012)

<i>Geogrid type</i>	<i>Aperture shape</i>	<i>Aperture size (mm)</i>		<i>Rib thickness (mm)</i>		<i>T_{ult}[#] (kN/m)</i>	
		MD	CMD	MD	CMD	MD	CMD
<i>G1</i>	Square	38	38	2.2	1.3	30	30
<i>G2</i>	Triangle	36	36	2.0	2.0	19	19
<i>G3</i>	Square	65	65	1.7	1.5	30	30
<i>G4</i>	Rectangle	44	42	1.0	1.0	30	30

MD-Machine direction; CMD-Cross machine direction; [#]Ultimate tensile strength (manufacturer supplied values).

Table 2 Placement location of FBG sensors above the subballast along with their wavelengths (after Hussaini et al. 2015b)

<i>Sensor No.</i>	<i>Position above subballast (mm)</i>	<i>Wavelength (nm)</i>			
		UR, G3 [*] , G1 [*]	G1 ⁺ , G2 ⁺	G4 ⁺ , G2 [*]	G3 ⁺ , G4 [*]
FBG-1	41	1555	1560	1560	1555
FBG-2	122	1545	1560	1550	1550
FBG-3	203	1535	1555	1540	1535
FBG-4	284	1535	1535	1535	1535

Geogrid placement position: ^{*}Subballast-ballast interface (i.e. $z = 0$ mm); ⁺65 mm above the subballast (i.e. $z = 65$ mm).

Table 3 Values of empirical coefficients α and β of different ballast samples

Parameter	UR	G1 [*]	G2 [*]	G3 [*]	G4 [*]	G1 ⁺	G2 ⁺	G3 ⁺	G4 ⁺
α	1.52	1.04	1.15	0.96	0.71	0.71	1.62	0.74	0.59
β	5.70	4.419	6.25	3.55	4.15	4.35	9.15	1.99	3.05
R^2	0.98	0.95	0.93	0.97	0.94	0.86	0.90	0.94	0.94

Geogrid placement position: ^{*}Subballast-ballast interface (i.e. $z = 0$ mm); ⁺65 mm above the subballast (i.e. $z = 65$ mm).

Table 4 Coefficient of uniformity C_{uf} , BBI (%), and void ratio (e_f) of different ballast samples after the testing

Parameter	UR	G1*	G2*	G3*	G4*	G1 ⁺	G2 ⁺	G3 ⁺	G4 ⁺
C_{uf}	1.93	1.92	1.93	1.93	1.92	1.92	1.94	1.89	1.89
$BBI^{\#}$ (%)	9.89	7.78	8.91	6.49	6.29	5.99	11.00	4.80	4.60
e_f	0.65	0.69	0.68	0.69	0.70	0.71	0.64	0.71	0.71

Geogrid placement position: * Subballast-ballast interface (i.e. $z = 0$ mm); ⁺65 mm above the subballast (i.e. $z = 65$ mm). [#] BBI data sourced from Indraratna et al. (2013).

FIGURES

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