Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 49 No. 4 December 2018 ISSN 0046-5828

A Critical Review of the Performance of Geosynthetic-Reinforced Railroad Ballast

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ABSTRACT: In the recent times, railway organizations across the world have resorted to the use of geosynthetics as a low-cost solution to stabilize ballast. In this view, extensive studies have been conducted worldwide to assess the performance of geosynthetic-reinforced ballast under various loading conditions. This paper evaluates the various benefits the rail industry could attain because of the geosynthetic reinforcement. A review of literature reveals that geogrid arrests the lateral spreading of ballast, reduces the extent of permanent vertical settlement and minimizes the particle breakage. The geogrid was also found to reduce the extent of volumetric compressions in ballast. The overall performance improvement due to geogrid was observed to be a function of the interface efficiency factor (α). Moreover, studies also established the additional role of geogrids in reducing the differential track settlements and diminishing the stresses at the subgrade level. The geosynthetics were found to be more beneficial in case of tracks resting on soft subgrades. Furthermore, the benefits of geosynthetics in stabilizing ballast were found to be significantly higher when placed within the ballast. The optimum placement location of geosynthetics has been reported by several researchers to be about 200-250 mm below the sleeper soffit for a conventional ballast depth of 300-350 mm. A number of field investigations and track rehabilitation schemes also confirmed the role of geosynthetics/geogrids in stabilizing the tracks thereby helping in removing the stringent speed restrictions that were imposed earlier, and enhancing the time interval between maintenance operations.

KEYWORDS: Cyclic loading, Geosynthetics, Vertical settlement, Lateral spreading, Ballast breakage, Differential settlement.

1. INTRODUCTION

Railways are one of the major modes of transportation around the world and play a vital role in the economy of any country. It is responsible for transporting freight and bulk commodities between major cities, ports and industries, apart from carrying passengers in busy urban networks. In the recent years, owing to the increased number of rail commuters, railways face the challenge of increasing the competitiveness and attractiveness of rail transport in terms of speed (reduced travel time), increased tonnages, higher frequency of trains, availability and reliability with promising passenger comfort and safety. This in turn necessitates better quality of track, the performance of which is highly affected by the complex interaction of its components in response to train loading. Hay (1982) reported that majority of track failure and maintenance costs are related to the track substructure comprising of ballast, subballast and subgrade layers. Alias (1984) also stated that the track performance mainly depends on the effective functioning of the ballast layer and the corresponding track deformation and degradation characteristics.

The large vertical train loads combined with relatively small horizontal confining stress leads to lateral flow of ballast under the cyclic loading conditions (Baessler and Rucker 2003). This lateral flow of particles can reduce the horizontal residual stresses that confine the ballast, hence reducing the stability of the track (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 lateral flow of ballast also leads to attrition, corner breakage and the splitting of particles (Figure 1a) that contributes towards the vertical deformation of ballast and distortion of track segments (Figure 1b). Moreover, the settlement and breakage of ballast is non-uniform along the track length due to the differences in subgrade characteristics, thus leading to the differential settlement of rails that significantly affects the track safety (Figure 1c). The other prominent problem in a typical track is due to the fines generated as a result of attrition and particle degradation that migrate downwards and fill the voids between other particles that subsequently reduce the ability of ballast to drain the water due to a decrease in permeability (Figure 1d). The above mentioned track problems increase significantly with the increase in train speed, as higher vibrations contribute to increased track settlement due to higher ballast degradation and the lateral flow of ballast. The practical implications of the aforementioned track problems are to either impose speed restrictions on the affected track segments or to repair the concerned portions by replacing the ballast. However, when the rail authorities worldwide are compelled to introduce high-speed trains to attract the commuters, the imposition of speed restrictions does not seem to be 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 so that they can carry high-speed trains without creating any major track problem.

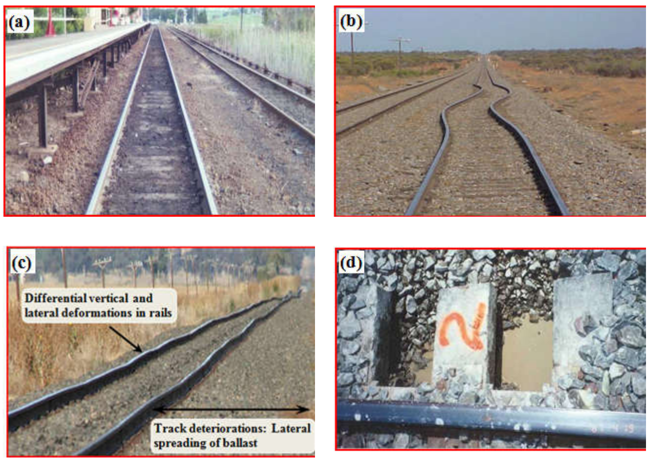

Figure 1
(a) Ballast breakage in a rail track (after Indraratna et al. 2011),
(b) Buckling of track due to insufficient lateral confinement (after Indraratna et al. 2011);
(c) Track deteriorations and the differential settlement of rails (modified after Suiker 2002); and
(d) Ponding of water in the load bearing ballast (after Indraratna et al. 2011)

Realizing the important role played by ballast in the efficient functioning of a rail track, a number of researchers have conducted both laboratory and field investigations on ballast reinforced with geosynthetics. In this context, the existing literature on performance of reinforced railroad ballast is critically reviewed and the key findings are encapsulated in this current paper.

2. LABORATORY INVESTIGATIONS ON BALLAST-GEOSYNTHETIC INTERFACES UNDER DIRECT SHEAR CONDITIONS

A number of researchers have described the behaviour of sand-geosynthetic interfaces under direct shear conditions (e.g. Bakeer et al. 1998; Tang et al. 2008; Liu et al. 2009; Abdi and Arjomand 2011). However, the literature pertaining to the performance of ballast-geosynthetic interfaces is very scant. Indraratna et al. (2012) is the only comprehensive study that explored the performance of railroad ballast-geosynthetic interfaces using a large-scale direct shear testing apparatus. They concluded that the shear strength of the ballast-geogrid interfaces is significantly affected by the normalized geogrid aperture size (A/D_{50}) (Figure 2). Based on the variation of interface shear strength, they have categorized the ratio A/D_{50} into three key zones: (a) Feeble Interlock Zone, with $A/D_{50} < 0.95$ (b) Optimum Interlock Zone, with $0.95 < A/D_{50} < 1.20$ and (c) Diminishing Interlock Zone, with $1.20 < A/D_{50} < 2.50$. The best geogrid aperture size to optimize the interface shear strength was determined to be $1.20D_{50}$. Furthermore, the minimum and maximum aperture sizes desired to attain the beneficial effects via geogrids were established as $0.95D_{50}$ and $2.50D_{50}$, respectively. Brown et al. (2007) have identified the optimum aperture size of geogrid as $1.35D_{50}$ for ballast gradations as per the British standards. Similarly, the geogrid was also found to enhance the shear strength of coal-fouled ballast under direct shear conditions (Indraratna et al. 2011a). Dash and Shivadas (2012) have reported an improvement in the performance of ballast-subballast interface upon its reinforcement with geocell.

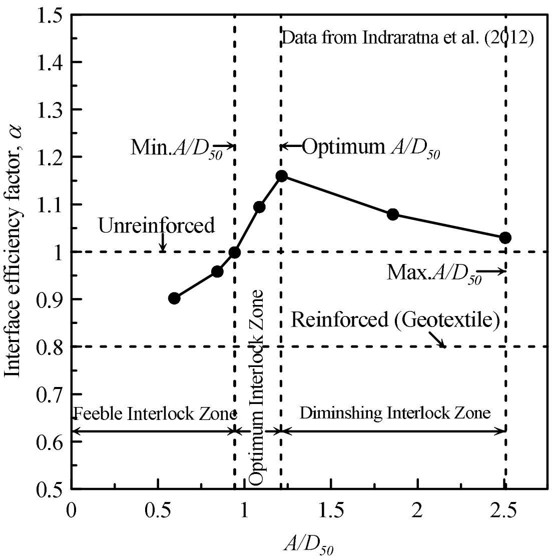

Figure 2 Variation of interface efficiency factor (α) with A/D_{50} (modified after Indraratna et al. 2012)

3. LABORATORY INVESTIGATIONS ON GEOSYNTHETIC-REINFORCED BALLAST UNDER CYCLIC LOADING CONDITIONS

3.1 Role of geosynthetics on vertical, lateral and volumetric strains in ballast

Railway tracks undergo millions of loading cycles of varying axle loads and loading frequencies during their service life. The overall performance of a track depends predominantly on the effective functioning of ballast layer. However, ballast owing to its unbound granular nature spreads laterally thereby causing vertical deformations in track, corner breakage and the splitting of particles that eventually leads to the distortion of the track segment. The cyclic densification of ballast that occurs as a consequence of loading is of paramount importance for optimum design, safety and operational efficiency of tracks. With a primary objective of arresting the lateral spread of ballast and hence to enhance the track performance, the rail engineers have resorted to the use of geosynthetics (i.e. geogrids).

The initial studies on geosynthetic-reinforced ballast were conducted in Canada at Royal Military College and Queens University (Bathurst and Raymond 1987; Raymond and Bathurst 1987). These studies on geogrid-reinforced ballast were conducted using a large-scale rigid test box 3 m long by 1.5 m wide at loading frequencies of 0.5-3 Hz, which approximately represents train speeds in the range of 4 to 22 km/h (for an axle spacing of 2.02 m). The samples were subjected to a sleeper-ballast contact pressure of 370 kPa. Bathurst and Raymond (1987) have concluded that the geogrid reduces the rate of settlement of ballast. They further commented that the effect of reinforcement in reducing the permanent deformations of ballast is more pronounced in case of tracks laid on soils with low California bearing ratios. The study involved the placement of geogrid at variable depths below the sleeper soffit based on which the optimum depth of reinforcement to tie (sleeper) breadth ratio (D_r/B) was reported to be in the range of 0.2-0.4. Furthermore, the number of load cycles required for causing a permanent vertical deformation of 50 mm increased by a factor of ten (10) when a geogrid was used.

Matharu (1994) described the results from full-scale laboratory tests on a 20 m long track section using a rolling load rig. The weight of the rolling load rig used could be varied from 8 to 40 tonnes, 90% of which was carried by the main central axle. The rolling rig was made to traverse over the test track at a rate of 1 m/s which in effect corresponds to three load applications per minute (i.e. 3 load cycles/minute). The total load applied in each test was 2 million gross tonnes (MGT). Matharu (1994) concluded that for tracks laid on soft subgrade, geogrid helped in reducing the vertical settlement significantly to the extent that they performed as good as the tracks laid on firm subgrade but without any geogrids.

Shin et al. (2002) conducted large-scale model tests using a steel box measuring 1.4 m in length, 1 m in width and 2 m in height. A maximum stress of 545 kPa was applied on to the test samples. The frequency of the cyclic load was increased gradually from 0.01 Hz to 3.5 Hz (train speed: ~0.07-25 km/h) to simulate the gradual increase in speed of the train. The study involved exploration of ballast behaviour with multiple layers of geosynthetics with one layer each at the interface of the subgrade soil and subbase course, middle of subbase layer and interface of the subballast and subbase course. They observed that the most beneficial effect in terms of reduction in settlement is realized when a layer of geotextile and a layer of geogrid are placed at the interface of the subbase layer and the subgrade soil. Shin et al (2002) concluded that as the number of layers of reinforcement was increased from one (geocomposite: geogrid plus geotextile), to two and three layers, the total reduction in the settlement of ballast was observed to be 47%, 58% and 80% respectively.

Raymond and Ismail (2003) described the results from tests conducted on model tracks made to an approximate one-tenth (1/10th) scale of that of railway tracks in practice. A track with tie (sleeper) minimum length of 2000 mm was modelled by a 200 mm long footing the same width as the test tank used by them to give plane strain conditions and 200 mm wide in the length direction of the tank. The cyclic loads to cause a maximum average contact footing pressure of 45 kPa were applied at a frequency of 1 Hz (~train speed: 7.2 km/h). They reported that a single layer of geogrid decreased the settlement after 10,000 cycles of loading. With regards to the placement position of geogrid, the greatest benefit was reportedly obtained when the placement depth ratio (D_r/B) was between 0.18 and 0.5. They further concluded that for ballast reinforced with two layers of geosynthetics, the effect of second layer was evident only at higher number of load cycles. In addition, they established the second layer of reinforcement to be most effective when the same is placed at a depth ratio D_r/B of 0.2-0.6.

Indraratna et al. (2006a&b) conducted a series of tests on fresh and recycled ballast reinforced with geosynthetics using a cubical triaxial apparatus with movable boundaries (side walls) that could allow the lateral spreading of ballast under cyclic loading. The apparatus was designed by Indraratna et al. (2000) and could accommodate samples measuring 800 mm long, 600 mm wide and 650 mm deep. A vertical stress of 460 kPa that is representative of 25 tonnes axle load was applied on to the test samples and continued for 500,000 load cycles. Recognising the importance of testing ballast under realistic train speeds, a relatively higher loading frequency of 15 Hz (~train speed: 110 km/h) was used. Small lateral confining pressures (σ_2 =10 kPa and σ_3 =7 kPa) were applied on the movable side walls by means of static actuators to simulate field confinement. They have reported that the inclusion of geocomposite in both fresh and recycled ballast improves its resistance to settlement, and that the recycled ballast reinforced with geosynthetics performs as good as the fresh ballast without geosynthetics. Indraratna et al. (2006a) have further commented that the inclusion of either geotextile or geogrid in recycled ballast improves the settlement behaviour moderately, but not to the same extent as that of the geocomposite. As the testing facility allowed monitoring the lateral movements of side walls, they measured the lateral deformations in ballast as well. A decrease in the extent of lateral strain in recycled ballast by the use of geotextiles and geocomposites was reported by them. More significantly, recycled ballast stabilised with geocomposites or woven-geotextiles was shown to exhibit lateral strain (ε_3) less than that of fresh ballast (without any geosynthetics) at higher number of load cycles. The performance of geosynthetic-reinforced ballast under cyclic loading conditions was evaluated under wet conditions by Indraratna et al. (2006b). It was established that the ballast under wet conditions experienced a greater extent of deformations as against dry conditions, which was attributed to the lubricating effect of water on ballast.

Brown et al. (2007) reported results of full-scale tests that were conducted with an aim to identify the key parameters that influence geogrid-reinforcement of railway ballast. All the tests were conducted with a maximum applied load of 20 kN, that created a contact stress of 114 kPa, at a loading frequency of 2 Hz (train speed: ~14.5 km/h) and for 30,000 load cycles. They too reported a reduction in settlement due to the geogrid reinforcement of ballast. Furthermore, the optimum geogrid aperture size for minimizing settlement was found to be 70 mm for ballast that comprised of 50 mm sized particles.

Kennedy (2011) conducted full-scale laboratory tests to assess the influence of different geosynthetics on the performance of rail track. The tests were conducted in a steel tank 3.0 m long, 1.072 m wide and 1.15 m high. A vertical load of 90 kN was applied at a loading frequency of 3 Hz (train speed: ~22 km/h). It was reported that the geocomposite increased the track stiffness by 9-12% thereby reducing the track settlement by 25%. However, they further commented that the geocell reinforcement caused a decrease in the track stiffness by 5-7% that eventually led to an increase in settlement by 37%. The impaired performance in this case was attributed to the difficulty in compacting ballast in the individual cells of geocell.

Indraratna et al. (2013) conducted a series of tests on geogrid-reinforced ballast using the modified version of the apparatus designed originally by Indraratna et al. (2000). The modification was essential to allow the non-uniform spreading of ballast along its depth in the outward direction. The central portion of one of the side walls of the apparatus consists of a setup of five independently movable plates each measuring 600 mm in width and 64 mm in height assembled along the depth. A small gap of 1 mm between the adjacent plates ensures the free lateral movement of each individual plate under the applied loading (Hussaini 2013).

The ballast was reinforced with geogrids of different aperture sizes. The geogrids were placed at either the subballast-ballast interface or within the ballast at 65 mm above the subballast. A vertical stress of 460 kPa was applied on to the test samples at a loading frequency of 20 Hz (train speed: ~146 km/h) and continued for 250,000 load cycles. The study established the beneficial role of geogrids in reducing the vertical settlements in ballast (Figure 3).

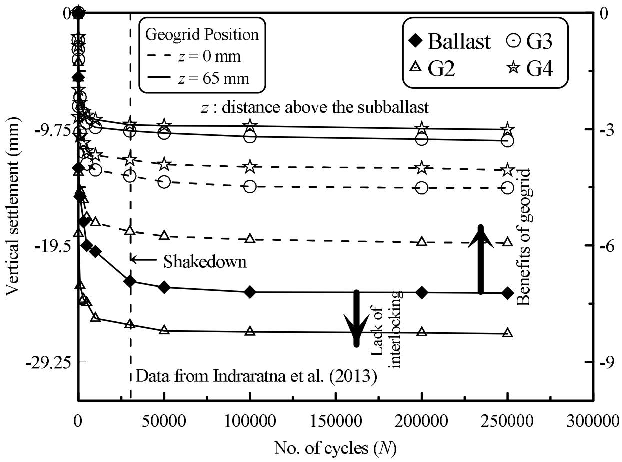

Figure 3 Vertical settlements in unreinforced and geogrid-reinforced ballast (modified after Indraratna et al. 2013)

The study further concluded that placing the geogrid within ballast (at 65 mm above the subballast) helps better stabilising the ballast in comparison to geogrid placed at the subballast-ballast interface. The increase in settlements in case of geogrid with A/D_{50} of 0.6 (Figure 3) was attributed to improper particle interlocking when the same is placed within the ballast. The optimum geogrid placement position was determined to be a function of A/D_{50}. The study established the optimum geogrid placement position to be the subballast-ballast interface for A/D_{50} < 0.95, and the same to be 65 mm above the subballast for 0.95 < A/D_{50} <2.5. The novel design of the apparatus also allowed obtaining the variation of lateral strains along the ballast depth. Based on the lateral strain profiles, it was found that the beneficial effect of geogrid in arresting the lateral spreading exists up to a distance (i.e. geogrid influence zone) of about 160 and 225 mm from itself when placed at the subballast-ballast interface and at 65 mm above the subballast, respectively (Figure 4). The lateral strain measurements based on a novel optical-based fiber Bragg grating (FBG) sensing technology also confirmed that the beneficial effects of geogrid diminishes with distance away from itself (Hussaini et al. 2015a, 2016).

Indraratna and Nimbalkar (2013) have carried out large-scale cyclic tests on ballast reinforced with geosynthetics (biaxial, nonwoven geotextile and geotextile) using the cubical triaxial apparatus. The tests were conducted in a manner similar to those conducted by Indraratna et al. (2006a), as described in the previous section. The tests were conducted with one and two layers of geosynthetics. In case of single-layer arrangement the reinforcement was placed at the subballast-ballast interface and in case of dual layer arrangement the second layer of geocomposite was placed at the subballast-subgrade interface. The study concluded that the biaxial geogrid would be a suitable reinforcement to be placed below the ballast for overall railroad track stabilization. However, the same needs to be placed in conjunction with a geotextile to act as an effective separator. The geocomposite was shown to be very effective at controlling both vertical settlements and particle breakage. The study also demonstrated that dual-layer reinforcements, i.e., geogrid at the ballast-subballast interface and geocomposite at the subballast-subgrade interface, are better at reducing settlement than single-layer reinforcements.

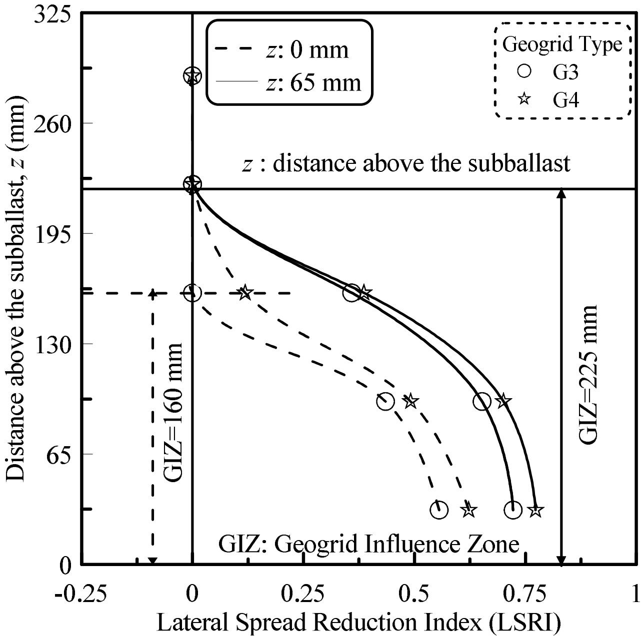

Figure 4 Variation of lateral spread reduction index with distance above the subballast (data sourced from Indraratna et al. 2013)

The reduced extent of vertical settlement and lateral deformations in ballast due to geogrid also implies that reinforced ballast undergoes lesser volumetric strains in comparison to unreinforced conditions. Hussaini et al. (2014) have highlighted that all the ballast samples, both with and without geogrids, tested by them underwent volume reduction (i.e. cyclic densification) upon loading (Figure 5). However, the extent of volume reduction was found to be relatively lower for reinforced ballast implying that geogrid stabilises the track without causing any significant densification, thus maintaining sufficient voids in it that are imperative for the quick drainage of water. These experimental observations correlate well with the field study of geosynthetic-reinforced ballasted tracks reported earlier by Indraratna et al. (2010a).

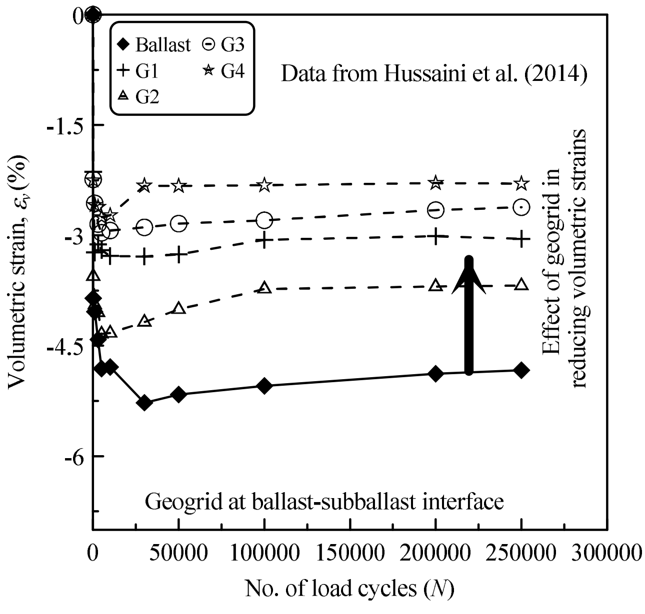

Figure 5 Variation of volumetric strains (ε_v) with load cycles (N) (modified after Hussaini et al. 2014)

The various studies conducted by different researchers to capture the behaviour of geosynthetic-reinforced ballast under cyclic loading conditions are summarised in Table 1(a & b). It is to be noted that these studies were conducted at different magnitudes of axle loads, loading frequencies, confining pressures and boundary conditions. Nevertheless, all the studies have invariably established the beneficial effect of geosynthetics in reducing the extent of deformations in ballast (mostly vertical settlements and lateral displacements wherever reported). The only exceptions to this being the use of geocells where proper compaction of ballast within the individual cells of it was not possible owing to its geometry (Kennedy 2011), and the use of geogrid with smaller aperture size (A/D_{50} of 0.6) when placed within ballast as the same could not allow the interlocking of particles within its apertures (Indraratna et al. 2013). These observations point out that while geosynthetics in general can be used as a means to effectively stabilise the rail tracks, it is important to carefully choose the type of geosynthetic and its placement position as they can otherwise lower the track stability.

3.2 Role of geosynthetics on ballast breakage

The degradation of granular materials upon loading occurs mainly due to the breakage of sharp corners, splitting of particles into two or more approximately equal parts and the attrition of asperities (Lees and Kennedy 1975). The breakage of particles is generally represented by ballast breakage index (*BBI*), an index proposed originally by Indraratna et al. (2005). However, prior to the introduction of *BBI* the degradation of ballast was evaluated in terms of Marsal's breakage index, B_g (Indraratna et al. 2006b). The extent of particle breakage depends predominantly on the particle size distribution of ballast, loading conditions (i.e. static or cyclic loading), loading frequency, and the confining pressure acting on ballast. For instance, the particle degradation under cyclic loading conditions first decreases for an initial increase in confining pressure from about 30 to 60 kPa and increases again with the further increase in confining pressure (Indraratna et al. 2005; Lackenby et al. 2007). Similarly, the extent of particle breakage increases with the increase in applied deviatoric stress and the loading frequency (Lackenby et al. 2007; Indraratna et al. 2010b). The role of geosynthetics in reducing the particle breakage (Marsal's breakage index: B_g) is first studied by Indraratna et al. (2006b). Subsequently, several other researchers have established the effect of geosynthetics on particle breakage (Fernandes et al. 2008; Indraratna et al. 2013; Hussaini 2013). Fernandes et al. (2008) have shown that the extent of ballast breakage (B_g) increases with track operation time and at any instance reduces when ballast is reinforced with geosynthetics. Hussaini (2013) has given an empirical relationship to compare the extent of breakage (BBI) with that available in the literature in terms of B_g.

$$B_g = 0.25 \times BBI + 0.32 \qquad (1)$$

The laboratory investigations conducted by Nimbalkar et al. (2012) reported a reduction in *BBI* due to use of shock mats under impact loading. Table 2 summarises the values of *BBI* reported by various researchers for ballast reinforced with geosynthetics. Although the quantum of particle breakage from these studies is not comparable, these studies invariably point out a significant reduction in ballast breakage due to geosynthetics.

3.3 Role of geosynthetics on differential settlement in ballast

Since the inception of geosynthetics, a number of researchers have conducted comprehensive studies on geosynthetic-reinforced ballast and have established the role of geosynthetics in reducing the permanent deformations in ballast. However, a railway track under operating conditions would often undergo differential settlement as some track segments are subjected to vertical dynamic stress higher than others due to the presence of irregularities on the surfaces of

Table 1a Summary of the test conditions of various laboratory studies on geosynthetic-reinforced ballast under cyclic loading conditions

Researcher	**Apparatus size (L × W × H) (m)**	**Loading conditions**				**Remarks**
		Vertical stress applied (kPa)	**Confining pressure (kPa)**	**Loading frequency (Hz)**	**No. of load cycles (*N*) /Total load (MGT)**	
Bathurst and Raymond (1987)	3 × 1.5 (w)	370 kPa	NA	0.5-3	12 MGT	Tests were conducted on a large-scale model comprising of single-tie and ballast system
Matharu (1994)	20 (L)	Rolling load: 80-400 kN	NA	3 load cycles/min	2 MGT	Tests were conducted under rolling load conditions
Shin et al. (2002)	1.4 × 1 × 2	545 kPa	NA	0.01-3.5	*N*: 500,000	Frequency of loading gradually changed during the test
Raymond and Ismail (2003)	0.2 × 0.2 (w)	45 kPa	NA	1	*N*: 10,000	Tests conducted at a reduced scale of 1/10
Indraratna et al. (2006a,b)	0.8× 0.6× 0.65	460 kPa	10	15	*N*: 500,000	The apparatus used had movable side walls
Brown et al. (2007)	1.4 × 0.7 (w)	114 kPa	NA	2	*N*: 30,000	Composite Element Test (CET) was conducted under normal and overburdened cases.
Kennedy (2011)	3.0 × 1.072 ×1.15	Cyclic load: 90 kN	NA	3	*N*: 500,000/12.5 MGT	The effect of tamping was considered
Indraratna et al. (2013); Hussaini et al. (2014, 2015a, 2015b, 2016)	0.8 × 0.6× 0.65	460 kPa	10	20	*N*: 250,000	The apparatus used allowed non-uniform spreading of ballast along its depth
Indraratna and Nimbalkar (2013)	0.8× 0.6× 0.65	447 kPa	10	15	*N*: 200,000	The apparatus used had movable side walls

Table 1b Summary of the results from various laboratory studies on geosynthetic-reinforced ballast under cyclic loading conditions-Part 1

Researcher	Parameters studied	Type of reinforcement	Salient conclusions
Bathurst and Raymond (1987)	Vertical settlement, Optimum depth of reinforcement	Single layer of geogrid placed at variable depths below the sleeper soffit	The geogrid reduces the rate of permanent settlement for tracks laid over compressible subballast-subgrade formations. The optimum depth of reinforcement to tie (sleeper) breadth ratio (D_r/B) is in the range of 0.2-0.4.
Matharu (1994)	Vertical settlement	Geogrid placed at 50 and 100 mm above the soft subgrade	The geogrid reduces the extent of settlement. The depth of placement does not alter the ballast response significantly
Shin et al. (2002)	Vertical settlement	Multiple layers of geosynthetics with one layer each at the interface of the subgrade soil and subbase course, middle of subbase layer and interface of the subballast and subbase course	The most beneficial effect of settlement reduction is realized when a layer of geotextile and a layer of geogrid are placed at the interface of the subbase layer and the subgrade soil. With the placement of one layer of geotextile and a layer of geogrid, the magnitude of total track settlement reduced by about 47%.
Raymond and Ismail (2003)	Vertical settlement	Single and two layers of geogrid placed at variable depths below the sleeper soffit	For a single layer of geogrid, the maximum reduction in settlement was obtained when the placement depth ratio (D_r/B) was between 0.18 and 0.5. For double layer of geogrid reinforcement, with the top layer at D_t/B =0.0625, the optimum position for placing a second geogrid reinforcement (D_r/B) so as to reduce settlement was found to be in the range of 0.2-0.5.
Indraratna et al. (2006a,b)	Vertical settlement, lateral deformation, ballast breakage	Single layer of geogrid, geocomposite placed at the subballast-ballast interface	The geocomposite reduces the extent of settlement by 25 and 28% and particle breakage by 5 and 48 % for fresh and recycled ballast respectively. The recycled ballast with geocomposites performs as good as fresh ballast without any reinforcement.
Brown et al. (2007)	Vertical settlement, identification and optimisation of geogrid properties	Single layer of geogrid, geocomposite placed at either the subballast-ballast interface or 50 mm above the subballast	The effect of geogrid was found to be more pronounced for soft subgrades than the stiffer ones. For the 50 mm ballast that was used, the optimum aperture size was found to lie in the range of 60-80 mm. Geogrid aperture size, tensile strength, and junction strength were identified to influence the effectiveness of reinforcement.

Table 1b Summary of the results from various laboratory studies on geosynthetic-reinforced ballast under cyclic loading conditions-Part 2

Researcher	Parameters studied	Type of reinforcement	Salient conclusions
Kennedy (2011)	Settlement, track stiffness, effect of tamping and ballast depth on settlement	Geocell, geocomposite placed at the subballast-ballast interface	Geocell increased the track settlement by 37% The geocomposite reduced the extent of settlement by 25%. The settlement at 10,000 cycles increased by 350% when the ballast depth was reduced from 300 to 250 mm.
Indraratna et al. (2013); Hussaini et al. (2014)	Settlement, lateral strain profiles, ballast breakage, optimum geogrid placement position, geogrid influence zone (GIZ) Volumetric strains	Single layer of geogrid having various aperture sizes placed at either subballast-ballast interface or 65 mm above the subballast	The geogrid with A/D_{50} of 1.21 reduces the ballast settlement and particle breakage by 58 and 53%, respectively. *Optimum geogrid placement position:* A/D_{50}< 0.95: z=0 mm; 0.95 < A/D_{50}<2.5: z= 65 mm; GIZ extends up to 160 and 225 mm for geogrid placed at z=0 and 65 mm respectively (z: distance above the subballast). Geogrid while stabilising ballast also reduces the extent of volumetric compression/cyclic densification.
Indraratna and Nimbalkar (2013)	Settlement, lateral deformation, ballast breakage	*Single-layer arrangement:* One layer of geogrid/geotextile/geocomposite was placed at the subballast-ballast interface. *Dual layer arrangement:* An additional layer of geocomposite was placed at the subballast-subgrade interface.	The biaxial geogrid placed below the ballast would be a suitable reinforcement for overall railroad track stabilization. A geotextile/geocomposite is an ideal option for separator. The dual-layer reinforcement, i.e., geogrid at the ballast base and geocomposite at the subballast-subgrade interface, is better at reducing settlement than single-layer reinforcements.
Hussaini et al. (2015a)	FBG based lateral strains	Single layer of geogrid having various aperture sizes placed at either subballast-ballast interface or 65 mm above the subballast	The optical based FBG sensing system is capable of measuring the internal lateral deformations in ballast.
Hussaini et al. (2015b, 2016)	Settlement of ballast, role of ballast-geogrid interface on lateral spread of ballast; subballast settlement, FBG based lateral strains.		The geogrid reduces the extent of differential settlement and breakage in ballast by 53 and 50%, respectively The lateral deformation in reinforced ballast under cyclic loading is a function of the interface efficiency factor (α). The vertical strain in subballast layer was observed to be only about 3% in comparison to that of about 7.25% in ballast. The lateral deformations measured using LVDTs and FBGs follow similar trend with N and along the ballast depth.

Table 2 Summary of particle breakage of geosynthetic-reinforced ballast under cyclic loading conditions

Researcher	Test Specimen	B_g	BBI[#]	Researcher	Test Specimen	B_g[1]	BBI[2]
Indraratna et al. (2006b)	Fr. ballast	1. 50	4.72	Hussaini (2013)[1] Indraratna et al. (2013)[2]	Fr. ballast	2.80	9.89
	Recy. ballast	2. 96	10.56		Fr. ballast with geogrid G1*	2.30	7.80
	Recy. ballast with GT	1. 56	4.96		Fr. ballast with geogrid G1+	1.80	6.00
	Recy. ballast with geogrid	1. 70	5.52		Fr. ballast with geogrid G2*	2.60	8.90
	Recy. ballast with GC	1. 52	4.80		Fr. ballast with geogrid G2+	3.21	11.00
	Fr. ballast with GT	1. 54	4.88		Fr. ballast with geogrid G3*	1.90	6.50
	Fr. ballast with geogrid	1. 49	4.68		Fr. ballast with geogrid G3+	1.71	4.80
	Fr. ballast with GC	1.42	4.40		Fr. ballast with geogrid G4*	1.75	6.30
	---	---	---		Fr. ballast with geogrid G4+	1.55	4.60

Fr. ballast: fresh ballast; Recy. ballast: recycled ballast; GT: Geotextile; GC: Geocomposite; Geogrid placement position: *Subballast-ballast interface (i.e. z = 0 mm); +65 mm above the subballast (i.e. z = 65 mm); #Computed by using the empirical equation 1.

rail and wheel (e.g. Indraratna et al. 2011b, Jenkins et al. 1974 & Indraratna et al. 2010a). This is also evident from the field studies conducted by Indraratna et al. (2010a) which demonstrated that for an axle load of 25 tons, the sleeper-ballast contact stress generally ranged up to 230 kPa but occasionally reached a peak of about 415 kPa upon the arrival of a wheel-flat. To explore the role of geogrids in reducing the differential track settlements, Hussaini et al. (2015b) have conducted studies with sleeper-ballast contact stress of 460 and 230 kPa that represent track sections with and without rail/wheel irregularities. They have shown that while two adjacent unreinforced track sections would undergo a permanent differential settlement of 14 mm, the geogrid-reinforced ballast undergoes a total differential settlement of only 6.60 mm, which is more than 50% lesser in comparison to unreinforced conditions (Figure 6). These results highlight the beneficial role of geogrid in curtailing the differential settlement of ballast in addition to permanent deformations thus helping in maintaining the track geometry.

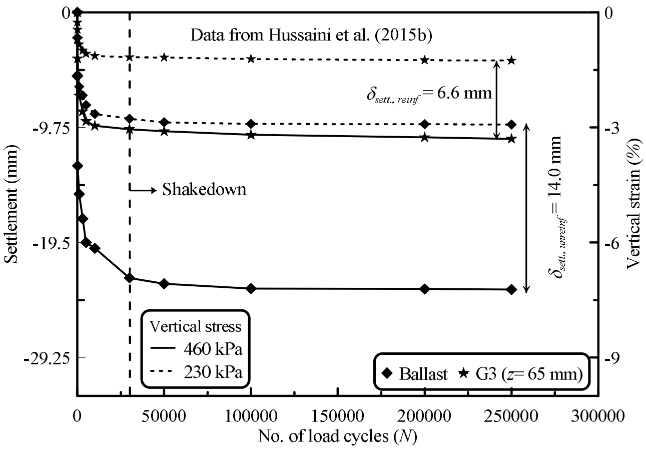

Figure 6 Role of geogrid in reducing the differential settlement in ballast (modified after Hussaini et al. 2015b)

3.4 Role of geosynthetics on stress at ballast-subballast interface/ Subgrade stresses

One of the important functions performed by ballast is to distribute the applied wheel load onto a wider area thereby reducing the stresses in the subgrade soils. The energy dissipation because of the particle rearrangement and their breakage also helps in reducing the stresses to acceptable levels. However, a further reduction in the vertical stress might be desired in case it is inevitable to lay tracks on weaker foundation soils. The role of geosynthetics in achieving this objective was explored by Indraratna et al. (2010a, 2011b) in an instrumented track section. Based on the data obtained from rapid-response hydraulic earth pressure cells they reported a significant reduction of stress at ballast-subballast interface in case of tracks reinforced with geosynthetics. The laboratory investigations by Indraratna et al. (2013) also revealed that for an applied vertical stress (sleeper-ballast contact stress) of 460 kPa, the vertical stress at the subballast-ballast interface reduced from 220 kPa (for ballast without geogrid) to 176 and 155 kPa upon the geogrid reinforcement of ballast (Figure 7). These results signify the role of geogrid in dissipating the applied vertical stresses thereby implying their possible usage in case of railway tracks to be constructed on soft soils.

4. FIELD INVESTIGATIONS ON GEOSYNTHETIC-REINFORCED RAIL TRACKS UNDER OPERATING CONDITIONS

In the past few decades, several researchers have conducted field trials to examine the performance of geosynthetic-reinforced ballasted rail tracks under operating conditions. Amsler (1986) reported a case study in Geneva describing the performance of a track that was completely rebuilt using a traditional design cross-section (without any geosynthetics) and another following a new design cross-section incorporating non-woven geotextiles at the subbase-subgrade interface. Amsler (1986) commented that the use of geotextiles not only significantly improved the track quality but also helped maintaining the track alignment for a relatively long period.

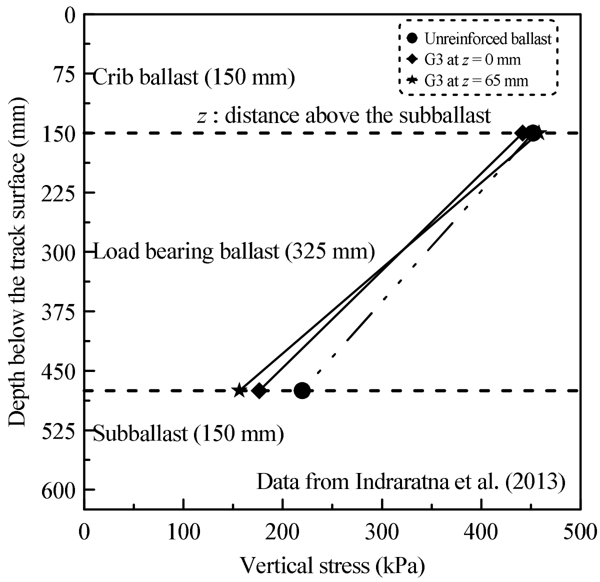

Figure 7 Variation of applied vertical stress with ballast depth (data sourced from Indraratna et al. 2013)

On the contrary, track rehabilitation without geosynthetics improved the performance for a relatively shorter period of time and deteriorated almost to the pre-renewal level within about 1-2 years. For a similar track rehabilitation project involving a mainline track in Alabama, Walls and Galbreath (1987) reported that the inclusion of geogrid improved the performance of a portion of rail track that was laid on soft subgrade and posed serious problems demanding maintenance operations in about every two to three weeks. They reported that the geogrid-reinforcement solved the track problems, helped increase the speed restriction to be raised from about 8 km/h to 56 km/h, and removed the need for frequent maintenance operations. The role of geosynthetics in track rehabilitation was again established by Alexander and Sanders (1994) that described the case history of a 700 m long section of rail track located at Cavan, near Adelaide in South Australia that posed problems due to underlying poor ground conditions topped up by high ground water table. The rehabilitation involved placing of geocomposite layer over the subgrade followed by a 450 mm thick subballast layer and a layer of geogrid on to it. The ballast layer as in the original track structure was then placed to form the railway ballast foundation. The reconstructed track was reported to perform well with no noticeable settlements.

The field study carried by Ashpiz et al. (2002) also confirmed the effectiveness of geosynthetics in augmenting the track performance. Montanelli and Recalcati (2003) presented a case study pertaining to rehabilitation of the Foligno-Terontola railway line, founded on an old embankment (second-half of the XIX century) subject to continuous and differential settlements. The solution required the reinforcement of the sub-ballast by means of a double geocomposite layer (instrumented) and the excavation/replacement of the first 0.70 m of sub-ballast with free-drainage granular fill soil. The tracks under consideration were reconstructed during the night to avoid train traffic interruption. The tracks rehabilitated by means of geocomposite reinforcement performed better than the original ones. A similar study conducted by Sharpe et al. (2006) described a full-scale field test undertaken at Coppull Moor on the West Coast Main Line, UK. The track under consideration was constructed over a fairly soft subgrade and had a long history of problems requiring frequent maintenance. In an attempt to ameliorate the track condition, a biaxial geogrid was incorporated within the ballast section during one of the regular track maintenance operations. They reported that as a consequence of geogrid insertion, the rate of track settlement reduced considerably from 1.40 mm/year to 0.4 mm/year thus lengthening the time periods between successive ballast cleaning operations. Moreover, Indraratna et al. (2010a) have carried out the field trials in Bulli, Sydney, Australia to study the effectiveness of reinforcing the track with geosynthetics. The field investigations confirmed that the geosynthetic reinforcement of rail track reduces the vertical settlement and the lateral displacement of fresh and recycled ballast. Hornicek et al. (2010) have commented that the geogrid inserted directly under the ballast bed helped reducing the extent of settlement. They have also reported the performance of a railway track trial section with a geocomposite reinforced ballast bed to be exhibiting smaller imperfections in the rail geometric parameters in comparison to unreinforced conditions.

Geol (2011) has described the case study of a mainline rail track in Nagykanizsa, Hungary, that required monthly re-surfacing. To improve the track condition, the decision was made to include a geogrid within the ballast layer during a rehabilitation operation. The geogrid eliminated the need for frequent maintenance thereby removing the service disruptions and also helped reducing the dynamic deflection upon train loading. On a similar project constructed near Cologne, Germany, the inclusion of a geogrid within a roadbed constructed over a soft formation allowed the thickness of sub-ballast to be reduced from 1050 mm to 700 mm. Recently, Nimbalkar and Indraratna (2016) carried out an extensive field trial in the town of Singleton, New South Wales (NSW), Australia. The study involved use of four different types of geosynthetics and a shock-mat installed below the ballast layer (at subballast-ballast interface) in selected sections of track constructed on three different subgrades (soft alluvial clay, hard rock, and concrete bridge). The performance of the instrumented track was monitored for a period of five years under track operating conditions. The authors reported that the geogrids and geocomposites decreased the settlement of the ballast by about 35%. Moreover, the geogrids were reported to reduce the transient track deformation by 40-65% at the soft alluvial deposit, and by 15% at the hard rock. The study further concluded that the placement of shock-mat on a concrete bridge contributed to reduced ballast breakage. All these field investigations invariably confirm the observations from laboratory studies and highlight the beneficial role of geosynthetics in improving the track performance under operating conditions.

5. CONCLUSION

This paper presented a review of the shear behaviour of geosynthetic-reinforced ballast under direct shear and cyclic triaxial conditions including the field investigations and track rehabilitation schemes using geosynthetics. A review of the literature reveals that the geogrid/geocomposite reinforcement of ballast offers several major benefits to the rail industry. It arrests the lateral spreading of particles that subsequently reduces the extent of permanent settlement of ballast. The geogrid is also found to be helpful in reducing the extent of differential settlement of ballast. Moreover, it minimises the extent of particle breakage, reduces the vertical stress at the subballast-ballast interface implying a reduction in the subgrade stresses. The reduced volumetric compressions in case of reinforced ballast imply that the geogrid helps maintaining sufficient voids in ballast that are imperative for the quick drainage of water. Moreover, the overall performance improvement due to geogrid was observed to be a function of the interface efficiency factor (α). The aforementioned benefits (the quantum of which differed from one study to another owing to the different particle size gradations, geosynthetic type and their placement positions, loading and boundary conditions) of geosynthetics as observed from laboratory studies are also confirmed from field studies conducted under track operating conditions.

A number of field studies conducted by several researchers establish beyond doubt the role of geosynthetics in improving the track performance by maintaining the track alignment, reducing the need for frequent maintenance operations, and enhancing the allowable train speed on tracks.

The placement position of geosynthetics in case of field studies and track rehabilitation schemes was generally at the subballast-subgrade interface or subballast-ballast interface. On the other hand, the laboratory experimental studies considered placing not only a single layer of geosynthetics beneath the ballast layer but also one or more layers of geosynthetics at variable depths below the sleeper soffit. The geosynthetics in either case were found to enhance the track performance. However, the benefits of geosynthetics in stabilising ballast were found to be significantly higher when placed within the ballast. Moreover, the geosynthetics were found to be more beneficial in case of tracks resting on soft subgrades. The only exceptions to the observations that geosynthetics effectively stabilise the rail tracks are the studies involving the use of geocell and a geogrid with smaller aperture size (A/D_{50} of 0.6) placed within ballast. In case of geocell the improper compaction of ballast within its individual cells/pockets owing to its geometry, and for geogrid with smaller aperture size the lack of interlocking of particles within its apertures led to increased settlements in ballast. From practical considerations, the optimum placement location of geosynthetics as reported by several researchers is 200-250 mm below the sleeper soffit for a conventional ballast depth of 300-350 mm.

6. REFERENCES

Abdi, M. R., and Arjomand, M. A. (2011) “Pullout tests conducted on clay reinforced with geogrid encapsulated in thin layers of sand”. Geotextiles and Geomembranes, 29 (6), pp 588-595 (doi: 10.1016/j.geotexmem.2011.04.004).

Alexander, W.W. and Sanders, L. J. (1994) “Geogrid encapsulation of railway formation, Proceedings of the Fifth International Conference on Geotextiles”. Geomembranes, and Related Products, Singapore: 167-169.

Alias, J. (1984) “La voie ferrée-Tome 1: Techniques de Construction et d’Entretien”. Ecole Nationale des Ponts et Chaussées, Eyrolles, Paris, France, pp 269 (in French).

Amsler, P. (1986) “Railway track maintenance using geotextile”. Proceedings of 3rd International Conference on Geotextiles, Vienna, pp. 1037-1041.

Ashpiz, E. S., Diederich, R., and Koslowski, C. (2002) “The use of spun bonded geotextile in railway track renewal on the St. Petersburg- Moscow line”. Proc., 7th Int. Conf. on Geosynthetics, Nice, France, pp 14-19.

Baessler, M., and Rucker, W. (2003) “Track settlement due to cyclic loading with low minimum pressure and vibrations”. In: System dynamics and long-term behaviour of railway vehicles, Track and subgrade, Popp K, and SchiehlenW. (Editors), Springer, Berlin; pp 337-356.

Bakeer, M. R., Sayed, M. S., Cates, P., and Subramanian, R. (1998) “Pullout and shear tests on geogrid reinforced lightweight aggregate”. Geotextiles and Geomembranes, 16 (2), pp 119-133.

Bathurst, R.J, Raymond, G.P. (1987) “Geogrid reinforcement of ballasted track”. In: Transportation Research Record, National Research Council, Transportation Research Board; 1153: pp 8-14.

Brown, S.F., Kwan, J., and Thom, N.H., (2007) “Identifying the key parameters that influence geogrid reinforcement of railway ballast”. Geotextiles and Geomembranes, 25(6), pp 326-335.

Dash, S.K, and Shivadas, A.S. (2012) “Performance Improvement of Railway Ballast Using Geocells”. Indian Geotechnical Journal; 42(3): pp 186-193 (DOI 10.1007/s40098-012-0017-3).

Geol, J. P.C. (2011) “The use of geogrids on mainline and intermodal facility projects”. AREMA, September, 2011.

Fernandes, G., Palmeira E.M., and Gomes, R.C. (2008) "Performance of geosynthetic-reinforced alternative sub-ballast material in a railway track". Geosynthetics International, 15 (5), pp 311-321.

Hay, W.W. (1982) "Railroad Engineering". John Wiley & Sons, New York, NY

Horníček, L., Tyc, P., Lidmila, M., Krejčiříková, H. and Jasanský, P. (2010). "An investigation of the effect of under-ballast reinforcing geogrids in laboratory and operating conditions". Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 224(4), pp 269- 277.

Hussaini, Syed K.K. (2013) "An Experimental study on the deformation behaviour of geosynthetically reinforced ballast". PhD Thesis, University of Wollongong, Australia.

Hussaini, Syed K. K., Indraratna, B., and J.S. Vinod. (2014) "An Experimental Investigation on the Deformation and Degradation Behaviour of Geogrid-Reinforced Ballast". In J. Pombo, (Editor): "Proceedings of the Second International Conference on Railway Technology: Research, Development and Maintenance", Civil-Comp Press, Stirlingshire, UK, Paper 125, 2014. doi:10.4203/ccp.104.125

Hussaini, S.K. Karimullah., Indraratna, B, and Vinod, J. S. (2015a) "Application of Optical-Fiber Bragg Grating Sensors in Monitoring the Rail Track Deformations". Geotechnical Testing Journal, ASTM, 38(4), pp 387-396, doi: 10.1520/GTJ20140123. ISSN 0149-6115.

Hussaini SK Karimullah, Indraratna B, and Vinod, J.S. (2015b) "Performance assessment of geogrid-reinforced railroad ballast during cyclic loading". Transportation Geotechnics, 2, pp 99-107. (Doi: http://dx.doi.org/10.1016/j.trgeo.2014.11.002).

Hussaini SK Karimullah., Indraratna, B., and Vinod, J.S. (2016) "A laboratory investigation to assess the functioning of railway ballast with and without geogrids". Transportation Geotechnics, 6, pp 45-54. (doi:10.1016/j.trgeo.2016.02.001).

Indraratna, B., Ionescu, D., and Christie, H. D. (2000) "State-of-the-art Large Scale Testing of Ballast". In: Conference on Railway Engineering CORE2000: Railway Technology for the 21st Century. Adelaide, 21-23 May 2000, pp. 208-220.

Indraratna, B., Lackenby, J., and Christie, D. (2005) "Effect of confining pressure on the degradation of ballast under cyclic loading". Geotechnique; 55(4): pp 325-328.

Indraratna, B., Shahin, M., and Rujikiatkamjorn, C. (2006a) "Stabilisation of ballasted rail tracks and underlying soft formation soils with geosynthetic grids and drains". ASCE Special Geotechnical Publication No. 152, Proceedings of Geo-Shanghai; 152: pp 143-152.

Indraratna, B., Khabbaz, H., Salim, W., and Christie, D. (2006b) "Geotechnical properties of ballast and the role of geosynthetics in rail track stabilisation". Ground Improvement, 10 (3), pp 91-101.

Indraratna, B., Nimbalkar, S., Christie, D., Rujikiatkamjorn, C., and Vinod. J.S. (2010a) "Field Assessment of the Performance of a Ballasted Rail Track with and without Geosynthetics". Journal of Geotechnical and Geoenvironmental Engineering, 136(7), pp 907-917.

Indraratna, B., Thakur, P. K., and Vinod, J. S. (2010b) "Experimental and Numerical Study of Railway Ballast Behavior under Cyclic Loading". International Journal of Geomechanics, 10 (4), pp 136-144.

Indraratna, B., Ngo, N.T., Rujikiatkamjorn, C. (2011a) "Behavior of geogrid-reinforced ballast under various levels of fouling". Geotextiles and Geomembranes, 29 (3), pp 313-322.

Indraratna, B., Salim, W., and Rujikiatkamjorn, C. (2011b). Advanced rail geotechnology- ballasted track, CRC Press, London.

Indraratna, B., Syed K.K. Hussaini., and Vinod, J.S. (2012) "On the shear behavior of ballast-geosynthetic interfaces". Geotechnical Testing Journal, ASTM, 35(2), pp 305-312 (DOI: 10.1520/GTJ103317).

Indraratna, B., Syed K.K. Hussaini, and Vinod, J.S. (2013) "The lateral displacement response of geogrid-reinforced ballast under Cyclic Loading". Geotextiles and Geomembranes, 39: pp 20-29.

Indraratna, B., and Nimbalkar, S. (2013) "Stress-Strain Degradation Response of Railway Ballast Stabilized with Geosynthetics". Journal of Geotechnical Geoenvironmental. Engineering 139(5), pp 684-700

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

Kennedy, J. (2011). "A full-scale laboratory investigation into railway track substructure performance and ballast reinforcement". PhD thesis, Heriot-Watt University, UK.

Lackenby, J., Indraratna, B., McDowell, G., and Christie, D. (2007) "Effect of confining pressure on ballast degradation and deformation under cyclic triaxial loading". Geotechnique; 57 (6), pp 527-536.

Lees, G., and Kennedy, C. K. (1975) "Quality, shape and degradation of aggregates". Journal of Engineering Geology, 8, pp193-209.

Liu, C-N., Ho, Y-H., and Huang, J-W. (2009) "Large scale direct shear tests of soil/PET-yarn geogrid interfaces". Geotextiles and Geomembranes, 27, pp 19-30.

Matharu, M.S. (1994) "Geogrid cut ballast settlement rate on soft substructures". Railway Gazette International, 150(3), pp 165-166.

Montanelli, F., and Recalcati, P. (2003) "Geogrid reinforced railways embankments: Design concepts and experimental test results". Proc., IABSE Symp., Antwerp, Netherlands, 212-213.

Nimbalkar, S., Indraratna, B., Dash, S.K., and Christie, D. (2012) "Improved Performance of Railway Ballast under Impact Loads Using Shock Mats". Journal of Geotechnical and Geoenvironmental Engineering, 138(3), pp 281-294.

Nimbalkar, S., and Indraratna, B. (2016) "Improved Performance of Ballasted Rail Track Using Geosynthetics and Rubber Shockmat". Journal of Geotechnical and Geoenvironmental Engineering, 142(8), pp 04016031.

Raymond, G.P, and Bathurst, R.J. (1987) "Performance of large-scale model single tie ballast systems". Transportation Research Record, 1131, pp 7-14.

Raymond, G. P. (1999) "Railway rehabilitation geotextiles". Geotextiles and Geomembranes, 17(4), pp. 213-230.

Raymond, G.P., and Ismail, I. (2003) "The effects of geogrid reinforcement on unbound aggregates". Geotextiles and Geomembranes, 21(6), pp 355-380.

Selig, E.T, and Waters, J.M. (1994) "Track geotechnology and substructure management". Thomas Telford Services Ltd., London, UK.

Sharpe, P., Brough, M., and Dixon, J. (2006) "Geogrid trials at Coppull Moor on the West Coast Main Line". Railway Foundations, 6, pp 367-375.

Shin, E.C., Kim, D.H., and Das, B.M. (2002) "Geogrid-reinforced railroad bed settlement due to cyclic load". Geotechnical and Geological Engineering, 20, pp 261-271.

Suiker, A. S. J. (2002) "The Mechanical Behaviour of Ballasted Railway Tracks". Delft University Press, the Netherlands, 2002.

Tang, X., Chehab, G.R., and Palomino, A. (2008) "Evaluation of geogrids in stabilizing weak pavement subgrade". International Journal of Pavement Engineering, 9 (6), pp 413-429.

Walls, J.C., and Galbreath, L.L. (1987) "Railroad ballast reinforcement using geogrids". Proceedings of Geosynthetics, 87(1), pp 38-45.