A Review on the Role of Geosynthetics in Preventing the Excessive Settlement and Mud Pumping of Ballasted Railway Track

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Abstract Railways are the primary mode of public transport around the world and play a pivoting role in the day-to-day transportation needs of commuters. Hence, an improved railway track infrastructure demands high-quality control. Excessive settlement in rail tracks is a common failure phenomenon incurring an extra maintenance cost. Installation of railway tracks on soft grounds is a daunting task for any railway engineer. Inefficient drainage results in storage of impregnated water beneath the railway tracks. Consequently, under repeated wagon loading results in a phenomenon known as mud pumping. The present paper mainly reviews the role of geosynthetics to mitigate the mud pumping, thereby controlling the excessive settlement and degradation of the track geometry.

Keywords Mud pumping · Geosynthetics · Ballast breakage index · Deterioration · Interlocking

1 Introduction

Developing countries like India have a huge demand for a high-speed train and freight corridors due to a rapid increase in population and urbanisation. Most of these developing countries have conventional ballasted railway track framework containing sleepers and rails resting on the layer system due to its low construction cost (Selig and Waters 1994). In addition, the maintenance of this track is economical and cheap (Chrismer 1985; Esveld 2001). In order to construct high-speed railway tracks and freight corridors, there is a need to improve the existing track geometry and subgrade properties to prevent excessive settlements and lateral spreading of ballast. Geosynthetics are widely used in the railway tracks from the past one decade to increase the serviceability of the track due to its ease of installation and low cost.

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1.1 Factors Influencing the Performance of Ballast

The settlement and degradation of the ballast are influenced by the following factors: the strength of parent rock, the frequency of loading, particle size distribution (PSD), degree of compaction, confining pressure, subgrade soil properties, etc. Degradation of ballast is more in case of poor ballast material and leads to the excessive settlement of the ballast layer as well as drainage problems (Salim 2004; Indraratna et al. 2004). The loose packing of ballast due to improper degree of compaction leads to excessive settlement. Also, it accelerates the particle degradation (Knuston 1976). The vertical settlement of ballast is significantly affected by the confining pressure. The deformation of ballast decreases with increase in confining pressure. At low confining pressure less than 30 kPa, ballast exhibits dilation behaviour. As the confining pressure increases from 30 to 240 kPa, ballast exhibits compressive behaviour. With the increase in confining pressure, the ballast breakage index (BBI) initially decreases rapidly up to a certain limit, then remains constant for a small interval and thereafter increases. Based on the variation of BBI with respect to confining pressure, the optimum degradation zone is observed to be in the range of confining pressure 30–75 kPa (Indraratna et al. 2004).

Deformation and degradation of ballast are significantly affected by the amplitude of loading. Ballast deformation rapidly increases with the increase in the amplitude of deviatoric stress (Knuston 1976; Stewart 1982; Lackenby et al. 2007). Deformation of ballast increases logarithmically with an increase in the number of the load cycles (Raymonds and Williams 1978). The rate of increase in plastic strain in ballast increases with the load cycles up to 10,000, and thereafter, the increment was observed at a slow rate (Indraratna et al. 2010a). The frequency of loading on track increases with respect to increment in train speed, which in turn induces dynamic stresses in the ballast layer (Shenton 1975). Ballast densification is observed without any significant change in ballast breakage index in the frequency range of 20–30 Hz. Higher confining stresses are required to minimise the settlement and degradation of ballast under the high frequency of cyclic loading (Indraratna et al. 2010a).

2 Problems Associated with Ballasted Railway Track

Lateral spreading, excessive settlement of ballast and mud pumping are three significant problems in railway track due to poor subgrade soil, increase in train speeds and axle load, etc. The poor subgrade soil interacts with ballast under cyclic loading, which creates problems and affects the track performance. The performance of track majorly depends on the performance of the ballast layer. The performance of the ballast layer comprises deformation and degradation characteristics of ballast (Alias 1984).

Fig. 1 Lateral spreading of ballast in ballasted railway track (sourced from Hussaini et al. 2013)

2.1 Lateral Spreading

Lateral flow of ballast is due to less lateral confining stress (<30 kPa) (Baessler et al. 2003; Indraratna et al. 2010a & b). Lateral flow of ballast reduces the stability of the track, increases breakage of particle and the particle splitting and leads to the excessive vertical settlement of ballast layer (Chrismer 1985; Dash and Shivdas 2012). Figure 1 illustrates the lateral spreading of ballast in the railway track.

2.2 Differential Settlement

The track settlement and degradation of ballast are not uniform along the track length due to improper compaction and non-uniform subgrade soil. Differential track settlement occurs, which seriously affects the safety of the track and train speed (Chrismer 1985). The track deterioration and differential settlements of rails are shown in Fig. 2.

2.3 Mud Pumping

Mud pumping is one of the serious problems in railway track. The track constructed on poor subgrade soil experiences excessive settlement, and subgrade soil interacts with ballast. The fines are filled in voids present in the ballast layer and cause further abrasion, which leads to reduce the permeability of the ballast layer. These fines hold the moisture and form slurry under repeated loads. Shear strength of ballast reduces significantly due to mud formation in ballast which in turn causes excessive settlement and lateral spreading of ballast (Chrismer 1985). The effect of mud pumping in railway track is shown in Fig. 3. The mud pumping was observed for tracks on a

Fig. 2 Differential settlement of track (sourced from Suiker 2002)

Fig. 3 Mud pumping (sourced from Lieberenz et al. 2009)

typical silty soil subgrade. Due to the application of the cyclic load, highly permeable silty soil allows the pore water and fines from inside the subgrade to rise quickly. Also, the low plasticity of the silty soil makes it easier for rising pore water to dislodge the fine particles. The slurry water then softens the subgrade surface, thus resulting in the easy penetration of granular particles of the sub-ballast into the subgrade, which contributes to excessive settlement.

3 Role of Geosynthetics

Geosynthetics made from polymeric materials have been used widely in railways for the past ten years to improve the ballast performance. It has been found that additional confinement offered by the geosynthetic material used as reinforcement in ballast leads to improvement of the track performance. Lateral confinement occurs due to particle interlocking, residual compaction stresses and sleeper resistance. Indraratna et al. (2009) reported that using the geosynthetic material for ballast stabilisation is more suitable, easy and economical solution in comparison with the remaining ground improvement methods. The additional interlocking of ballast particle is due to the interaction between the ballast and geosynthetic, which in turn reduces the particle movement and increases the performance of ballast and track stability.

3.1 The Function of Geosynthetics in Railways

1. Geotextile prevents the rising of subgrade soil which in turn reduces the fouling of ballast.
2. Geogrid acts as a reinforcement to provide better interlocking and increases the confinement.
3. Geo-composite acts as both separator and reinforcement.
4. Geocell acts as reinforcement and provides three-dimensional confinement to the infill soil.

3.2 Reinforcement, Filtration and Separation Functions of Geosynthetics in a Ballasted Railway Track

3.2.1 Reinforcement

Generally, woven geotextile, geogrid and geocell serve as reinforcement in ballasted railway track. These materials are placed at the interface of ballast–sub-ballast and sub-ballast–subgrade layers to increase the bearing capacity. Geogrids are planar materials having a different aperture opening size and shape, which provides additional confinement to the ballast through interlocking effect. Geocells are three-dimensional honeycombed structure offering confinement three-dimensionally and improve the track performance and stability of the track. The main advantage of providing reinforcement such as geotextile, geogrid and geocells is that they reduce the magnitude of stresses from sleeper to subgrade by distributing the loads over a wider area. The mechanism of particle interlocking in geogrid aperture openings and three-dimensional confinement offered by geocells are shown in Figs. 4 and 5, respectively.

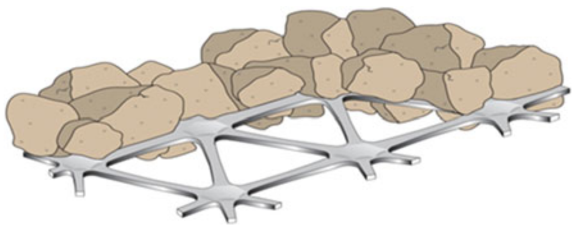

Fig. 4 Mechanism of particle interlocking within the geogrid aperture opening (sourced from Wrigley 1989)

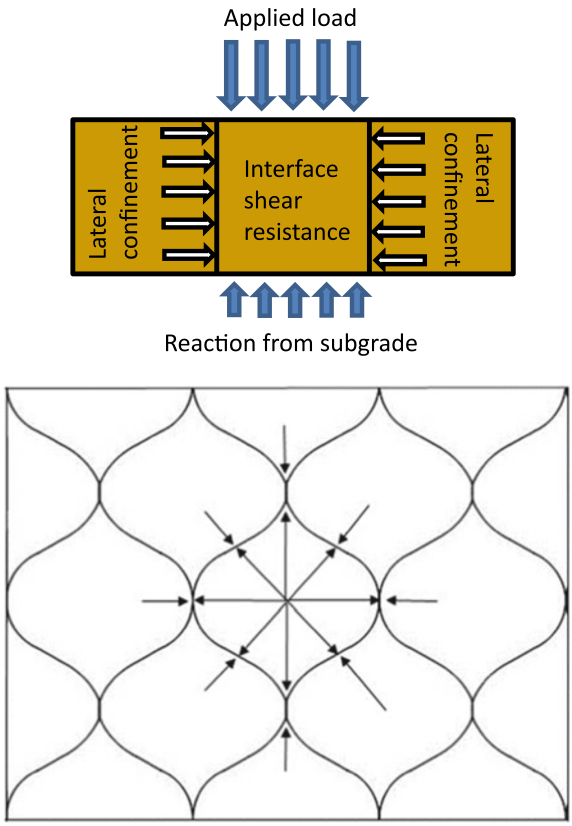

Fig. 5 Three-dimensional confinement and frictional resistance offered by geocell

3.2.2 Separation and Filtration

A non-woven geotextile used at the interface of subgrade–sub-ballast and sub-ballast–ballast layers prevents the rising fines from subgrade into sub-ballast and ballast layers. The aperture opening size (AOS) of geotextile must be less than that of the smallest particle size in subgrade and sub-ballast, which in turn satisfy the filtration and separation criteria. The geotextile should have enough permeability to dissipate the excess pore water pressure under repeated loading. The filtration and separation mechanism of the geotextile layer is illustrated in Fig. 6.

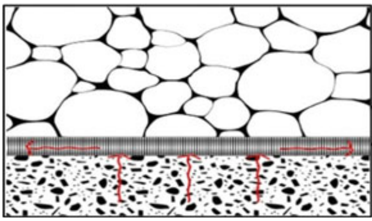

Fig. 6 Mechanism of filtration and separation

4 The Behaviour of Reinforced Ballast

4.1 Laboratory Studies

Several researchers have investigated the behaviour of geosynthetic-reinforced ballast under cyclic loading by using large-scale testing facilities in laboratory and field trials for the past two decades. Many factors, viz. aperture opening, type of geogrid (biaxial or uniaxial), depth of placement of for grid from the soffit of the sleeper, subgrade stiffness, etc., influence the track performance. The interaction between the geogrid and ballast particles plays a vital role in the interlocking mechanism. Tang et al. carried out a series of direct shear and pull-out test to investigate the interfacial shearing behaviour of the aggregates–geogrid surface. From the results of the direct shear test, the authors concluded that geogrid aperture size does not follow any trend with interface shear strength. However, from the results of the pull-out test, it has been reported that geogrid aperture size plays an essential role in its interaction with the aggregate. According to Indraratna et al. (2013), the optimum aperture opening (*A*) should be 1.2 times that of mean particle size (D_{50}) of ballast. The minimum and maximum aperture sizes of geogrid to obtain the beneficial effects of geogrid reinforcement should be $0.9D_{50}$ and $2.5D_{50}$.

The geogrid placed in ballast significantly reduces the settlement. However, the effect of reinforcement in reducing permanent deformation of ballast is more effective in the case of track constructed on poor subgrade soils having less CBR value less than 2. Inclusion of biaxial geogrid within ballast layer reduces the permanent deformation up to 50% after 100,000 load cycles. The number of load cycles required to cause permanent vertical deformation of 50 mm increased by a factor of 10 when geogrid was used as reinforcement compared to the unreinforced section (Bathurst and Raymond 1987; Matharu 1994). Shin et al. reported that the most beneficial effect of reinforcement to reducing track deformation is observed when geo-composite is used at the interface of subgrade soil and sub-ballast layer. The geogrid reduces the settlement of ballast, and the optimum depth for the inclusion of geogrid in the ballast is 125 mm from the sleeper soffit (Raymond et al. 1975).

Indraratna et al. (2006) had carried out a series of tests in the large-scale prismoidal triaxial chamber to investigate the deformation and degradation behaviour of railway ballast under cyclic loading by varying geosynthetic material. Three types of geosynthetic products (woven geotextile, geogrid and geo-composite) were used in their experimental study. The authors reported that the presence of geo-composite at the interface of sub-ballast and subgrade improved the deformation characteristics of the track. The influence of type of geosynthetic material on the performance of geosynthetic-reinforced ballast under cyclic loading is illustrated in Fig. 7. The track reinforcement increases the stiffness of track which in turn reduces the settlement significantly.

The track reinforcement increased with the stiffness of track by about 55–65% which in turn reduced the settlement to 99% compared to unreinforced track. Geo-composite increased stiffness by 9–12% and reduced settlement by 25% (Kennedy 2011). According to Brown et al. (2007), the stiffness and aperture size of geogrid are two key parameters that significantly affect the ballast settlements. Figures 8 and 9 illustrate the influence of geogrid stiffness and aperture opening on the settlement of ballast.

Chawla and Shahu (2016) have investigated the performance of modal track constructed on the compacted soil subgrades under static and cyclic loading. They have simulated a model track conditions after the rainfall and reported that the settlement of reinforced track under cyclic loading is not reached to a maximum limit of 25 mm even after 40,000 load cycles, but the unreinforced track is terminated at 10,500 cycles and reached to maximum permissible settlement. The stable behaviour of reinforced track is due to the better distribution of stresses inside the track. Similarly, Biabani et al. (2016) reported that the shear strength of sub-ballast improved substantially with increment in relative density and also at higher relative density, both unreinforced and reinforced sections show similar performance.

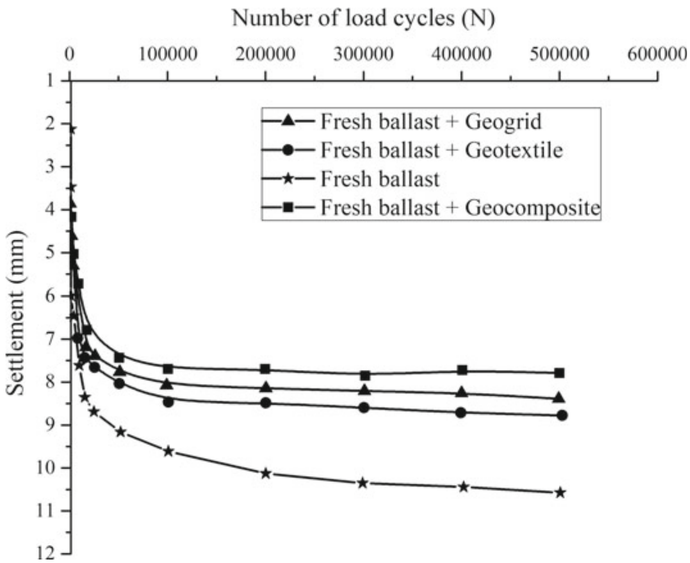

Fig. 7 Variation settlement with the number of load cycles (figure reproduced from Indraratna et al. 2006)

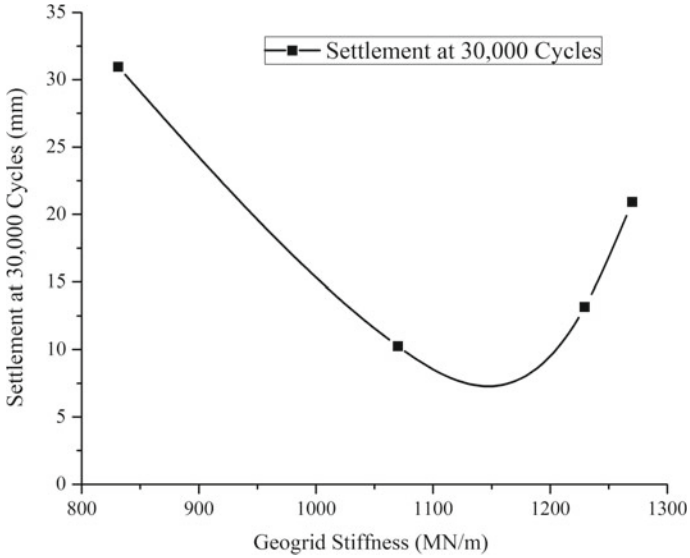

Fig. 8 Variation of settlement with varying geogrid stiffness (Figure reproduced from Brown et al. 2007)

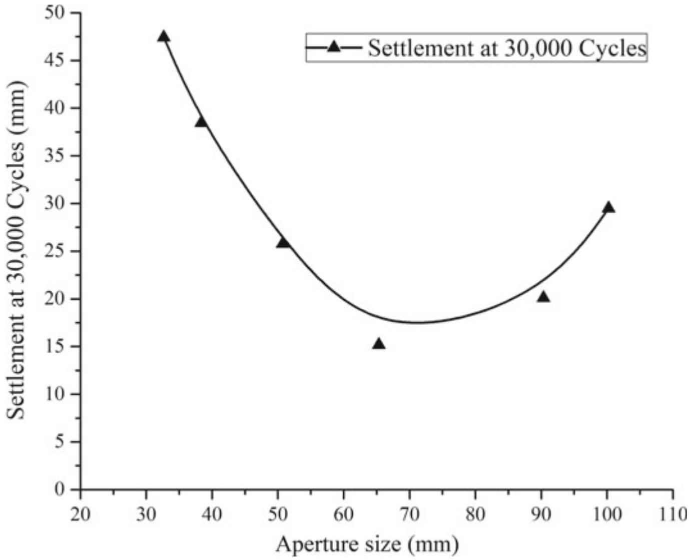

Fig. 9 Variation of settlement with varying aperture (Figure reproduced from Brown et al. 2007)

Ballast degradation occurred due to the number of passes which in turn led to considerable changes to ballast particle size, shape, as well as ballast packing. Due to degradation, fines were accumulated in the coarser particle, and spillage of coal from rail wagons also contributed to the ballast fouling (Qian et al. 2011). Indraratna et al. (2013) reported the stress–strain degradation response of railway ballast stabilised with geosynthetics. Geogrid provided at the interface of ballast and sub-ballast caused lesser damage compared to geotextile-reinforced track. The ballast bed reinforced with double layer of geosynthetics gives better interlocking and load dispersion over a large area and reduces the vertical, lateral and volumetric strains in ballast. Dual-layer reinforcements, i.e. geogrid at the ballast–sub-ballast interface and geo-composite at the sub-ballast–subgrade interface, are better at reducing settlement than single-layer reinforcements. According to Indraratna et al. (2013), the benefits of geogrid are more when it is placed at a depth of 130 mm above the sub-ballast layer causing less degradation of ballast under repeated loads.

4.2 Field Studies

Walls and Galbreath (1987) conducted a series of field trials and reported that the presence of geogrid at the interface of ballast and sub-ballast shows significant improvement on poor subgrade soils. It has been observed that the specific portion of track constructed on poor subgrade soil suffered from severe problems and it demands frequent maintenance operation about every 2–3 weeks. Due to this reason, the train speed is restricted to 8 km/h in affected portions. They have concluded that the inclusion of geogrid at the interface of ballast and sub-ballast increases the restricted train speed from 8 to 56 km/h.

Ashpiz et al. (2002) carried out field tests and concluded that the track performance is significantly improved in the case of geosynthetic-reinforced ballasted track compared to unreinforced track. Shape et al. (2006) carried out full-scale field studies in the UK. The track is constructed on soft subgrade soils, and it has a long history of problems and demanding frequent maintenance operations. From the outcomes of field trials, the authors reported that the rate of settlement of reinforced track is reduced to 0.4 mm/year as compared to unreinforced track 1.4 mm/year which in turn increases the time period between two successive maintenance operations.

5 Conclusion

The inclusion of geosynthetics during the construction of railway tracks shows a significant reduction of excessive settlement and mud formation in comparison with the unreinforced section. The performance of reinforced ballast depends on the type of reinforcement, aperture opening size of geogrid, depth from the soffit of the sleeper, the degree of ballast compaction and type of subgrade. In silty soil subgrades, mud pumping is avoided by providing the geotextile. Meantime, in the case of clay subgrades, mud pumping is not the primary issue; rather, a reinforcement is more relevant to provide better bearing capacity. Geo-composite gives combined benefits of both filtration and reinforcement. Meanwhile, geogrid at the ballast–sub-ballast interface and geo-composite at the sub-ballast–subgrade interface are better at reducing settlement than single-layer reinforcements. Providing geo-composite at ballast–sub-ballast interface satisfies both the reinforcement and filtration criteria.

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