Micro-analysis of sub-ballast direct shearing under normal stress

Jing Guoqing[1*], Liu Guixian[1], Xu Yang[1], Zhang Jiong[2]

[1] *Civil Engineering School, Beijing JiaoTong University, Beijing, P.R. China, 100044*

[2] *School of Civil Engineering, Shandong University, Jinan, P.R. China, 250100*

Received 27 January 2014, www.tsi.lv

Abstract

This paper presents sub-ballast material analysis through Discrete Element Modelling (DEM) method to investigate its direct shear tests behaviour. Laboratory direct shear box tests were conducted on granite sub-ballast aggregate samples under different normal stress. The size, particle size distribution (PSD) properties of the sub-ballast particles were considered in the analysis. Simultaneously, direct shear box DEM simulations were conducted for different normal stress conditions, the sub-ballast micro-characteristics of the direct shearing tests were analysed, the contact force, displacement etc. index variation interrelated with the direct shearing tests conditions. The shear stress-shear displacement curves predicted from the DEM simulations were in reasonably good agreement with laboratory test results at all normal stress levels that shear box tests were conducted at. The results of discrete element modelling and tests of direct shear test for sub-ballast were presented. Such analysis may provide useful information on the understanding of sub-ballast with discrete element models. The micro-analysis and the direct shear tests were of importance to investigate the sub-ballast behaviour under the track system.

Keywords: direct shearing test; DEM; sub-ballast, normal stress

1 Introduction

Sub-ballast is a free draining granular material that helps to distribute an induced cyclic load to the underlying subgrade at a reduced and acceptable level of stress, and filter the water [1]. The sub-ballast used in most newly built railway system is intended to prevent the mutual penetration or intermixing of the subgrade and the ballast and to reduce frost penetration. The sub-ballast granular is similar to highway base material, which is fine grained-smaller than ballast and better size particles, and it was compacted tight and dense with lower voids. It is imperative and necessary that the magnitude and distribution of stresses and displacements of sub-ballast under the track should be evaluated and investigated accurately. Large-scale biaxial and triaxial tests have been carried out to study the mechanical behaviour of sub-ballast materials under static and cyclic loading. Most works have been performed on ballast [2-4]. Large-scale laboratory tests such as direct shear have been used for studying the behaviour of railway sub-ballast materials, but microscopic response study receives less attention.

This paper focuses on the microscopic analysis of the sub-ballast shear tests. For this purpose, several tests were conducted on dry, clean granite sub-ballast of high speed lines using a medium-scale direct shear apparatus. In the tests, the materials were compacted dry and subjected to normal stress and shear loading. Sub-ballast direct shear tests were conducted under 4 different normal stress levels. The results of tests were compared with the analysis of discrete element method (DEM) simulations. The paper outlines the simulations and presents tests results, overall mechanical load-deformation response. Quantitative analysis of the sub-ballast fabric using the contact normal force and distributions allowed observations on the fundamental mechanisms under the observed response. The results indicate that the normal loading influences the inherent fabric characteristics of sub-ballast.

2 Material and method

2.1 APPARATUS

A middle-scale direct shear apparatus (30×30×20 cm) was used for tests as illustrated in Figure 1 [5]. The apparatus has an upper and a lower shear box, and the sample was sheared strain-controlled by pushing the lower shear box horizontally. Two gauges were used to measure lateral displacements and shearing forces. The vertical loading applied by a hydraulic jack is transferred through the rigid reaction frame and adds on a rigid load plate that is placed on top of the sub-ballast in the upper shear box. The normal load is constant during the tests.

* Corresponding author - Tel:+86-15901173048; fax:+86-10-51683764; E-mail: gqjing@bjtu.edu.cn

FIGURE 1 Shear test box

2.2 BALLAST MATERIAL

Clean sub-ballast samples were prepared in the lower shear box by layers under the conditions similar to the field according to sub-ballast specifications. The sub-ballast material is granite, well compacted before the shearing for each test sample with the same procedure. In the numerical simulation, all the particles are irregularly clumped particles generated according to the sample of tests. The diameters range from 0.075 mm to 45 mm uniformly. The particles generated in the DEM compared with the tests were illustrated by Figure 2.

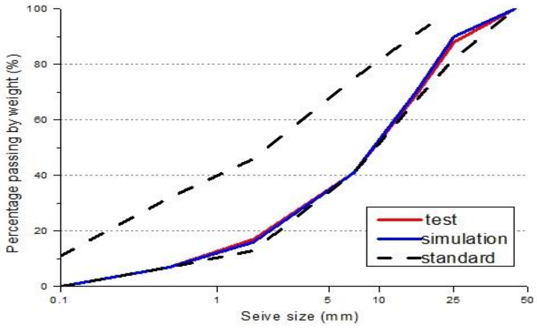


FIGURE 2 Ballast size distribution

2.3 DEM MODEL

Particle shape is one of the most important factors, which influence sub-ballast characteristics in both DEM simulations and experiments, and it is well acknowledged that the granular material (ballast and sub-ballast) shape and size is of great importance for particle interlock ability and rotation characteristics [6-8]. Clumps are efficient and precise compared with simple ball or complex polygons, and latest investigation illustrated that realistic shape to sub-ballast or ballast particles clumps were developed recently [7-10]. For this purpose, overlapping balls are used to form clumps using a simple procedure which gives control over the shape and size of the clumps, small spheres were generated and overlapped assemble according to configuration rules of irregular particles, by DEM inner language or outer assistance of software. Figure 3 presents several typical ballast particles formed by clump of balls. The box size is more than 20 times of the average particle size, so the size effects could be omitted in the simulation and tests.

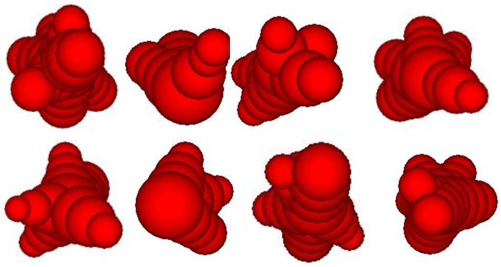


FIGURE 3 Ballast clump particles

The DEM samples were generated whose size and particle size distribution is the same as those of the tests. Once the particles were created, the gravity of the clumps was set as -9.8 m/s^2. The clumps fell to the bottom of shearing box. An equilibrium state was achieved by cycling the particle assembly. A DEM sample dimension of 30×30×20 cm was selected and treated as a representative elementary volume (REV), which consisted of 20.2 particles, and the tests' sub-ballast particle number was 57022. When the sample was generated, balanced to the equilibrium state, Then an initial compaction procedure was followed which led the sub-ballast particle assembly to the desired state before loading. All the sub-ballast sample was prepared with the same method for the tests and simulation.

Figure 4 illustrates DEM model of sub-ballast direct shear test numerical model similar to the test conditions. Direct shear condition was obtained by moving the lower boundary walls with a very slow loading rate while maintaining a constant lateral stress, which was achieved by moving the lateral walls inwards or outwards as needed. The constant volume simulation was to guarantee no volume change during the course of shearing. Under the normal force of P, the lower level of the wall was moved with a speed of 0.5mm/s till a total lateral displacement of 3.5 cm was reached in the DEM simulations. The sub-ballast contact force, number and the shearing force were recorded. The Mohr-Coulomb contact law was used in the simulations based on the ballast DEM simulations [8-10]. The contact parameters are listed on Table 1. The qusai-static and default damping value was used by manual.

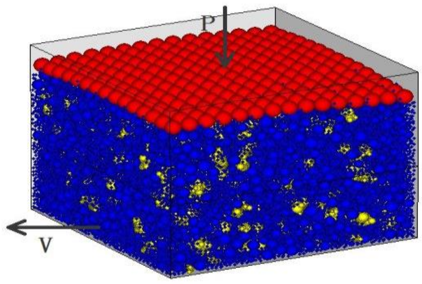


FIGURE 4 DEM model of sub-ballast direct shear test

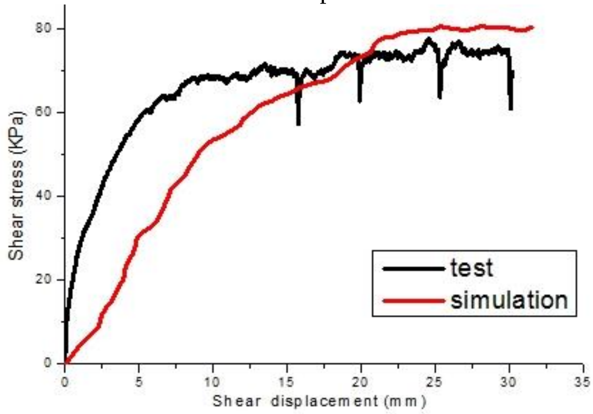
TABLE 1 Parameters used in numerical simulations

Parameters	Ballast	Wall
Tangential stiffness of particle (N/m)	5×10^8	1×10^9
Normal stiffness of particle (N/m)	5×10^8	1×10^9
Mass density (kg/m3)	2600	
Friction coefficient	0.5	
Damping coefficient	0.7	

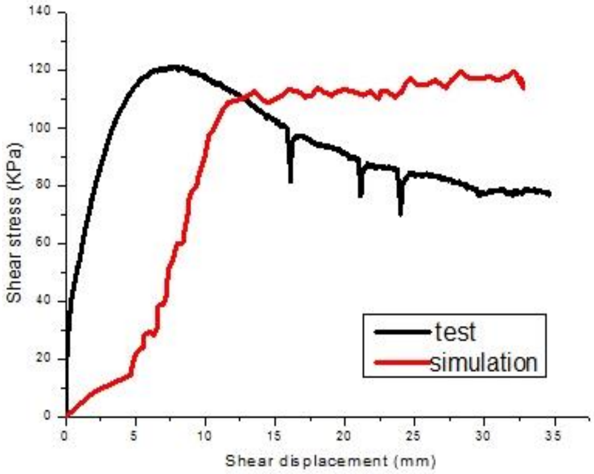
3 Results and Analysis

3.1 SHEAR STRESS AND DISPLACEMENT

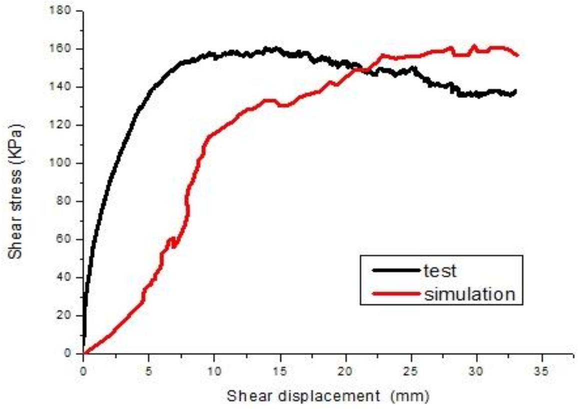
Figure 5 shows the recorded shear stresses against the shear displacements for both the laboratory and DEM simulation results under the normal stress of 50 kPa, 100 kPa, 150 kPa, and 200 kPa. Figure 5 indicates the maximum shear strength of 192.6 kPa that occurred at a horizontal displacement of 21.6 mm. The corresponding vertical stress at this deformation was 108 kPa. Thus, a maximum friction coefficient is 0.51. The results above indicate the DEM model predictions are in good agreement with the laboratory results at all normal stress levels for the clean ballast sample.



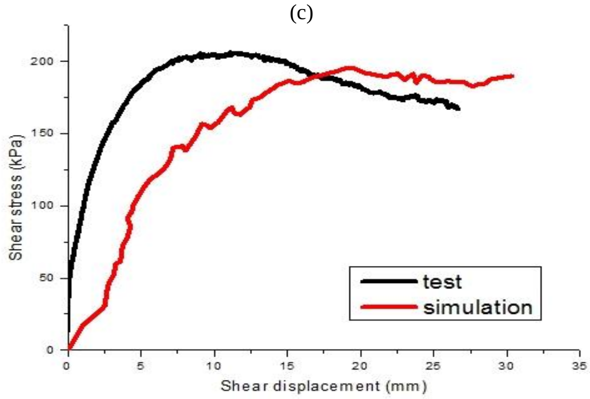
(a)



(b)



(c)



(d)

FIGURE 5 Shear force vs. displacement under different normal stress: (a) 50 kPa (b) 100 kPa and (c) 150 kPa (d) 200 kPa

3.2 PARTICAL DISPLACEMENTS

Figure 6 shows the ballast particle displacement vectors for the shear test at the displacement of 2 cm with 30 cm width of shearing box (a section of the box). The DEM results indicate that during the shearing process, the rear of the particles moved downwards with the front particles moving upwards. The movements were interrelated with the ballast contact force chain alteration discussed below. The micro-response of ballast particles under shearing displacements were presented, and could be used to further analyse the ballast-sleeper interaction as well as ballast particle response under sleeper dynamic loading.

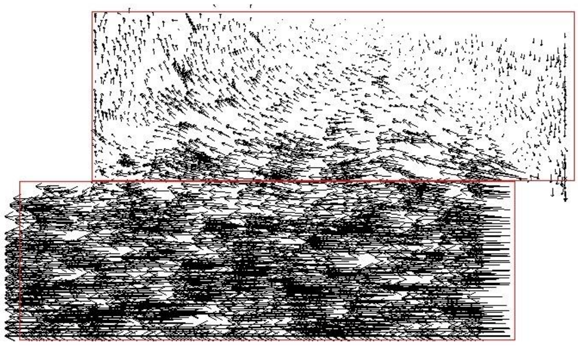
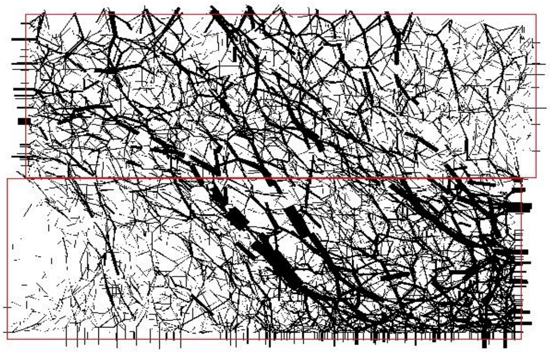


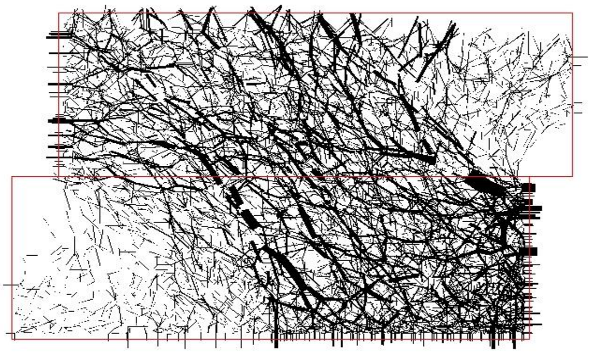
FIGURE 6 Particle displacements (lower box displacement of 2cm)

3.3 CONTACT FORCE CHAIN

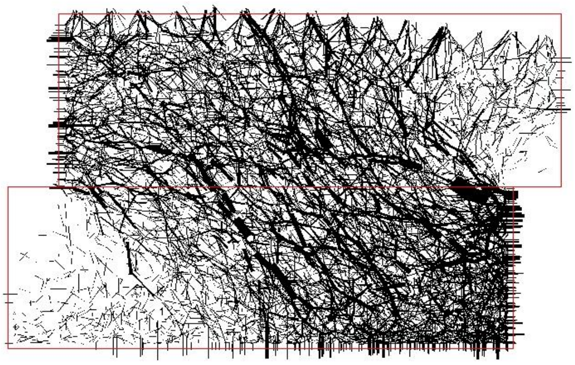
It is of importance to analyse the granular sample direct shear characteristics by investigating the fabric orientation and alteration of sub-ballast particle interlocking and contact. The contact forces were shown as lines with thickness proportional to the magnitude of the contact force. Figure 7 illustrates that with lateral increase of displacements with contact force chain evolutions. At the initial stage with zero wall displacements, the contact force was distributed uniformly throughout the whole assembly, and vertically transmitted, with the process of wall lateral displacements, the contact force chain was altered simultaneously, changing from vertically distributed into horizontally distributed, and the shear bond was observed, and the contact force and contact number were increased up to 3.5 cm displacement [10].



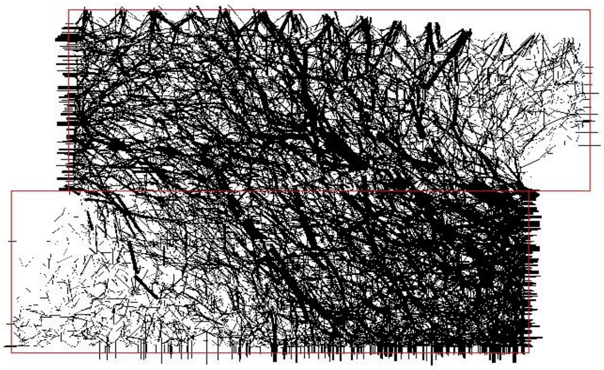
(a) Maximum contacts force: 401.8N; Average contacts force:12.1N; No. of contacts: 391912



(b) Maximum contacts force: 682.7N; Average contacts force: 12.8N; No. of contacts: 391029



(c) Maximum contacts force: 737.2N; Average contact force: 12.7N; No. of contacts: 390969



(d) Maximum contact force: 609.6N; Average contact force: 12.8N; No. of contacts: 390700

FIGURE 7 Contact force for normal stress of 200kPa
(a) 1cm; (b) 2cm; (c) 3cm; (d) 3.5cm

The microstructure changes can be represented through the coordination number (CN) and contact unit normal during the loading process. CN is a parameter to quantify and characterize the average contacts of each particle among the whole assemblage. The evolutions of CN during the shear are illustrated in Figure 8. It shows that a big decrease with the CN value occurred immediately after the shearing began. However, bigger CN values were produced under larger stress, indicating that ballast particles during the shear process were compacted. It also shows that CN values of various tests tended to become a constant as shown in Figure 8.

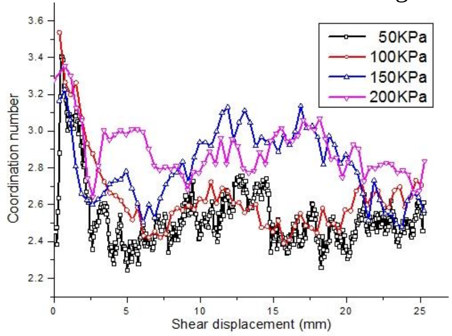


FIGURE 8 CN vs. displacement

3.4 NORMAL STRESS EFFECTS

Figure 9 presents the normal stress effects during the shearing process of sub-ballast material. The results show that the ballast shear stress increased with normal stress, especially before 1 cm of lateral displacements. The average and maximum contact force of shearing ballast, as well as contact number, coordination number under different normal stress were listed in Table 2 with upper box displacement of 1 cm. Table 2 indicates that the average contact force, maximum contact force and contact number increase accordingly as normal stress increase.

TABLE 2 Contacts variation under different normal stress (1cm displacement)

Normal stress (kpa)	Average contact force (N)	Maximum contact force (N)	Contact number	CN
50	7.3	353.1	392763	2.52
100	8.5	448.3	390153	2.61
150	11.9	409.7	387997	2.90
200	12.1	401.8	391912	2.95

Both for laboratory tests and DEM simulations, the forces T (shear force) and N (normal force) indicated as the Figure 9 were used to measure the stress ratio assuming that the T/N= τ/σ. In the DEM of direct shear tests, the force ratio was determined from the wall reaction forces shown by Figure 9 by the equation of (1). The results were listed by Table 3, indicated that higher intermediate normal stress of the ballast particles affect the contact density and distribution of contacts that provide lateral support to the force chains, indicating that higher lateral resistance was obtained with higher shear stress. But the stress ratio decreased as the normal stress increased. It indicated that the interaction of shear stress and normal stress was not linear.

$$\frac{T}{N}=\frac{Fn_1+Fn_2-Fn_3}{Fn_2+Ft_1-Ft_3} \quad (1)$$

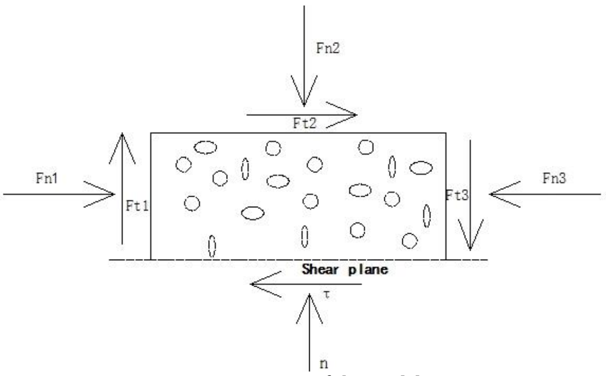


FIGURE 9 Force of the model

TABLE 3 Normal stress effects for the ratio value

Normal stress (kpa)	Maximum shear stress (kpa)	Displacement (mm)	Ratio value
50	78	26	1.56
100	109	27	1.09
150	157	28	1.04
200	197	20	0.985

The sub-ballast samples were sheared horizontally in the shear box under different normal pressures of 50, 100, 150 and 200 kPa, where the relationships between the normal stress and shear stress could be established. The maximum shear stress at failure under each applied normal pressure was recorded from each test, and indicted that the peak shear stress increased with the normal stress increasing.

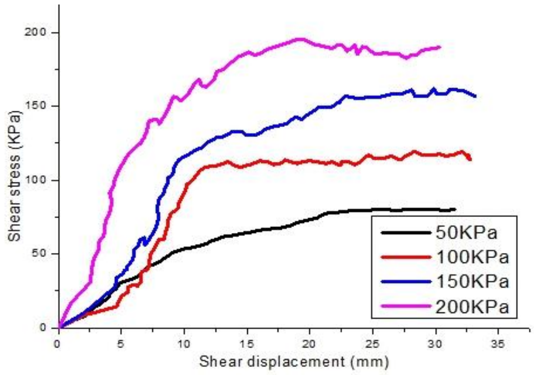


FIGURE 10 Normal stress effects of tests

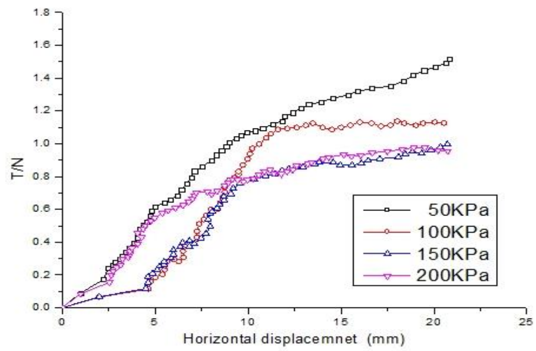


FIGURE 11 T/N vs. horizontal displacement

4 Conclusions and prospective

This paper has studied sub-ballast material response under direct shear tests. The sub-ballast granular is similar ballast, which is fine grained and smaller than ballast. The DEM simulations of biaxial shear test were developed to interpret the evolution of sub-ballast characteristics. The analysis of micro-mechanical characteristics interrelated with the DEM was studied by considering the shape of the particles, size and PSD. The shape property of sub-ballast was constructed based on irregular clumped spheres. The micro-analysis of the laboratory tests under different normal stress levels was conducted. A satisfactory agreement between discrete analysis and test results was achieved. Some conclusions are given as follows:

DEM successfully simulates the typical granular material behaviour in the direct shear compression tests, as observed from the experimental tests.

The peak angle of shearing resistance increases with the normal stress. A non-linear relationship between normal stress and response characteristics was observed. The shearing force value of sub-ballast was determined under different normal stress level, which could be referred for future track design.

Acknowledgements

This study has been carried out under financial support from NSFC (51108026, 51308324) and Fundamental Research Funds for Central Universities (2014JBM095).

References

[1] Selig E T, Waters J M 1994 *Track technology and substructure management* Thomas Telford, London

[2] Suiker A S J 2005 Static and cyclic triaxial testing of ballast and subballast *Journal of Geotechnical and Geoenvironmental Engineering* **131** 771-82

[3] Ismail and Raymond G P 2003 Monotonic load tests on layered granular aggregates, *Joint Proceedings 55th. Canadian Geotechnical Conference and 2003 North American Geosynthetics Society Conference, Winnipeg, Manitoba* **34** 1-8

[4] Wheat P, Smith A 2008 Assessing the marginal infrastructure maintenance wear and tear costs of Britains railway network *J. Transp. Econ. Policy* **42** 189-224

[5] Lings M L, Dietz M S 2004 An improved direct shear apparatus for sand *Geotechnique* **54**(4) 245-56

[6] Cundall P A, Strack O D L 1979 A discrete numerical model for granular assemblies *Geotechnique* **29** 47-65

[7] Kozicki J, Tejchman J, Mrz Z 2012 Effect of grain roughness on strength, volume changes, elastic and dissipated energies during quasi-static homogeneous triaxial compression using DEM. *Granular Matter* **14**(4) 457-68

[8] Lu M, McDowell G R 2010 Discrete Element Modelling of Railway Ballast underMonotonic and Cyclic Triaxial Loading *Geotechnique* **60**(6) 459-67

[9] Lackenby J, Indraratna B, McDowell G, Christie D 2007 Effect of confining pressure on ballast degradation and deformation under cyclic triaxial loading *Geotechenique* **5** 527-36

[10] Indraratna B, Ngo N, Trung 2011 Behaviour of geogrid-reinforced ballast under various levels of fouling *Geotextiles and Geomembranes* **29**(3) 313-22

Authors

Guoqing, Jing, born in May, 1979, Beijing, P.R. China

Current position, grades: Associate Professor of Beijing Jiaotong University, China.
University studies: He received his M.Eng. from Southwest Jiaotong University in China. He received his Ph.D. from INSA de Rennes in France.
Scientific interest: His research interest fields include railway ballast, Discrete Element Modelling (DEM).
Publications: more than 20 papers published in various journals and one book.
Experience: He has teaching experience of 6 years, has completed eight scientific research projects.

Guixian Liu, born in May, 1988, Beijing, P.R. China

Current position, grades: Graduate student of Beijing Jiaotong University, China.
University studies: He received his M.Eng. from Shijiazhuang Tiedao University in China.
Scientific interest: His research interest fields include railway ballast, Discrete Element Modelling (DEM).
Publications: 2 papers published in various journals and conference.

Yang Xu, born in April, 1987, Beijing, P.R. China

Current position, grades: Ph.D. of Beijing Jiaotong University, China.
University studies: He received his M.Eng. from Anhui Jianzhu University in China.
Scientific interest: His research interest fields include track engineering.
Publications: more than 5 papers published in various journals.

Jiong Zhan,born in August, 1980, Jinan, P.R. China

Current position, grades: Associate Professor of Shangdong University, China.
University studies: He received his M.Eng. in Environmental Engineering, Ocean University of China. He received his Ph.D. in Civil Engineering, Institute National des Sciences Appliquées (INSA) de Rennes, France.
Scientific interest: His research interest fields include, granular material and Computational Fluid Dynamics (CFD).
Publications: more than 12 papers published in various journals.
Experience: Teaching the Energy and Environment Experiments since 2008.