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Abstract

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Keywords

element, discrete, ballast, railway, method, reinforced, modelling, geogrid

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Modelling geogrid-reinforced railway ballast using the discrete element method

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ABSTRACT

Rail ballast is an unbounded granular material that spreads laterally when subjected to train loading. Railroads can be reinforced by geogrids to reduce lateral movement and to optimize track performance. This paper presents a study of the behaviour of geogrid-reinforced ballast subjected to monotonic and cyclic loading using a large-scale direct shear box and a novel Track Process Simulation Apparatus (TPSA). The shear stress-strain response of fresh and fouled ballast reinforced by geogrid was investigated using large-scale direct shear tests subjected to normal stresses from 15 kPa to 75 kPa, where the levels of fouling varied from 20% to 95% Void Contamination Index (VCI). Cyclic tests for fresh and fouled ballast were conducted using the TPSA to realistically simulate real track conditions. The experimental results showed that a geogrid provides extra internal confinement and interlocks the aggregates in its apertures, hence reduces ballast deformation. The discrete element method (DEM) was used to model geogrid-reinforced fresh and fouled ballast subjected to monotonic and cyclic loading. Irregularly-shaped particles and geogrid were simulated by clumping spherical balls together, while the coal fines were simulated by adding 1.5mm diameter spheres into the pore spaces of ballast. The predicted stress-displacement responses obtained from the DEM were in good agreement with those measured in the laboratory, where the peak shear stress of fouled ballast decreased and the dilation of fouled ballast increased with an increasing level of fouling. The contact force distributions and

the orientations of normal and shear force were analyzed to provide more insight into the behaviour of ballast subjected to shearing.

1. Introduction

Railways provide an efficient and economic mode of transport in many countries and ballast is an essential component of rail tracks used as a load bearing platform and for maintaining track alignment (Selig and Waters 1994). It usually consists of medium to coarse aggregates whose main functions are to: (i) distribute the train load to the layer of sub-ballast at a reduced level of stress; (ii) provide lateral confinement to the track, and (iii) provide a free draining condition. Upon repeated train loads ballast deteriorates and spreads laterally causing track instability (Indraratna *et al.* 2011a; Ngo *et al.* 2014). Moreover, due to progressive degradation and the infiltration of fine particles and mud-pumping from the lower subgrade, ballast becomes fouled, which adversely affects the strength and deformation of ballasted tracks (Budiono *et al.* 2004; Lackenby *et al.* 2007; Tutumluer *et al.* 2008; Fortunato *et al.* 2010; Indraratna *et al.* 2013). Given the typical Australian coal freight tracks, Feldman and Nissen (2002) reported that dry coal fines are responsible for 70-95% of the fouling materials in rail tracks.

Geogrids have been widely used in the substructure of rail tracks to reinforce the ballast and to increase the duration of track serviceability (Raymond 2002; McDowell and Stickley 2006; Brown *et al.* 2007; Fernandes *et al.* 2008; Kwon and Penman 2009; Indraratna *et al.* 2011a). It has been reported that due to the mechanical interlock with aggregates, geogrids can decrease lateral spreading and the degradation of ballast (Bathurst and Raymond 1987; Brown *et al.* 2006; Indraratna *et al.* 2013; Biabani *et al.* 2016a). Despite these benefits, current literature on the interface behaviour of geogrid-ballast subjected to monotonic and cyclic loadings is still limited both in experimental study and numerical simulation, particularly when ballast becomes fouled (Tutumluer *et al.* 2011; Chen *et al.* 2012; Ngo *et al.* 2015). This paper presents the major results of tests conducted in the laboratory at the University of Wollongong, where static and cyclic testing of ballast (latite basalt) were conducted using large-scale apparatus. Large-scale direct shear tests were carried out for fresh and coal-fouled ballast with and without the inclusion of geogrid to study the interface behaviour of ballast and geogrid. To examine the cyclic response of geogrid-reinforced fouled ballast, a novel Track Process Simulation Apparatus (TPSA) was also used for coal-fouled ballast under various levels of fouling. A numerical simulation using the discrete

element method (DEM) was carried out to model the interface behaviour of geogrid reinforced fouled ballast subjected to monotonic and cyclic loading.

2. Experimental study

1.1. Large-scale direct shear test

The large-scale direct shear test apparatus used in this study consisted of a 300mm x 300mm plane area and a 200 mm high steel box that was divided horizontally into two equal halves. A schematic diagram of the large-scale direct shear test is shown in Figure 1. A series of tests were conducted for fouled ballast with and without geogrid, subjected to relatively low normal stresses ranging from 15 kPa to 75 kPa, to simulate typical track conditions (Lackenby *et al.* 2007). Coal fines were used as fouling material and the Void Contamination Index (VCI) proposed earlier by (Indraratna *et al.* 2010a) was used to quantify the levels of ballast fouling, as given by:

$$VCI = \frac{1+e_f}{e_b} \times \frac{G_{sb}}{G_{sf}} \times \frac{M_f}{M_b} \times 100 \quad (1)$$

where e_f = the void ratio of fouling material, e_b = the void ratio of fresh ballast, G_{sb} = the specific gravity of ballast, G_{sf} = the specific gravity of fouling material, M_f = the dry mass of fouling material, and M_b = the dry mass of fresh ballast.

A series of large-scale direct shear tests for fresh and coal-fouled ballast reinforced by the geogrid were carried out and the results discussed elsewhere by Indraratna *et al.* (2011b), while some of these data were used in this study to calibrate DEM models. The test was sheared at a horizontal displacement of $\Delta h=37\text{mm}$ (e.g. the maximum movement allowed by the direct shear test apparatus). Figure 2 shows the stress-displacement and dilation response of fouled ballast with and without geogrid reinforcement where the level of coal fines varied from $VCI=20\%$ to $VCI=95\%$. Here the peak shear stresses of fouled ballast increased with an increase in normal stress and then decreased with an increased level of fouling. Strain softening and volumetric dilation behaviour were obtained for all tests, where the higher normal stresses (σ_n), the greater peak stress, and smaller dilations were observed. Tutumluer *et al.* (2008) also presented similar shear stress-strain softening behaviour of railway ballast that they had measured experimentally.

1.2. Track Process Simulation Apparatus (TPSA)

Cyclic tests for coal-fouled ballast were conducted using the TPSA (800 mm long, 600 mm wide and 600 mm high), fabricated to simulate realistic track conditions (Figure 3). The schematic plane view and cross-section of the TPSA is shown in Figure 4. The ballast and sub-ballast used in this study was collected from Bombo quarry near Wollongong, Australia, then cleaned and sieved according to AS 2758.7 (Australia Standards 1996). Ballast aggregates are obtained by quarrying the parent rock, latite basalt of volcanic origin. In the state of NSW, this is one of the most commonly used ballast for both heavy haul and commuter tracks. The subgrade was well-graded gravelly sand compacted at 7% moisture content to a unit weight of 18.5 kN/m^3 . The particle size distributions of the materials used in this study are shown in Figure 5. The sub-ballast was placed into the apparatus in 50 mm thick layers and then compacted to a field unit weight of approximately 18.5 kN/m^3 . Ballast aggregates were then placed on the layer of sub-ballast and compacted to obtain a field unit weight of 15.3 kN/m^3 . Two lateral pressures ($\sigma_2 = 10 \text{ kPa}$ and $\sigma_3 = 7 \text{ kPa}$) that corresponded to the confining pressures provided by crib and shoulder ballast in the field were applied to the vertical walls (Figure 3); they are based on actual track measurements (Indraratna *et al.* 2013; Biabani *et al.* 2016b). An initial vertical pressure of 45 kPa was then applied to stabilise the sleeper and ballast. To simulate a 30 tonne axle freight train travelling at approximately 80 km/h, a cyclic load was applied through a servo hydraulic actuator with a maximum pressure of 420 kPa and frequency of 15 Hz. During the tests, vertical and lateral movements were recorded automatically using a system of steel pegs and electronic potentiometers. All tests were conducted at a frequency of 15 Hz up to 500,000 load cycles. The results and analysis of these tests were presented elsewhere by Indraratna *et al.* (2013). They highlighted that geogrid-reinforced ballast exhibits less deformation when compared to an unreinforced assembly at any given level of fouling. As expected, an increasing level of fouling results in increased ballast settlement, as shown in Figure 6. All the specimens exhibited an initial rapid settlement up to 100,000 cycles, followed by a gradually increasing settlement within 300,000 cycles, and then remained relatively stable to the end (500,000 cycles). This clearly shows that ballast aggregates were subjected to a significant rearrangement and densification during initial load cycles, but when the ballast attained a threshold compression, any subsequent loading would resist further settlement and promote dilation, unless particle breakage occurs.

3. Discrete Element Modelling

The discrete element method (DEM) introduced by Cundall and Strack (1979) has been widely used to study shear behaviour of fresh and fouled ballast (Lim and McDowell 2005; Lobo-Guerrero and Vallejo 2006; Lu and McDowell 2008; Huang and Tutumluer 2011; Tutumluer *et al.* 2011; Chen *et al.* 2012; Indraratna *et al.* 2014; Ngo *et al.* 2014). The force-displacement law derives the contact force acting on two entities in contact with the relative displacement between them. If particle B with radius $R^{[B]}$ is in contact with particle A with radius of $R^{[A]}$, or in contact with a wall (Figure 7), the particle penetration depth (U^n) is defined as:

$$U^n = \begin{cases} R^{[A]} + R^{[B]} - d, & (\text{particle} - \text{particle}) \\ R^{[B]} - d, & (\text{particle} - \text{wall}) \end{cases} \quad (2)$$

where, d is the distance between the particle to particle centres, given as:

$$d = |x_i^{[B]} - x_i^{[A]}| = \sqrt{(x_i^{[B]} - x_i^{[A]})(x_i^{[B]} - x_i^{[A]})} \quad (3)$$

The location of the contact point is given by:

$$x_i^{[C]} = \begin{cases} x_i^{[A]} + \left(R^{[A]} - \frac{1}{2}U^n\right)n_i, & (\text{particle} - \text{particle}) \\ x_i^{[B]} + \left(R^{[B]} - \frac{1}{2}U^n\right)n_i, & (\text{particle} - \text{wall}) \end{cases} \quad (4)$$

where, n_i is the unit vector, and is determined by:

$$n_i = \frac{x_i^{[B]} - x_i^{[A]}}{d} \quad (5)$$

The force vector $\vec{F}$ that represents the interaction between the two particles is resolved into normal ($\vec{F}_N$) and shear component ($\vec{F}_T$) with respect to the contact plane:

$$\vec{F}_N = K_N \cdot U^n \quad (6)$$

$$\delta \vec{F}_T = -K_T \cdot \delta U^s \quad (7)$$

where, K_N and K_T are the normal and shear stiffnesses at the contact; δU^s is the incremental shear displacement, and $\delta \vec{F}_T$ is the incremental shear force.

The normal contact stiffness for the linear contact model used in this study was computed as:

$$K_N = \frac{k_n^{[A]} k_n^{[B]}}{k_n^{[A]} + k_n^{[B]}} \quad (8)$$

and the contact shear stiffness is given by:

$$K_T = \frac{k_s^{[A]} k_s^{[B]}}{k_s^{[A]} + k_s^{[B]}} \quad (9)$$

where, $k_n^{[A]}$, $k_n^{[B]}$, $k_s^{[A]}$, $k_s^{[B]}$ are the normal stiffness and shear stiffness of particle A and B, respectively.

The new shear contact force is determined by summing the old shear force existing at the start of the time-step with the shear elastic force increment

$$\vec{F}_T \leftarrow \vec{F}_T + \delta \vec{F}_T \leq \mu \vec{F}_N \quad (10)$$

where, μ is the coefficient of friction.

3.1. Modeling the ballast, coal fouling, and geogrid in DEM

The irregular shaped grains were modelled by connecting and overlapping together many spheres of different sizes and positions (ITASCA 2012). The commercial software package, Particle Flow Code in Three Dimensions (PFC3D) version 4.0 produced by ITASCA (2012) has been employed in this study. A library of nine varying shaped ballast was then developed to simulate ballast aggregates, as shown in Figure 8a. This method has been widely used by Lim and McDowell (2005); Lu and McDowell (2008); Ferrellec and McDowell (2010); Thakur et al. (2010). A large scale shear box (300mm long $\times$ 300mm wide $\times$ 200mm high) was simulated in DEM with rigid walls to simulate fresh and fouled ballast (VCI=40%), as shown in Figures 8c-d. These simulated irregular particles were then placed in the shear box at random orientations and compacted to a void ratio of 0.82 (i.e. porosity of 45%) to resemble experiment conditions.

Fouling is caused by fine particles that accumulate within ballast voids. In this study, fouled ballast was simulated in DEM by adding a certain amount of fine particles into the voids to represent different values of VCI. Fouled ballast with 40%VCI was modelled by injecting 145,665 1.5mm diameter spheres into the voids of fresh ballast (Figure 8d). Geogrids with 40mm $\times$ 40mm

apertures, similar to those tested in the laboratory, were modelled by bonding small spherical balls together (i.e., balls with a 2mm radius at the ribs and a 4mm radius at the junctions), as shown in Figure 8b. These balls were connected by parallel bonds that represent the geogrid's tensile strength. Based on the test results obtained from large-scale direct shear testing reported by Indraratna et al. (2011b), a set of micromechanical parameters adopted for DEM simulation of ballast, geogrid, and coal fines are given in Table 1. A linear contact model, following previous studies, was used for the numerical simulations (e.g. Thakur et al. 2010; Indraratna et al. 2010b; McDowel et al. 2006).

4. Results and discussion

4.1. Shear stress-strain and volumetric change analysis

A series of large scale direct shear tests were conducted in the laboratory and DEM simulation to examine the shear stress-displacement of fresh and fouled ballast reinforced by geogrid. While the major experimental results were presented and discussed elsewhere by Indraratna et al. (2011b), some of their results are presented herein to compare with the DEM model. The shear box consists of an upper box that was restrained from any lateral movement, while the lower box was forced to shear horizontally at a rate of at 2.5 mm/min. Figures 9a, 9b present comparisons of the shear stress-displacement and volumetric dilation of the geogrid-reinforced fresh and fouled ballast measured in the laboratory, and those obtained from the DEM simulations, while Figures 9c, 9d show shear stress-displacement and volumetric dilation of unreinforced-fresh and fouled ballast (VCI=40%), respectively. The predicted results at any given normal stress agree well with the experimental data, indicating that the proposed DEM model could capture the shear behaviour of fresh and fouled ballast. As expected, fresh ballast exhibited higher shear stress and lower volumetric dilation than the 40%VCI-fouled ballast. The strain softening behaviour of ballast follows a similar trend with other rockfill aggregates of comparable sizes (e.g. Marsal, 1973; Charles and Watts, 1980), and as expected, volumetric dilation was also observed in all simulations, whereby the greater the normal stress the higher the peak stress and the smaller the dilation. The DEM analysis showed a slightly higher dilation than the experimental data for $\sigma_n = 27 \text{ kPa}$ compared to the higher normal stress levels in a shear displacement range of 10-25 mm (i.e. 4-8% shear strain). This difference is basically associated with some particle breakage that was not captured in the DEM simulation. Lackenby et al. (2007) reported that particle

degradation could increase ballast compression. The Ballast Breakage Index (BBI) after the tests of fresh and fouled ballast (VCI=40%) were measured at 0.123 and 0.083, respectively. The laboratory results also showed a sudden drop in shear stress at 4-8% shear strain, before picking up the load again, which further supports the initiation of particle degradation at this level of shear strain.

Strains that developed in the geogrids could not be measured in the laboratory due to the complexity of installing strain gauges to the geogrid, and the difficulty of preventing them from being damaged by compaction and the sharp edges of ballast aggregates. By taking advantage of the numerical analysis, the strains developed across the geogrid in a horizontal shearing direction were captured in the simulations. Figure 10a-b shows the contours of strain that developed across the geogrid at the end of the shear test ($\Delta h = 37$ mm) for fresh ballast and fouled ballast (VCI=40%); they indicate that the strains developed non-uniformly across the geogrid, and the magnitude of strain depends on the interlock between the geogrid and ballast particles. The geogrids placed in the 40%VCI fouled ballast assembly experienced a slightly lower maximum strain than those in fresh ballast (i.e. 1.00% strain for fouled ballast compared to 1.405% strain in fresh ballast). This would be associated with the decreased interlocking effect by the geogrid and ballast particles due to coal fines clogging the interface of geogrid-ballast.

4.2. Load-deformation response of ballast subjected to cyclic load

A total of 10 cyclic tests using the TPSA for coal-fouled ballast with and without geogrid, and VCI were carried out. The particle size distributions of materials used for the tests were shown earlier in Figure 5. The lateral displacement and vertical settlement of the ballast were measured during the test using potentiometers and settlement plates, as shown in Figure 3-4. The lateral displacement and settlement of coal-fouled ballast with and without geogrid are presented in Figure 11. It was observed that geogrid-reinforced ballast deformed less than the unreinforced ballast assembly for any given VCI. All the samples experienced an initial rapid settlement up to 100,000 cycles, followed by gradually increasing settlement within 300,000 cycles, and then remained relatively stable thereafter; probably because the geogrid created a strong mechanical interlock with the surrounding ballast grains and prevented them from free movement. This interlocking effect enabled the geogrid to act like a non-displacement boundary which decreased ballast deformation. This agreed with previous studies conducted by (McDowell *et al.* 2006) where the discrete element method (DEM) was used to examine the interaction between geogrid

and ballast. They reported that the geogrid formed a stiffened zone inside the ballast assembly that acted like reinforcement. An increased level of fouling resulted in much higher settlement, indeed as the fouling increases the coal fines acted like a lubricant and helped the particles to slide and/or roll over each other, which in turn, increased deformation. However, the ability of geogrid to decrease ballast deformation also decreased as the VCI increased because as coal fines accumulated in the apertures of the geogrids it reduced their effective size (Indraratna et al. 2011b).

DEM simulation was also used to examine the cyclic behaviour of fresh and fouled ballast by simulating the TPSA in a plane strain condition. The ballast aggregates simulated in two dimensions that were developed by Indraratna et al. (2010b) were used in the analysis where clusters of bonded circular particles were used to model irregular-shaped ballast aggregates and the degradation of bonds within a cluster was possibly considered to represent ballast breakage. It is noted that the shape of particles directly influences how coarse angular aggregates interact, which reflects its specific stress-strain and degradation characteristics. It is noteworthy that if a 3D DEM model is conducted for cyclic loading then the number of cycles and the rate of convergence are further affected compared to a 2D cyclic analysis. The difference between 3D analysis and 2D analyses in terms of particle shape effect can affect both the shear strength and the corresponding volumetric change of ballast assemblies, because angular particles in 3D represent increased inter-particulate interaction or interlock compared to the 2D projection of particle angularity. Therefore, given the same set of micromechanical properties of ballast assembly, the three-dimensional analysis would exhibit a higher shear strength and greater volumetric dilation (i.e. higher friction angle gives a higher dilation angle) compared to those obtained from two-dimensional analysis. Due to a limitation of the commercial software package, PFC3D- Particle Flow Code that the Authors used to perform a 3D analysis, where “clump logic” was used to represent the actual particle angularity. These clumps behave like rigid bodies (i.e. internal contacts are ignored, hence no particle breakage), whereas in 2D analysis, the Authors have used “bonding contacts” which allow particle breakage to be considered. So this 2D analysis is approximate simplified approach where particle degradation under cyclic loads can still be captured (albeit not perfectly) within a reasonable computational timeframe.

The DEM models used to simulate fresh and fouled ballast in the TPSA are illustrated in Figure 12. A small uniformly distributed load of 2.5 kPa was applied on the ballast surface to simulate the slight confining effect induced by ballast cribs. Subroutines were developed by the Authors to

apply a stress-controlled cyclic load to the models, similar to the boundary loading condition tested in the laboratory. Cyclic tests for fresh and fouled ballast at $VCI=10\%$, 20% , 40% and 70% were simulated to a number of load cycles, $N=4000$, where most of the ballast deformation and degradation took place, as observed in the laboratory. Lateral displacement and vertical settlement of the fresh and fouled ballast assembly corresponding with load cycles were captured during these simulations. Figure 13 presents the comparisons of predicted lateral displacements and settlements with those measured in the laboratory, and they indicated that the DEM simulation capably captured the deformation of fresh and fouled ballast subjected to cyclic loading at any given VCI. The DEM simulations confirmed that the degree of fouling affected ballast deformation with increase in VCI that resulted in an increase in lateral displacement that led to increased settlement. Moreover, the volumetric dilation predicted by DEM was somewhat higher than the dilation actually measured because the inevitable variation in particle angularity between the DEM model and actual ballast, as well as particle degradation, was not considered in the numerical analysis.

It is noted that for studying the behaviour of rail track a higher number of cycles should normally be considered (i.e. laboratory or finite element analysis) to fully capture the deformation and degradation of granular assemblies over a longer period of cyclic loading. However, the highest rate of particle densification and breakage of high angular corners of particles occur during the initial loading cycles, $N < 5000$ (Indraratna et al. 2011a). The DEM analysis was performed for 4000 cycles to insightfully capture this initial deformation of ballast aggregates in a micromechanical perspective, while recognizing the serious limitation of most discrete element software to converge at large number of cycles unlike continuum-based FEM software. The current DEM models (PFC3D) have obvious limitations due to excessive computational time required, where a large number of cycles (e.g. $N=100,000$) cannot be simulated, even with the high-end DELL super-computer used for this study

5. Micromechanical analysis

Load transfer in a granular assembly depends on the orientation of contacts where the applied load is transmitted to a granular assembly through an interconnected network of force chains at contact points (Oda and Iwashita 1999). When subjected to shearing, the contact forces of ballast assemblies evolve so that the number of load-carrying contacts and their orientations inevitably

change. In this study, the second-order density distribution tensor introduced by Rothenburg (1980) was used to examine the anisotropy of contact forces of the ballast assembly at different settlements. These tensors were incorporated into the DEM models and are given as follows:

$$F_{ij} = \int_0^{2\pi} E(\theta) n_i n_j d\theta = \frac{1}{N_c} \sum_{k=1}^{N_c} n_i^k n_j^k \quad (11)$$

$$N_{ij} = \frac{1}{2\pi} \int_0^{2\pi} \frac{\bar{f}_n(\theta)}{\bar{f}_0(\theta)} n_i n_j d\theta = \frac{1}{N_c} \sum_{k=1}^{N_c} \frac{f_n^k}{\bar{f}_0} n_i^k n_j^k \quad (12)$$

$$S_{ij} = \frac{1}{2\pi} \int_0^{2\pi} \frac{\bar{f}_s(\theta)}{\bar{f}_0(\theta)} t_i n_j d\theta = \frac{1}{N_c} \sum_{k=1}^{N_c} \frac{f_s^k}{\bar{f}_0} t_i^k n_j^k \quad (13)$$

where, F_{ij} , N_{ij} , and S_{ij} are fabric, average contact normal force and average contact shear force tensors, respectively; $E(\theta)$, $\bar{f}_n(\theta)$, and $\bar{f}_s(\theta)$ are the corresponding density distribution functions; f_n^k and f_s^k are contact normal force and shear force, respectively; $\mathbf{n} = (\cos\theta, \sin\theta)$ is unit normal vector, and $\mathbf{t} = (-\sin\theta, \cos\theta)$ is the vector perpendicular to $\mathbf{n}$; and N_c is the total number of contacts in the assembly. $\bar{f}_0$ is the average contact normal force determined by:

$$\bar{f}_0 = \frac{1}{2\pi} \int_0^{2\pi} \bar{f}_n(\theta) d\theta = \frac{1}{N_c} \sum_{k=1}^{N_c} f_n^k \quad (14)$$

The force-fabric is characterised by the distribution of inter-particle contact orientations that can be described by the following Fourier series approximations proposed by Rothenburg and Bathurst (1989), as given below:

$$E(\theta) = \frac{1}{2\pi} [1 + a \cos 2(\theta - \theta_a)] \quad (15)$$

$$\bar{f}_n(\theta) = \bar{f}_0 [1 + a_n \cos 2(\theta - \theta_n)] \quad (16)$$

$$\bar{f}_s(\theta) = \bar{f}_0 [-a_s \cos 2(\theta - \theta_s)] \quad (17)$$

where, a , a_n , and a_s are the coefficients of contact normal, contact normal force and contact shear force anisotropies, respectively; θ_a , θ_n , and θ_s are the corresponding major principal directions of anisotropies, respectively.

5.1. Contact force distributions

The DEM models of the direct shear test in the current analysis were also able to capture contact force distributions of particles during shearing. Figure 14 shows the distributions of contact force chains of fresh and fouled ballast (VCI=40%) with and without geogrid reinforcement subjected to a given normal stress of 51 kPa, at a shear displacement of $\Delta h = 18$ mm. The contact forces between particles were plotted as lines whose thickness is proportional to the magnitude of the force. The thickness of the contact force lines represents the magnitude of forces while the length of each line connects the centerlines of two particles in contact. It is noteworthy that only the number of contacts and the corresponding maximum forces could be captured in the PFC3D analysis, thus the legends for the length of maximum contact force could not be applied. The fouled ballast (Figure 14b and Figure 14d) exhibited greater contact chains and reduced maximum contact force compared to those in the fresh ballast specimen (Figure 14a and Figure 14c) because fine particles accumulated in the voids between the large particles and then partially supported and transmitted forces across the specimen. Compared to the unreinforced ballast, the reinforced ballast experienced a considerable increase in the amount and magnitude of contact forces. This mobilisation of high contact forces within the geogrid-reinforced ballast assembly stemmed from the interlocking that took place between them. Maximum contact forces induced in ballast assemblies would govern the breakage where an increased intensity of inter-particle contact stresses would cause particle splitting or the breakage of angular corners.

5.2. Polar histogram of contact forces

The micromechanical analysis presented herein focussed on the evolution of contact force distributions of particles in the shear box at varying shear displacements. Eqs. (11)-(14) were used to capture the contact information of every particle in the DEM model while Eqs. (15)-(17) were used for the Fourier series approximation. Figure 15 shows the polar histogram of inter-particle contact force distributions for the VCI fouled ballast (VCI=40%) at different shear displacements, Δh , captured from the DEM simulation and those obtained from the Fourier approximation. Polar histograms of the contact forces were obtained by collecting the contact force information at the predefined bin angle $\Delta\theta=10^\circ$. When shearing commenced the inter-particle forces were almost uniformly distributed in all orientations (i.e., isotropic), as shown in Figure 15a. The normal contact force anisotropy was coaxial with vertical axes, having a principal direction of almost $\theta_n = 4^\circ$, which is the major principal stress in the assembly. In this stage the contact shear force

anisotropy was very small and its direction with the vertical axis was almost zero due to a very low induced shear stress. With an increase of applied shear load the contact force chains develop to resist shear and disperse the loads from the surface into the ballast. Anisotropies of average contact normal force and shear force grow and rotate vigorously as shearing progresses, and reach their values of $\theta_n = 33^\circ, 51^\circ$ at corresponding shear displacements of $\Delta h = 9$ mm, and 18 mm, respectively. As shear displacement increases (Figure 15b, Figure 15c), the contact force anisotropies tend to align towards the horizontal axis as the number of contacts in a horizontal shearing direction increase. This provided more insight into the orientation of contacts where the applied load was transmitted to a granular assembly through an interconnected network of forces that are difficult to measure in the laboratory.

Figure 16 shows the comparisons of contact force orientation of clean ballast, geogrid-reinforced ballast and fouled ballast (VCI=40%) at a shear displacement of $\Delta h = 9$ mm. It is seen that contact force orientation in the geogrid-reinforced ballast assembly exhibits a principal direction of $\theta_a = 15^\circ$, while the clean and fouled ballast (40%VCI) show contact force orientations of $\theta_a = 24^\circ$ and $\theta_a = 32^\circ$, respectively. The inclusion of geogrid in the fresh ballast results in increased number of contacts in the vertical direction than the unreinforced assemblies (i.e. due to the interlock between the geogrid and aggregates). The contact force orientation in the fresh ballast slightly aligns towards the vertical direction than that in the fouled ballast assembly (i.e. having a principal direction of 24° compared to 32° for the fouled ballast).

The micromechanical analysis presented in this paper is focusing on the evolution of contact and force orientations at varying shear displacements. This provides more insight into the orientation of contacts transmitted in ballast assemblies. It is believed that the inherent anisotropy affects the overall shear strength of ballast assemblies, while stresses within the ballast medium are composed of multiple stress chains, which can lead to localized high stress concentrations. Such high stress concentrations may lead to crushing of single particles even under relatively low applied stresses. Therefore, understanding the contact force distribution in the ballast assemblies and its evolution is most beneficial.

6. Practical Implications

Based on extensive laboratory tests carried out in this study, it is found that the inclusion of geogrids provides considerable improvement on the performance of geogrid-reinforced ballast in terms of the mobilized shear strength and deformation, while the presence of fouling materials adversely decreases the performance of ballast. These influential factors need to be considered in track design when geosynthetics are utilized. In the absence of current large-scale laboratory tests on geosynthetics-reinforced ballast under monotonic and cyclic loads, the proposed DEM model in this study can be used to predict the mobilized shear strength and deformation of a composite assembly for a given degree of fouling (VCI) at a corresponding normal stress.

This DEM model offers some original insight for the practitioner to improve track design as well as to conduct a performance verification of the track considering the reduced shear strength of ballast associated with an increased level of fouling. This model is also helpful for the practitioner to perform direct shear tests and cyclic tests on granular assemblies with and without the inclusion of planar geosynthetics.

7. Conclusions

This paper presents the results of large-scale laboratory tests and numerical modelling using the discrete element method (DEM) to study the performance of geogrid reinforced fouled ballast at various levels of coal fouling. The beneficial effects of geogrids on the shear strength and dilation of ballast were assessed using large scale direct shear tests. The results clearly indicated that geogrid increases the shear strength and reduces ballast dilation at a given VCI. This was justified by interlocking between the geogrid and ballast grains at the interface. Conversely, coal fines acting as lubricant coated the surfaces of ballast grains, which subsequently reduced the inter-particle friction and the shearing resistance of fouled ballast assembly. A series of cyclic tests were also carried out to investigate the load-deformation response of coal-fouled ballast using a novel rail process simulation testing apparatus. The results showed that all the ballast samples experienced a considerable amount of deformation within 100,000 cycles, followed by a gradual increase in settlement up to 300,000 cycles, and then remained relatively stable.

DEM simulations were also carried out to investigate the stress-strain behaviour and corresponding volumetric change of fresh fouled ballast (VCI=40%). Irregular ballast grains were modelled by connecting many spherical balls together, while coal fines were simulated by placing a pre-determined amount of fine spherical balls into the ballast voids. The geogrid was modelled using bonded spherical particles with a 2 mm radius at the rib and a 4 mm radius at the junction. For a given normal stress and level of fouling the DEM simulation captured the shear stress-strain and corresponding dilation of fouled ballast. As expected, fresh ballast exhibited higher shear stress and lower volumetric dilation than the fouled ballast of VCI=40%. The contact force distributions were also examined and indicated that the fouled ballast assembly experienced more uniform contact force distribution and reduced maximum contact force than fresh ballast. Contact force orientation was also analysed, and it provided more insight into the orientation of contacts transmitted in a granular assembly.

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9. Notations

a	coefficient of contact anisotropy
a_n	coefficient normal force anisotropy
a_s	coefficient shear force anisotropy
d	distance between the particle to particle centre
e_f	void ratio of fouling material
e_b	void ratio of fresh ballast
$E(\theta)$	density distribution function of fabric tensor
$\vec{F}_N$	normal force vector
$\vec{F}_T$	shear force vector
$\delta\vec{F}_T$	incremental shear force
F_{ij}	fabric tensor
$\bar{f}_n(\theta)$	density distribution function of contact normal force tensor
$\bar{f}_s(\theta)$	density distribution function of contact shear force tensor
f_n^k, f_s^k	contact normal force and shear force
$\bar{f}_0$	average contact normal force
$G_{s,b}$	specific gravity of ballast
$G_{s,f}$	specific gravity of fouling material

k_n	contact normal stiffness
k_s	contact shear stiffness
k_{n-wall}	contact normal stiffness of wall-particle
k_{s-wall}	contact shear stiffness of wall-particle
M_f	dry mass of fouling material
M_b	dry mass of fresh ballast
n_i	unit vector
N_c	total number of contacts
N_{ij}	contact normal force tensor
$R^{[A]}, R^{[B]}$	radii of particles A, B
S_{ij}	contact shear force tensor
U^n	particle penetration depth
VCI	Void Contamination Index
μ	inter-particle friction coefficient
$x_i^{[A]}, x_i^{[B]}$	particle's centres
Δh	shear displacement
σ_n	normal stress
$\sigma_{2,3}$	lateral confining stresses
θ_a	major principal directions of contact anisotropy
θ_n	major principal directions of contact normal force anisotropy
θ_s	major principal directions of contact shear force anisotropies

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Table 1. Micromechanics parameters of geogrid, ballast, and coal fines adopted for DEM simulations

Parameter	Geogrid	Ballast	Coal fines
Particle density (kg/m^3)	750	2700	800
Coefficient of friction	0.5	0.8	0.2
Contact normal stiffness, k_n (N/m)	1.77×10^7	0.52×10^8	1.27×10^4
Contact shear stiffness, k_s (N/m)	0.88×10^7	0.52×10^8	1.27×10^4
Contact normal stiffness of wall-particle, $k_{n\text{-wall}}$ (N/m)	1×10^8	1×10^8	1×10^8
Shear stiffness of wall of wall-particle, $k_{s\text{-wall}}$ (N/m)	1×10^8	1×10^8	1×10^8
Parallel bond radius multiplier, r_p	0.5		
Parallel bond normal stiffness, k_{np} (kPa/m)	5.68×10^8		
Parallel bond shear stiffness, k_{sp} (kPa/m)	5.68×10^8		
Parallel bond normal strength, σ_{np} (MPa)	456		
Parallel bond shear strength, σ_{sp} (MPa)	456		

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Contact orientation

Normal force orientation

Shear force orientation

(a) Shear displacement $\Delta h = 0$ mm

(b) Shear displacement $\Delta h = 9$ mm

(c) Shear displacement $\Delta h = 18$ mm

— Simulation data
 - - Fourier series approximation

Figure 15. Polar histograms of contact and force orientations in the fouled ballast assembly (VCI=40%) at varying shear displacement Δh : (a) $\Delta h = 0$ mm; (b) $\Delta h = 9$ mm; and (c) $\Delta h = 18$ mm

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