Investigating the Shear Behaviour of Fouled Ballast Using Discrete Element Modelling

Ngoc Trung Ngo, Buddhima Indraratna, Cholachat Rujikiathmakjornr

Abstract—For several hundred years, the design of railway tracks has practically remained unchanged. Traditionally, rail tracks are placed on a ballast layer due to several reasons, including economy, rapid drainage, and high load bearing capacity. The primary function of ballast is to distributing dynamic track loads to sub-ballast and subgrade layers, while also providing lateral resistance and allowing for rapid drainage. Upon repeated trainloads, the ballast becomes fouled due to ballast degradation and the intrusion of fines which adversely affects the strength and deformation behaviour of ballast. This paper presents the use of three-dimensional discrete element method (DEM) in studying the shear behaviour of the fouled ballast subjected to direct shear loading. Irregularly shaped particles of ballast were modelled by grouping many spherical balls together in appropriate sizes to simulate representative ballast aggregates. Fouled ballast was modelled by injecting a specified number of miniature spherical particles into the void spaces. The DEM simulation highlights that the peak shear stress of the ballast assembly decreases and the dilation of fouled ballast increases with an increase level of fouling. Additionally, the distributions of contact force chain and particle displacement vectors were captured during shearing progress, explaining the formation of shear band and the evolutions of volumetric change of fouled ballast.

Keywords—Railway ballast, coal fouling, discrete element modelling, discrete element method.

I. INTRODUCTION

FOR over a hundred years the standard railway has consisted of a framework of rails and sleepers that are supported through a tamped bed of igneous or metamorphic rock ballast. Ballast is used to transfer wheel loading through the rails and sleepers to the foundation soil at a reduced and acceptable stress level [1]. The ballast is under laid with sub-ballast, which is used primarily for drainage and load bearing platform. Ballast undergoes gradual and continuing degradation under highly dynamic and cyclic train loadings. This degradation leads to undesirable properties such as increased deformation, decreased shear-strength and lower

Ngoc Trung Ngo is lecturer at Centre for Geomechanics and Railway Engineering, Faculty of Engineering and Information Sciences, ARC Centre of Excellence for Geotechnical Science and Engineering University of Wollongong, Wollongong, NSW 2522, Australia (corresponding author: phone: +61 2 4221 4892; fax: +61 2 4221 3238; e-mail: trung@uow.edu.au).

Buddhima Indraratna is research director and professor of Civil Engineering, Centre for Geomechanics and Railway Engineering, Faculty of Engineering and Information Sciences, ARC Centre of Excellence for Geotechnical Science and Engineering, University of Wollongong, Wollongong, NSW 2522, Australia (e-mail: indra@uow.edu.au).

Cholachat Rujikiathmakjornr is Associate Professor at Centre for Geomechanics and Railway Engineering, Faculty of Engineering and Information Sciences, ARC Centre of Excellence for Geotechnical Science and Engineering, University of Wollongong, Wollongong, NSW 2522, Australia (e-mail: cholacha@uow.edu.au).

porosity, which reduces the drainage capabilities of the ballast [1], [4]. Feldman & Nissen [5] reported that freight tracks in Australia that are predominantly used to transport coal where coal fines account for 70%-95% of fouling materials and ballast breakage accounts for from 5%-30%. It was reported by [3] that fine particles coated the ballast grains, acting presumably as a lubricant which leads to increased ballast dilation. In order to prevent ballast degradation and reduce ballast fouling, various techniques using geosynthetics have been applied in practice with the aim to improve the ballast's response to dynamic loading [6]. A geogrid is a common type of geosynthetics used to increase the lateral resistance of ballast in tracks, as it can provide a strong mechanical interlock between the grid aperture and particles of ballast [7]-[9].

When ballast gets fouled, the beneficial effect of a geogrid may decrease substantially because fine particles clogged in the apertures of the geogrid and decreased the mechanical interlocking between the ballast and geogrid [3], [4]. There have been limited attempts to investigate the fouled ballast both in the experiment and via numerical modeling [2], [3]. In these previous studies, ballast grains were simulated with either circular balls or spheres and hence, they did not examine influences of particle shape and fouling materials contaminated in the geogrid-reinforced ballast specimen. This study presents results of large-scale direct shear tests for examining the stress-displacement and volumetric change behaviour of coal fouled ballast reinforced by geogrid obtained from DEM simulations and those measured in the laboratory.

II. EXPERIMENT STUDY

Large-scale direct shear test apparatus used in this study has 300 mm x 300 mm plane area and 200 mm high steel box that was divided horizontally into two equal halves. A series of shear tests were carried for fresh and fouled ballast with and without a geogrid inclusion, subjected to relatively low normal stresses, ranging from 27 kPa to 75 kPa, simulating typical track conditions [10]. Coal fines were used as the fouling material and the Void Contamination Index (VCI) proposed earlier by [11] was adopted to quantify the levels of ballast fouling, as given by:

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

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

World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:9, No:12, 2015

specific gravity of fouling material, M_f= the dry mass of fouling material, M_b= the dry mass of fresh ballast. The advantage of the VCI is that it considers different types of fouling materials such as coal, mud or pulverised ballast by incorporating their respective specific gravity ratios into the equation. Particle size distribution of fresh and fouled ballast at various values of VCI used in this study is presented in Fig. 1. A type of geogrid used in this study was produced from polypropylene and had 40mm × 40mm apertures. Ballast aggregates were placed in the shear box and compacted to a field density approximately of 15.3 kN/m³. A geogrid was horizontally placed in the mid plane of the shear box and secured to the apparatus by clamping it with anchors. A predetermined amount of coal fines was uniformly added to the fresh ballast to meet a desired VCI. These coal fines then migrated and clogged into pore spaces of ballast aggregates under subsequent compaction. The tests were conducted at three normal stresses of 27, 51, and 75 kPa. During the tests, shear forces and associated vertical movement of the top plate were recorded at every 1mm of horizontal displacement. The test was forced to shear to a displacement of Δh=37mm which is a maximum displacement allowed by the apparatus. While the experimental results were analysed and discussed in detail elsewhere by [6], some of these results are used to compare with the current DEM analysis. The experimental results show that the peak shear stress increases with an increase of the normal stresses, but decreases as the VCI increases. Indraratna et al. [6] presented this is related to coal fines coating the surface of ballast particles, thereby decreasing the interlocking benefit between the geogrid and ballast grains. In other words, the coal fines may act as a lubricant, thereby facilitating the ballast aggregates to slide and roll over each other more easily, resulting in increased dilation.
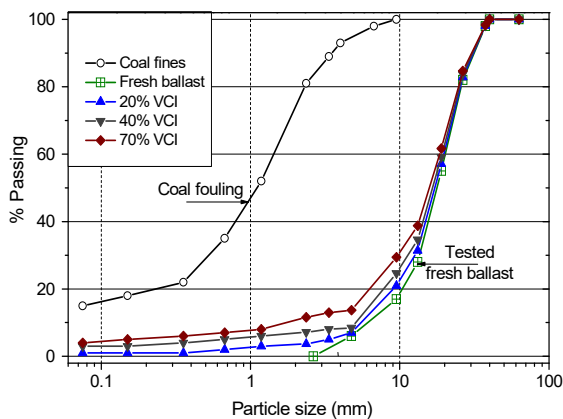

Fig. 1 Particle size distributions of ballast and coal fines tested in the laboratory
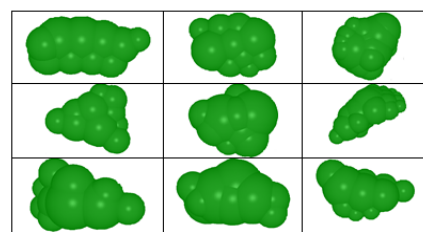
III. DISCRETE ELEMENT MODELLING

The discrete element method (DEM) introduced by [12] was used in this study to model the large scale direct shear test of fresh and fouled ballast. The irregularly-shaped grains of ballast were simulated by connecting and overlapping a number of spherical balls with different sizes and coordinates
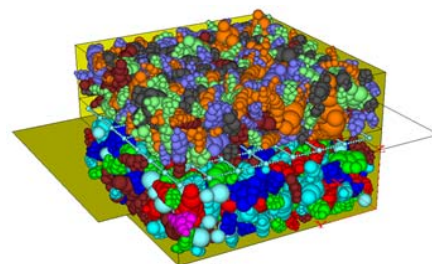
together [13]. This method has been widely used to simulate irregular shape of granular materials in DEM as presented by [14]-[16]. A library of nine typical ballast shapes and large-scale direct shear box were developed in the current analysis, as shown in Fig. 2 (a). A geogrid with 40 mm × 40 mm size apertures, similar to that tested in the laboratory, was simulated by connecting a number of small spherical balls together (i.e., balls with a 2mm radius at the ribs and a 4mm radius at the junctions). These balls were connected by parallel bond strengths that represented the geogrid's tensile strength. Coal fines were simulated by adding 1.5 mm-radius spheres within void spaces of the fresh ballast. The simulated large scale direct shear tests in DEM for fresh and fouled ballast (VCI=40%) are shown in Figs. 2 (b) and (c), respectively. By calibrating with the experimental results presented by [6], a set of micromechanical parameters adopted for DEM simulation of fresh and fouled ballast reinforced by geogrid are presented in Table I.

TABLE I
MICROMECHANICAL PARAMETERS OF GEOGRID, BALLAST AND COAL FINES ADOPTED IN DEM SIMULATION

Parameter	Geogrid	Ballast	Coal fines
Particle density (kg/m3)	800		
Coefficient of friction	0.5		
Contact normal stiffness, kn (N/m)	1.77×10^7		
Contact shear stiffness, ks (N/m)	0.88×10^7		
Contact normal stiffness of wall-particle, kn-wall (N/m)	1×10^8	2700 0.8	800 0.2
Shear stiffness of wall of wall-particle, ks-wall (N/m)	1×10^8	0.52×10^8 0.52×10^8	1.27×10^4 1.27×10^4
Parallel bond radius multiplier, r_p	0.5	1×10^8	1×10^8
Parallel bond normal stiffness, k_{np} (kPa/m)	5.68×10^8	1×10^8	1×10^8
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		

(a)

(b)

World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
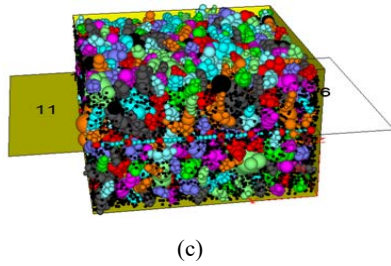Vol:9, No:12, 2015

(c)

Fig. 2 (a) Ballast particle shape; (b) DEM model for fresh ballast; (c) DEM model for 40%VCI fouled ballast (modified after [2])

IV. RESULTS AND DISCUSSION

A. Stress-Strain Behaviour of Fresh Ballast

Laboratory tests and DEM simulations for the fresh ballast reinforced by geogrid were carried out for large-scale direct shear tests subjected to three normal stresses of 27kPa, 51kPa, and 75kPa. Fig. 3 shows comparisons of the shear stress-strain and the volumetric behaviour of fresh ballast between the DEM simulation and experimental results. Generally, the DEM results match reasonably well with the laboratory data at any given normal stress. The strain softening response and volumetric dilation are captured as expected for granular materials. It is noticed that the DEM analysis exhibits a discrepancy in the stress-strain curves at a shear strain of 4-8% compared to the experimental results. This difference may be attributed to some ballast breakage that could not be accurately modelled in the current DEM analysis. Moreover, the discrepancy in the shear stress-strain response could also be a result of reduced interlocking by the irregularly-shaped ballast which affects their rolling resistance and also the re-arrangement of ballast particles.
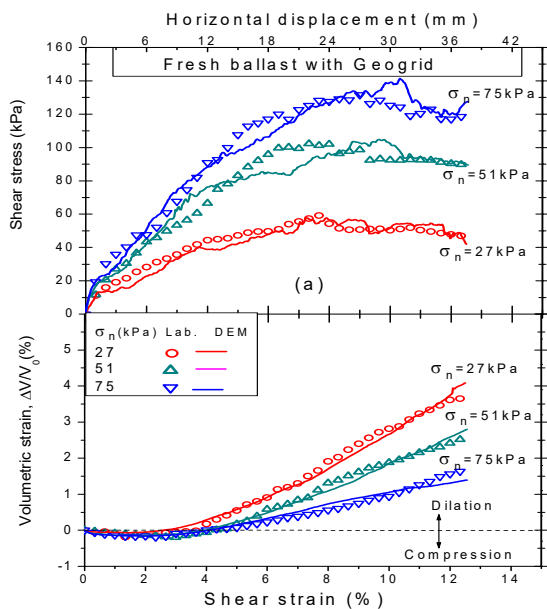

Fig. 3 Comparisons of shear stress-strain and volumetric response of fresh ballast between experiment and DEM (modified after [2])

B. Stress-Strain Behavior of Coal Fouled Ballast

Large-scale direct shear for fouled ballast subjected three different normal stresses of 15kPa, 27kPa and 75kPa were carried out in the laboratory and simulated in the DEM. Fig. 4 shows comparisons of the stress-strain behaviour and volumetric change between DEM simulations and experimental results for the coal fouled ballast (VCI=40%). It is clearly seen that the shear stress-strain curves predicted by DEM simulations are generally in good agreement with those measured experimentally. A strain softening behaviour of ballast is predicted by DEM exhibited a significant dilation at shear strain exceeding 5%. Compared to fresh ballast, the fouled ballast (VCI=40%) experiences a lower peak shear stress and slightly greater dilation, as expected. This is because of the coal fines decrease the inter-particle friction of the ballast by coating the surface of rough aggregates, causing a reduction in shear strength. The fouled ballast exhibits a compression at the beginning of the test, followed by significant dilation. This is expected of dense granular materials that normally exhibit a strain softening at high dilation rates. Based on these observations, it is possible to conclude that the proposed DEM model is capable of capturing the shear stress-strain response of fresh and fouled ballast subjected to a given normal stress.
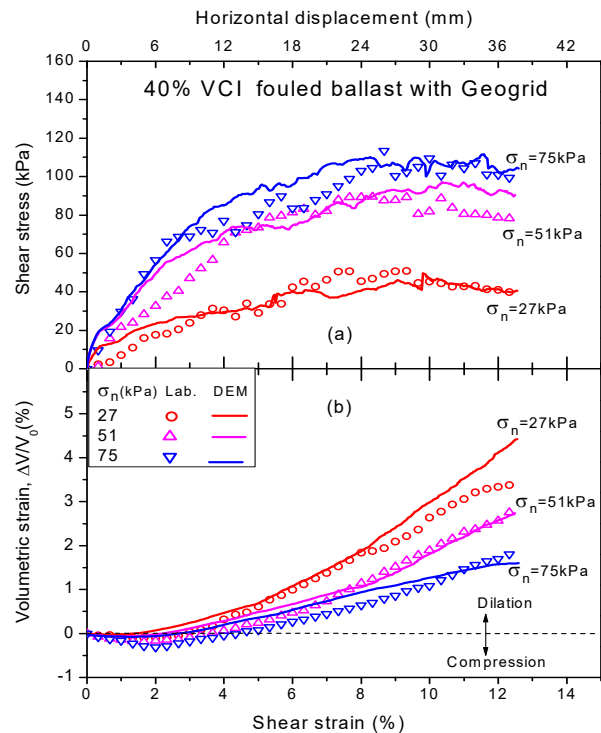

Fig. 4 Comparisons of shear stress-strain and volumetric response of fouled ballast (VCI=40%) between experiment and DEM simulation (modified after [2])

C. Contour of Strains Developed in the Geogrid

Owing to some difficulties in installing the geogrid and protecting strain gauges being damaged caused by the sharp edges of ballast and compaction, strains developed across in

World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:9, No:12, 2015

the geogrid could not be measured in the laboratory. Taking advantage of DEM simulation, the strains developed across the geogrid in the horizontal shearing direction were captured in the current DEM analysis. Figs. 5 (a) and (b) present contours of strain induced in the geogrid at the end of the shear test for fresh and coal fouled ballast (VCI=40%), respectively. It can be observed that the strains develop non-uniformly across the geogrid and the maximum values of strain could depend on the interlocking that occurred between the geogrid and ballast aggregates. The geogrid placed in the fresh ballast experiences a slightly greater maximum strain than those in the fouled ballast (i.e. 1.405% strain for fresh ballast compared to 1.0% strain in 40%VCI-fouled ballast). This could be attributed to reduced interlocking benefit of the geogrid and ballast aggregates due to coal fines clogging the interface between the ballast and geogrid.
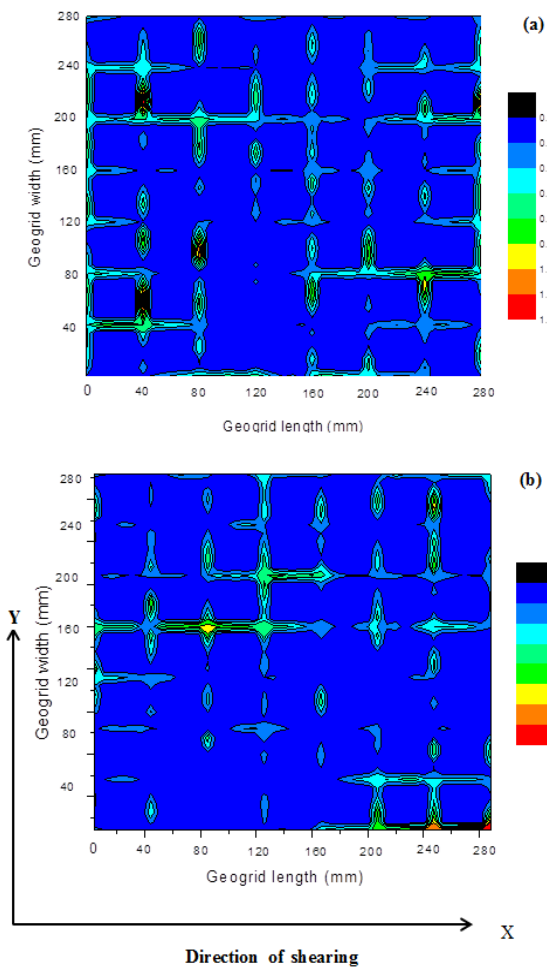

Fig. 5 Contour strain developed across the geogrid at the end of test: (a) fresh ballast; (b) 40%VCI-fouled ballast (modified after Ngo et al. [2])

D. Particle Displacement in a Simulated Direct Shear Test

The evolution of displacement vectors at shear strains of 3% and 13% of particles in direct shear test subjected to a normal stress of 51kPa are presented in Figs. 6 (a) and (b), respectively. At 3% shear strain (Fig. 6 (a)); while particles in the lower box move horizontally, particles in the upper box displace downwards causing densification (compression) of the ballast specimen. However, at much higher shear strain (e.g. 13%), particles in the upper box tend to move upwards causing dilation. This micromechanical investigation clearly show an insightful evolution of volumetric changes during shearing within a ballast assembly and corresponding strain softening response, which a continuum mechanics approach is difficult to deliver the same level of clarity. It is also seen from the DEM simulation that during shearing the ballast particles at the rear of shear box displace downwards while particles at the front of the shear box displace upwards (Fig. 6 (c)). Volumetric strain does not uniformly distribute within the ballast assembly, in which dilation tends to occur at the front of the shear box and compression occurs at the back of the shear box. This can be attributed to the formation of contact force chain in shear band, in which particles within the shear band displace and rotate greater than those outside the shear band as also observed by [17], [18].
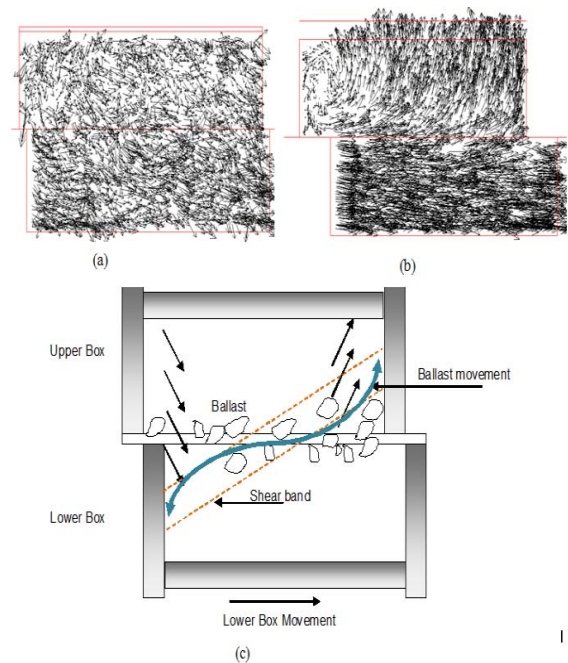

Fig. 6 Displacement vectors of particles in the shear box for normal stress of 51kPa, (a) shear strain $\varepsilon\sigma = 3\%$, (b) shear strain $\varepsilon_s = 13\%$ and (c) conceptual displacement of particles

V. CONCLUSION

Experiment and DEM simulations of large scale direct shear tests for fresh and coal fouled ballast (VCI=40%) were conducted to investigate the volumetric change and corresponding stress-strain behaviour. All tests were conducted at three normal stresses of 27kPa, 51kPa, and 75kPa to simulate low confining pressure in the field. Irregular shaped ballast particles were simulated by connecting and overlapping a number of spheres together in proper sizes and coordinates. Coal fines were modelled by placing a specified number of miniature spherical balls into the ballast voids. For

a given normal stress, the results obtained from the DEM simulation agreed reasonably well with the data measured experimentally, showing that the proposed DEM model in this study could adequately capture the stress-strain behaviour of fresh and fouled ballast. Based on the DEM simulation, the strains developed in the geogrid were also captured. The geogrids in the fouled ballast (VCI=40%) experienced a slightly lower maximum strain than those in the fresh ballast, mainly because the fines accumulating in the ballast-geogrid interface would decrease interlocking between them.

REFERENCES

[1] Selig, E.T. and J.M. Waters, Track geotechnology and substructure management. 1994: Thomas Telford, London.
[2] Ngo, N.T., B. Indraratna, and C. Rujikiatkamjorn. "DEM simulation of the behaviour of geogrid stabilised ballast fouled with coal". Computers and Geotechnics. 2014. 55(2014): pp. 224-231.
[3] Indraratna, B., N.T. Ngo, and C. Rujikiatkamjorn. "Studying the Deformation of Coal Fouled Ballast Stabilised with Geogrid under Cyclic Load". Journal of Geotechnical and Geoenvironmental Engineering, ASCE. 2013. 139(8): pp. 1275-1289.
[4] Indraratna, B., Ngo, N., Rujikiatkamjorn, C. , and Vinod, J.. "Behavior of Fresh and Fouled Railway Ballast Subjected to Direct Shear Testing: Discrete Element Simulation". International Journal of Geomechanics. 2014.14(1): 34-44.
[5] Feldman, F. and Nissen, D. "Alternative testing method for the measurement of ballast fouling". Conference on Railway Engineering. (2002). Wollongong, RTSA.
[6] Indraratna, B., N.T. Ngo, and C. Rujikiatkamjorn. "Behavior of geogrid-reinforced ballast under various levels of fouling". Geotextiles and Geomembranes. 2011. 29(3): pp. 313-322.
[7] Bathurst, R.J. and G.P. Raymond. 'Geogrid reinforcement of ballasted track". Transportation Research Record. 1987. 1153: p. 8-14.
[8] Brown, S.F., N.H. Thom, and J. Kwan. "Optimising the geogrid reinforcement of rail track ballast". In Railfound Conference. 2006. Birmingham.
[9] McDowell, G. R., Harireche, O., Konietzky, H., Brown, S. F. , and Thom, N. H. "Discrete element modelling of geogrid-reinforced aggregates". Proceedings of the ICE - Geotechnical Engineering. (2006). 159(1): 35-48.
[10] Lackenby, J., Indraratna, B., McDowell, G. R. , and Christie, D.. "Effect of confining pressure on ballast degradation and deformation under cyclic triaxial loading". Géotechnique. (2007). 57(6): 527–536..
[11] Indraratna, B., S. Nimbalkar, and N. Tennakoon, The Behaviour of Ballasted Track Foundations: Track Drainage and Geosynthetic Reinforcement. GeoFlorida 2010: Advances in Analysis, Modeling & Design (GSP 199), 2010a. Fratta, D., Puppala, A. and Muhunthan, B. (Eds.) p. 2378-2387.
[12] Cundall, P.A. and O.D.L. Strack. "A discrete numerical model for granular assemblies". Geotechnique. 1979. 29(1): p. 47-65.
[13] Itasca, Particle flow code in three dimensions (PFC3D). Itasca Consulting Group, Inc., Minnesota, 2008.
[14] Lobo-Guerrero, S. and L.E. Vallejo. "Discrete element method analysis of railtrack ballast degradation during cyclic loading". Granular Matter. 2006. 8(3-4): pp. 195-204.
[15] Ferellec, J.F. and G.R. McDowell. "Modelling of ballast–geogrid interaction using the discrete-element method". Geosynthetics International. 2012. 19(6):pp. 470–479.
[16] Lim, W.L. and G.R. McDowell. "Discrete element modelling of railway ballast'. Granular Matter. 2005. 7(1): p. 19-29.
[17] Cui, L. and C. O'Sullivan. "Exploring the macro- and micro-scale response of an idealised granular material in the direct shear apparatus'. Geotechnique. 2006. 56(7): p. 455-468.
[18] Zhang, L. and C. Thornton. "DEM simulation of the direct shear test". in 15th ASCE Engineering Mechanics Conference. June 2-5, 2002, Columbia University, New York, NY. 2002.