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Modelling geogrid-reinforced railway ballast using the discrete element method

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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 geogird were simulated by clumping spherical balls together, while the coal fines were simulated by adding 1.5 mm 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.

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;

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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
$k_{n\text{-wall}}$	contact normal stiffness of wall-particle
$k_{s\text{-wall}}$	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

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.

Experimental study

Large-scale direct shear test

The large-scale direct shear test apparatus used in this study consisted of a 300 mm × 300 mm 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 Fig. 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:

$$\mathrm{VCI} = \frac{1+e_f}{e_b} \times \frac{G_{sb}}{G_{sf}} \times \frac{M_f}{M_b} \times 100 \tag{1}$$

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 Δh = 37 mm (e.g. the maximum movement allowed by the direct shear test apparatus). Fig. 2 shows the stress-displacement and dilation response of fouled ballast with and without geogrid reinforcement

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