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Abstract

Geogrids are commonly used in railway construction for reinforcement and stabilisation. When railway ballast becomes fouled due to ballast breakage, infiltration of coal fines, dust and subgrade soil pumping, the reinforcement effect of geogrids decreases significantly. This paper presents results obtained from Discrete Element Method (DEM) to study the interface behaviour of coal-fouled ballast reinforced by geogrid subjected to direct shear testing. In this study, irregularly-shaped aggregates (ballast) were modelled by clumping together 10-20 spheres in appropriate sizes and positions. The geogrid was modelled by bonding a large number of small spheres together to form the desired grid geometry and apertures. Fouled ballast with 40% Void Contaminant Index (VCI) was modelled by injecting a predetermined number of miniature spheres into the voids of fresh ballast. A series of direct shear tests for fresh and fouled ballast reinforced by the geogrid subjected to normal shear stresses varying from 15 kPa to 75 kPa were then simulated in the DEM. The numerical results showed a good agreement the laboratory data, indicating that the DEM model is able to capture the behaviour of both fresh and coal-fouled ballast reinforced by the geogrid. The advantages of the proposed DEM model in terms of capturing the correct stress-displacement and volumetric behaviour of ballast, as well as the contact forces and strains developed in the geogrids are discussed.

Keywords

simulation, behaviour, geogrid, fouled, stabilised, coal, ballast, dem

Disciplines

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DEM simulation of the behaviour of geogrid reinforced ballast fouled with coal

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ABSTRACT

Geogrids are commonly used in railway construction for reinforcement and stabilisation. When railway ballast becomes fouled due to ballast breakage, infiltration of coal fines, dust and subgrade soil pumping, the reinforcement effect of geogrids decreases significantly. This paper presents results obtained from Discrete Element Method (DEM) to study the interface behaviour of coal-fouled ballast reinforced by geogrid subjected to direct shear testing. In this study, irregularly-shaped aggregates (ballast) were modelled by clumping together ten to twenty spheres in appropriate sizes and positions. The geogrid was modelled by bonding a large number of small spheres together to form the desired grid geometry and apertures. Fouled ballast with 40% Void Contaminant Index (VCI) was modelled by injecting a pre-determined number of miniature spheres into the voids of fresh ballast. A series of direct shear tests for fresh and fouled ballast reinforced by the geogrid subjected to normal shear stresses varying from 15kPa to 75kPa were then simulated in the DEM. The numerical results showed a good agreement the laboratory data, indicating that the DEM model is able to capture the behaviour of both fresh and coal-fouled ballast reinforced by the geogrid. The advantages of the proposed DEM model in terms of capturing the correct stress-displacement and volumetric behaviour of ballast, as well as the contact forces and strains developed in the geogrids are discussed.

1. Introduction

Ballast is a free draining granular material used as a load bearing platform in railroads (Selig and Waters 1994). It usually consists of medium to coarse particle sized aggregates with the main functions being to: (i) distribute axle loads from sleepers to the sub-ballast layer at a reduced stress level; (ii) offer lateral confining pressure to the track, and (iii) provide a free draining condition. Upon repeated train loading, ballast degrades due to the breakage of sharp corners and edges, infiltration of fines from the surface, and mud pumping from the subgrade. Consequently, ballast becomes fouled and less angular, hence overall shear strength decreases (Selig and Waters 1994; Indraratna et al. 2011a). Budiono et al. (2004) and Dombrow et al. (2009) studied the behaviour of fouled ballast and stated that fouling adversely affects the strength and stiffness of track structure and as the percentage of fouling increases, the shear strength steadily decreases. Feldman and Nissen (2002) stated that for coal freight corridors in Australia, coal fines contribute from 70–95% of the contaminants and ballast breakage accounts for 5% - 30%.

Geosynthetics have been increasingly utilised in rail tracks to provide reinforcement and confinement to the ballast layer. The behaviour of reinforced ballast has been studied in the past (e.g. Bathurst and Raymond 1987; Raymond and Bathurst 1994; Raymond and Davies 1978; Bergado et al. 1995; Raymond 2000; McDowell and Stickley 2006; Fisher and Horvat 2011; Indraratna et al. 2011b; Indraratna et al. 2012; Villard et al. 2009) but with limited DEM simulation. These studies have shown that geogrid reinforcement in ballast can be effective in reducing the rate of permanent deformation associated with lateral ballast spreading. The reinforcement effect of geogrid is generally attributed to the tensile strains developed in the geogrids via the interlock between the geogrids and surrounding aggregates. As a result, the geogrids provide lateral and vertical confinement to the ballast and, thereby reducing its settlement (Bathurst and Raymond 1987; Leng and Gabr 2002; Brown et al. 2007).

The interaction mechanism and behaviour of the geogrid and ballast at their interfaces, particularly when the ballast is severely fouled are not well understood. This is due to the steady accumulation of fine particles that decreases the aperture sizes, which then dramatically reduces the beneficial effects often causing substantial deformation (Indraratna et al. 2011a). Most of the aforementioned studies for fresh ballast were conducted experimentally and only limited attempts were made to study the geogrid-ballast interaction

numerically (McDowell et al. 2006; Tutumluer et al. 2011; Ferrellec and McDowell 2012). Furthermore, all of these studies were modelled in a limited way for fresh ballast and did not consider the irregular shaped ballast aggregates and the effects of fouling materials contaminated at the geogrid-ballast interface (Ferrellec and McDowell 2012). Therefore, the current study is an attempt to apply DEM to numerically model the coal-fouled ballast and geogrid interaction with the main aims are to study the effect of coal fines on stress-strain behaviour of ballast and to examine the associated changes of contact force distributions and strains developed across the geogrids.

2. Experimental Investigation

The apparatus for the large-scale direct shear test used in this current study was a 300 mm x 300 mm plane area and 200 mm high steel box that was divided horizontally into two equal halves. A series of direct shear tests were conducted for coal-fouled ballast at varying fouling degrees subjected to relatively low normal stresses, ranging from 15kPa to 75kPa, to simulate typical track conditions (Lackenby et al. 2007). Coal fines were used as the fouling material and the Void Contamination Index (VCI) proposed earlier by Indraratna et al.(2010), was adopted 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 = 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, M_b = the dry mass of fresh ballast.

The advantage of using Equation (1) is that it has the flexibility to consider different types of fouling materials such as coal, mud, or pulverised ballast having different specific gravities, unlike the previous methods of quantifying fouling (e.g., Selig and Waters, 1994; Feldman and Nissen, 2002). Past large-scale triaxial tests conducted by researchers (e.g., Marsal, 1973; Indraratna et al., 1993) have proven that as long as the ratio of the testing chamber dimension/ maximum particle size is higher than 6-7, the boundary effects can be neglected. Therefore, to eliminate the boundary effects, slightly reduced ballast with a maximum size (d_{100}) of 40mm and with parallel gradation were selected to replace the d_{100} of 55-60mm used in typical Australian tracks (Indraratna et al. 2011a). The particle size distributions of fresh and 40% VCI coal fouled ballast are presented in Figure 1.

Details of the large-scale direct shear tests and materials used for fresh and coal-fouled ballast reinforced by the geogrids that were conducted in this study were presented elsewhere by Indraratna et al. (2011b). Each specimen was sheared to a horizontal displacement of $\Delta h = 37\text{mm}$ which is the maximum movement allowed by the apparatus. While the laboratory results of these direct shear tests were discussed earlier by Indraratna et al. (2011b), some of the results were adopted to compare with the current DEM analysis and to calibrate the numerical model. The results of these tests highlighted that the inclusion of geogrids increases the shear strength and apparent angle of shearing resistance, while only slightly reducing the vertical displacement of the composite geogrid-ballast assembly. This was attributed to the interlock between the ballast and geogrid, which decreased any movement of the ballast particles. However, when ballast becomes fouled by coal fines, the reinforcement effect of geogrids diminishes substantially. This is because coal fines fill the voids between the ballast particles and coat their surfaces, and clog up the geogrid apertures, which in turn reduce the inter-particle friction and shearing resistance at the interface, and substantially decreases the interlock occurring at the ballast-geogrid interfaces. More comprehensive results of large scale direct shear tests on coal fouled ballast reinforced by geogrid are discussed by Indraratna et al. (2011b).

3. Discrete Element Method for Geogrid-Reinforced Fouled Ballast

3.1. Modelling Geogrids in DEM

In this study, a bi-axial geogrid with an aperture of 40 mm x 40 mm, similar to the geogrids tested in the laboratory was modelled by clumping a number of small spheres together, i.e. spheres of 2.00 mm radius at a rib and 4.00 mm radius at the junction, as shown in Figure 2a. These spheres were connected by parallel bond strengths that correspond to geogrid's tensile strength in the elastic range, as determined by the tensile test data presented later. The parallel bond properties were back calculated based on tensile test results assuming that the normal stiffness along a rib and between rib and junction is the same. Each bond represents the force-displacement behaviour of a finite sized piece of cementitious material deposited between two spheres (Itasca 2008). These bonds established an elastic interaction between particles which can transmit both forces and moments between them. It can be represented by a set of elastic springs with constant normal and shear stiffnesses, that are distributed

uniformly over a circular cross-section lying on the contact plane, and centred at the contact point (Figure 2b).

The total force and moment associated with the parallel bond are denoted by $\bar{F}_i$ and $\bar{M}_i$, with the convention that this force and moment represent the action of the bond on sphere B of Figure 2b. Each of these vectors can be resolved into normal and shear components using the following relationships (Itasca, 2004; Potyondy and Cundall, 2004):

$$\bar{F}_i = \bar{F}_i^n + \bar{F}_i^s \quad (2)$$

$$\bar{M}_i = \bar{M}_i^n + \bar{M}_i^s \quad (3)$$

The elastic force-increments occurring over a timestep of Δt are determined by:

$$\Delta \bar{F}_i^n = (-\bar{k}_n A \Delta U_i^n) n_i \quad (4)$$

$$\Delta \bar{F}_i^s = -\bar{k}_s A \Delta U_i^s \quad (5)$$

The elastic moment-increments are calculated by:

$$\Delta \bar{M}_i^n = (-\bar{k}_s J \Delta \theta_i^n) n_i \quad (6)$$

$$\Delta \bar{M}_i^s = -\bar{k}_n I \Delta \theta_i^s \quad (7)$$

with, $\Delta \theta_i = (\omega_i^{[B]} - \omega_i^{[A]}) \Delta t$

where, $\bar{k}_n$ and $\bar{k}_s$ are normal and shear stiffnesses of the bond, respectively; ΔU_i^n and ΔU_i^s are the normal and shear relative displacement increments, respectively; $\Delta \theta_i^n$ and $\Delta \theta_i^s$ are the normal and shear relative rotation increments, respectively; $\omega_i^{[A,B]}$ are rotational velocity of ball A, B; A, J and I are the area, polar moment and moment of inertia of the bond cross-section, respectively, and are defined as functions of the radius $\bar{R}$ of the bonding disk between spheres, as given:

$$A = \pi \bar{R}^2 \quad (8)$$

$$I = \frac{1}{2} \pi \bar{R}^4 \quad (9)$$

$$J = \frac{1}{4} \pi \bar{R}^4 \quad (10)$$

By using the elastic beam theory, the maximum normal and shear stresses acting on the bond periphery are computed as:

$$\sigma_{max} = \frac{\overline{F}_i^n}{A} + \frac{|\overline{M}_i^s|}{I} \overline{R} \quad (11)$$

$$\tau_{max} = \frac{|\overline{F}_i^s|}{A} + \frac{|\overline{M}_i^n|}{J} \overline{R} \quad (12)$$

If either of these maximum stresses exceeds its corresponding bond strength the parallel bond breaks, this corresponds to the geogrid breaking.

3.2. Calibration of the Geogrids

In this study, the micromechanics parameters of the simulated geogrid were calibrated using tensile tests, as shown in Figure 3a. In the laboratory, the geogrids were tested using an INSTRON apparatus following ASTM Standard D6637 (2011). The geogrids were fixed at one end and the other end was pulled with the increasing load until the geogrids failed. The tensile strain corresponding to the tensile load imposed on the geogrid was monitored during testing and these data were adopted for calibration purposes. After conducting a series of DEM simulations of tensile test for geogrid (Figure 3a), and comparing them with the results measured experimentally, a set of micromechanical parameters adopted for modelling of the geogrid were then determined and are given in Table 1.

Geogrids are visco-elastic materials, and their load-strain behaviour is affected by the strain rate, duration of loading and temperature. Shinoda and Bathurst (2004) and Wilson-Fahmy et al. (1994) conducted a series of short-term in-isolation tensile tests for geogrids subjected to constant rate of strain and concluded that the stiffness, rupture strength and strength at rupture are dependent on the rate of strain. In the laboratory, the geogrid was subjected to a given axial strain rate of 1%/min. However, in DEM, the two junctions at the end of the geogrid were pulled down at a small velocity (V) of 1×10^{-8} m/step to reduce computational error. It is important to mention that the apparent stiffness of a visco-elastic material such as a geogrid depends on the strain rate (Shinoda and Bathurst 2004). In this study, the DEM model adopted an elastic spring at the contact of two particles (contact-bond model) and as a result the visco-elastic behaviour of the geogrid could not be captured. As DEM is not able to simulate the exact strain rate representing the laboratory condition at all times, the laboratory tensile test results were employed to back-calculate the most appropriate DEM parameters. It

was noticed that the simulation of the tensile test using DEM to calibrate the parameters for the geogrid was limited to the elastic range of maximum strain of 5%, following ASTM Standard D6637 (2011). The tensile loads obtained from the DEM model were compared with data measured in the laboratory for calibration purpose. The Authors understand that for calibration and validation at least two independent sets of geogrids would be required (e.g. results obtained from tensile tests for calibration and direct shear test for validation), and this is noticed as a limitation of this study. Figure 3b shows a reasonable agreement between the DEM simulation and the laboratory results indicating that the micromechanical parameters adopted in Table 1 are reasonable. These parameters were used for the simulation of a large-scale direct shear test of ballast reinforced with geogrid.

3.3. Modelling of Fresh and Fouled Ballast in DEM

The DEM model of a large-scale direct shear box for ballast was introduced earlier by the authors (Indraratna et al. 2013), and the same DEM parameters for fresh and coal-fouled ballast were adopted in the current analysis. Several methods have been used to model non-circular particles, as introduced by Houlsby (2009); Bertrand et al. (2005); Cho et al. (2007), among others. In this paper, irregularly-shaped aggregates were modelled by clumping of ten to twenty spherical balls together in appropriate sizes and positions (Figure 4a). A large-scale direct shear box was simulated by rigid walls with free loading plate placed on the top boundary to allow particles to displace vertically during shearing. Following the process conducted in the laboratory, the bottom half of the shear box was initially filled with the simulated particles and compacted to a specified void ratio of 0.82 (e.g., density of 1530 kg/m³). The simulated geogrid sheet was then generated on the top of the previously generated ballast layer at the middle of the shear box. The remaining simulated ballast particles were then placed on the top half of the shear box, and cycling process was conducted to bring the model into equilibrium. The DEM models of large-scale direct shear test for fresh and 40% VCI coal-fouled ballast with the inclusion of the geogrid at the middle of the shear box are presented in Figure 4b and Figure 4c, respectively.

The micromechanical parameters used to model the ballast and shear box were adopted from (Indraratna et al. 2013) and presented herein in Table 1. The DEM model was cycled until equilibrium was achieved, and the interlock between the geogrid and ballast particles occurs. The normal stress applied was kept constant by adjusting the position and velocity of the top loading plate using a numerical servo-control mechanism (Itasca, 2008). The lower part of

the shear box was then moved horizontally at a velocity of 0.1×10^{-4} mm/time step to a maximum horizontal displacement of 40 mm, while the upper section was fixed (Liu et al. 2005). During shearing, the displacement of the top plate was monitored to determine the associated change in volume, and the shear stress was captured using the subroutines developed by the Authors. Due to the interlock and friction occurring at the geogrid-ballast interfaces, tensile forces and strains developed across the geogrids. Subroutines were developed to compute the averaged volumetric strains in geogrids at a specified shear strain, and the results are presented in the following section.

There has only been limited studies of coal fouled ballast using a numerical method. Huang and Tutumluer (2011) introduced a method to model fouled ballast in DEM by decreasing the friction angles of ballast. This method captured the stress-strain behaviour of fouled ballast, but it was unable to capture the volumetric strain of a fouled ballast assembly. In this study, the injection of a predetermined number of 1.5 mm balls (e.g., 145,665 balls) into the voids of fresh ballast was used to model 40%VCI coal-fouled ballast. The micromechanical parameters suggested by (Indraratna et al. 2013) were adopted to simulate coal-fouled ballast and are presented Table 1.

3.4. Shear Stress-Displacement Analysis

DEM simulations of large-scale direct shear tests were conducted at three normal stresses of 27kPa, 51kPa, and 75kPa for fresh and 40%VCI fouled ballast, reinforced by geogrids. The shear stress-displacement data obtained from DEM analysis in comparison with the laboratory data for fresh and 40%VCI fouled ballast are presented in Figure 5a and Figure 5b, respectively. It is seen that the results obtained from DEM agree reasonably well with the experimental results at all normal stresses. The strain softening behaviour of ballast and volumetric dilation were also observed in all simulations, whereby the greater the normal stress (σ_n), the higher the peak stress and the smaller the dilation. This softening behaviour was also observed for unreinforced ballast and presented in Figure 6. The reinforcement effect of geogrid in increasing the shear strength of both fresh and fouled ballast was captured by comparing it with an assembly of unreinforced ballast. It was concluded that the DEM model proposed in this study could capture the shear stress-displacement and dilation behaviour of fresh and fouled ballast reinforced by geogrids. The DEM simulation exhibited a discrepancy in the stress-displacement curves at a horizontal displacement of 15-30 mm (e.g., considerably decreased stress and suppressed dilation) compared to the data measured

experimentally. This discrepancy may be associated with some particle breakage that could not be captured adequately in the DEM analysis, and the rigidity of the loading plate. Additionally, this difference in the response of the stress-displacement behaviour of fresh and fouled ballast assemblies between DEM and the experiment can also be attributed to the reduction of interlocking provided by the angular shape of ballast particles, which affects the rolling resistance and rearrangement of particles.

3.5. Contact Force Distribution and Contours of Strain Developed in the Geogrids

Figure 7 presents the contact force distributions of fresh and 40% VCI fouled ballast with and without geogrid reinforcement at a lateral displacement of 18 mm and a given normal stress of 51 kPa. Contact forces between particles were plotted as lines whose thickness is proportional to their magnitude. For the purpose of clarification, only those contact forces with a magnitude exceeding the average value in the assembly were plotted in Figure 7. The 40% VCI fouled ballast (Figures 7b and 7d) showed denser contact chains and reduced maximum contact forces, compared to those in the fresh ballast assembly (Figures 7a and 7c). This was due to the presence of coal fines that had accumulated in voids among the large particles and then partially carried and transmitted contact forces across the assembly. It was also seen that at the shearing plane, contact forces developed between the geogrid and surrounding ballast particles associated with significantly increased number of contact forces, which could be attributed to the interlocking effect. Compared to the unreinforced ballast, the geogrid-reinforced ballast exhibited a significant increase both in the number and in the magnitude of contact forces at the geogrid-ballast interface. This mobilisation of large contact forces within the geogrid-reinforced ballast assembly was due to the ballast–geogrid interlock. For fouled ballast the mobilised contact forces were less than those in fresh ballast due to the reduced effectiveness of the geogrid apertures.

Strains that developed in the geogrids could not be measured due to the complexity of installing strain gauges to geogrids and the difficulty of preventing the strain gauges from being damaged caused by the sharp edges of aggregates, and subsequent compaction. However, they can be captured via numerical simulation and are presented herein for the completeness. Taking advantage of the DEM simulation, strains in the horizontal shearing direction that developed across the geogrid were presented in this study. In DEM simulation, the strains obtained using the stresses (σ_x , σ_y , and τ_{xy}) in the spheres representing the

geogrids were recorded. The principal stresses $\sigma_{1,2}$ in the geogrids were then determined as follows:

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \quad (13)$$

The horizontal strains, ε_1 in the geogrids were then calculated as:

$$\varepsilon_1 = \frac{\sigma_1}{E_p} \quad (14)$$

where, E_p is the Young's modulus of the geogrid that was obtained based on Figure 3b.

Figure 8 shows the horizontal contours of strain developed across the geogrid at the end of shear test (horizontal displacement of 40 mm) for fresh ballast and 40%VCI fouled ballast. It can be seen that strains developed non-uniformly across the geogrid and the magnitude of strain depends on the interlock that occurs between the geogrid and ballast particles. The strains are well within the elastic range. The geogrid in 40%VCI fouled ballast assembly experienced a slightly lower maximum strain than those in the fresh ballast (i.e. 1% strain for fouled ballast compared to 1.4% strain in fresh ballast). This would be attributed to the decreased interlocking effect of the geogrid and ballast particles due to the presence of coal fines clogging the geogrid-ballast interface.

4. Conclusion

A series of DEM simulations for large-scale direct shear tests were conducted for fresh and 40%VCI coal-fouled ballast to study the stress-displacement behaviour effected by the inclusion of geogrid. Irregular shaped ballast particles were simulated in DEM by clumping many spheres together in appropriate sizes and positions. The geogrids were modelled using bonded spherical particles 2.00 mm radius at the rib and 4.00 mm in radius at the junction. The parallel bond strength between particles modelling the geogrid corresponded to its tensile strength, and was calibrated using tensile tests. The coal fines were modelled by introducing a predetermined number of miniature spheres into the ballast voids. Using the calibrated micromechanical parameters, large-scale direct shear test of ballast reinforced by the geogrid experiments were simulated to establish the simulation techniques for the interaction between

geogrid and ballast. The proposed DEM model was then simulated for large-scale direct shear tests of reinforced fresh and fouled ballast subjected to varying normal stresses of $\sigma_n = 27 \text{ kPa}$, 51 kPa and 75 kPa . The results obtained from the DEM model for fresh and coal ballast were in good agreement with the measured data and showed that the proposed model could accurately capture the stress-displacement behaviour of ballast. The presence of coal fines in the ballast assembly facilitated a reduced interlock between the ballast particles and geogrids that resulted in reduced shear strength. It is concluded that the interlocking of the ballast aggregates with the geogrid is the primary factor responsible for the enhanced performance of the geogrid-stabilised ballast assembly.

Based on DEM, strains developed non-uniformly across the geogrid and the magnitude of strain depends on the interlock between the geogrid and ballast. The geogrid in 40% VCI fouled ballast assembly experienced a slightly lower maximum strain than those in the fresh ballast (i.e. 1% strain for fouled ballast compared to 1.4% strain in fresh ballast). This is because of the decreased interlocking effect caused by the presence of coal fines clogging the geogrid interface. The number of contact forces in fouled ballast was more than those in the fresh ballast assembly. This was due to coal fines that accumulated in voids among large particles partially carrying and transmitting the contact forces across the assembly.

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6. Notation

A	area of the bond cross-section
e_f	void ratio of fouling material
e_b	void ratio of fresh ballast
E_p	Young's modulus
$G_{s,b}$	specific gravity of ballast
$G_{s,f}$	specific gravity of fouling material
M_f	dry mass of fouling material
M_b	dry mass of fresh ballast
d_{100}	maximum particle size
I	moment of inertia of the bond cross-section
J	polar moment of the bond cross-section
k_n	contact normal stiffness
k_s	contact shear stiffness
R	radius of the bonding disk between balls
VCI	Void Contamination Index
μ	inter-particle friction coefficient
k_{n-wall}	contact normal stiffness of wall-particle
k_{s-wall}	contact shear stiffness of wall-particle
$\overline{F}_i$	total force vector acting on parallel bond

$\overline{F}_i^n$	normal force vector
$\overline{F}_i^s$	shear force vector
$\Delta\overline{F}_i^n$	elastic normal force-increments occurring over a time step
$\Delta\overline{F}_i^s$	elastic shear force-increments occurring over a time step
$\overline{M}_i$	total moment vector acting on parallel bond
$\overline{M}_i^n$	normal moment vector component
$\overline{M}_i^s$	shear moment vector component
V	velocity
$\omega_i^{[A]}$	rotational velocity of ball A
$\omega_i^{[B]}$	rotational velocity of ball B
$\Delta\overline{M}_i^n$	elastic normal moment-increments
$\Delta\overline{M}_i^s$	elastic shear moment-increments
Δt	time step
ΔU_i^n	normal relative displacement increments
ΔU_i^s	shear relative displacement increments
$\Delta\theta_i$	relative rotation increments
$\Delta\theta_i^n$	normal relative rotation increments
$\Delta\theta_i^s$	shear relative rotation increments
σ_{max}	maximum normal stress
$\sigma_{1,2}$	principal stresses
τ_{xy}	shear stress
τ_{max}	maximum shear stress
ε_1	horizontal strain

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8. List of Tables

Table 1. Micromechanical parameters of geogrid, ballast and coal fines adopted for DEM simulation

Parameter	Geogrid	Ballast	Coal fines
Particle density (kg/m^3)	800	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 shears 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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Figure 1. Particle size distributions of fresh and 40% VCI fouled ballast

Figure 2. Model geogrid in DEM: (a) typical biaxial geogrid; (b) parallel bond depicted as a cylinder of cementitious material for modelling geogrids

Figure 3. Calibration of the geogrid, (a) tensile testing for biaxial geogrid and *DEM* simulation; (b) comparison of *DEM* and experimental results

(a)

(b)

(c)

Figure 4. DEM models of large-scale direct shear test with geogrid inclusion (a) library of ballast particle shapes simulated in DEM; (b) DEM models for fresh ballast; and (c) DEM models for 40% VCI fouled ballast

Figure 5. Comparison of shear stress and displacement relations for DEM simulation of reinforced ballast at normal stresses of $\sigma_n = 27\text{kPa}$, 51kPa , and 75kPa : (a) fresh ballast, and (b) 40% VCI fouled ballast

Figure 6. Comparison of shear stress and displacement relations for DEM simulation of unreinforced fresh ballast at normal stresses of $\sigma_n = 27$ kPa, 51 kPa, and 75 kPa.

Figure 7. Distribution of contact forces for a normal stress of 51kPa at a horizontal displacement of 18 mm : (a) unreinforced-fresh ballast; (b) 40% VCI-unreinforced ballast; (c) geogrid-reinforced fresh ballast; (d) 40% VCI-geogrid reinforced ballast

Figure 8. Contour strain (horizontal shearing direction) developed across the geogrid at the end of test: (a) fresh ballast; (b) 40% VCI fouled ballast