DEM Three-dimensional modeling of triaxial testing on railway ballast

DEM Modélisation tridimensionnelle des essais triaxiaux sur le ballast ferroviaire

Gino Vizcarra, Michéle Casagrande
Department of Civil Engineering, Pontifical Catholic University of Rio de Janeiro, Brazil, ginocalderon@hotmail.com

Sanjay Nimbalkar
Faculty of Engineering & Information Technology, University of Technology Sydney, Australia

ABSTRACT: This article presents the results of numerical simulations of cyclic loading tests conducted on particles that simulate railroad ballast. The objective of this study was to evaluate the deformation of ballast under a large number of loading cycles and to study the influence of the two different particle size distributions. One of them was according to particle size distribution recommended by Indraratna and co-workers in the past as an improvement to Australian Standard and the other was prepared in accordance with Brazilian standard. The discrete element method offers a new means of studying the response characteristics of railway ballast. The basic idea of discrete element method (DEM) is that arbitrary discontinuities are divided into a set of rigid elements, making each rigid element satisfy the equations of motion, use time step iteration method for solving the equations of motion of rigid elements, and then obtain the overall movement patterns of arbitrary discontinuities. In this study, the discrete element method of analysis has been used to simulate the geotechnical behaviour of railway ballast observed during the testing.

RÉSUMÉ : Cet article présente les résultats de simulations numériques des essais de charge cyclique effectués sur des particules simulant un ballast ferroviaire. L'objectif de cette étude était d'évaluer la déformation du ballast sous un grand nombre de cycles de charge et d'étudier l'influence des deux distributions granulométriques différentes. L'un d'eux était selon la distribution granulométrique recommandée par Indraratna et ses collègues dans le passé comme une amélioration à Australian Standard et l'autre a été préparé conformément à la norme brésilienne. La méthode des éléments discrets offre un nouveau moyen d'étudier les caractéristiques de réponse du ballast ferroviaire. L'idée de base de la méthode des éléments discrets (DEM) est que les discontinuités arbitraires sont divisées en un ensemble d'éléments rigides, rendant chaque élément rigide satisfaisant aux équations du mouvement, utilisant la méthode d'itération par pas de temps pour résoudre les équations de mouvement des éléments rigides, puis Obtenir les profils globaux de mouvements de discontinuités arbitraires. Dans cette étude, la méthode d'analyse par éléments discrets a été utilisée pour simuler le comportement géotechnique du ballast de chemin de fer observé au cours de l'essai.

KEYWORDS: Ballast, discrete elements method, gradation, railway.

1 INTRODUCTION

This article presents the results of numerical simulations of loading tests conducted on particles that simulate railroad ballast. The objective of this study was to evaluate the deformation of ballast under a number of loading cycles and to study the influence of the two different gradations. One of them was according to PSD recommended by Indraratna et al. [1] as an improvement to Australian Standard [2] and the other one was prepared in accordance with Brazilian standard [3].

The discrete element method offers a new means of studying the response characteristics of railway ballast. The basic idea of discrete element method is that arbitrary discontinuities are divided into a set of rigid elements, making each rigid element satisfy the equations of motion, use time step iteration method for solving the equations of motion of rigid elements, and then obtain the overall movement patterns of arbitrary discontinuities.

2 NUMERICAL SIMULATION

DEM is a numerical method for simulating discrete matter in a series of events called time-steps. By generating particles and controlling the interaction between them using contact models, the forces acting on all particles can be calculated. Newton´s second law of motion is then applied and the position of all particles can be calculated for the next time-step. When this is repeated, it gives the capability of simulating how particles are flowing in particle-machine systems [4].

The model used for this simulation is the Hertz-Mindlin Contact Model. In this model, the normal force component is based on Hertzian contact theory and a tangential force model is based on the work of Mindlin-Deresiewicz [5].

Figure 1 illustrates the collision between the two particles A and B using a linear spring-dashpot model which represents the elastic and non-elastic particle behavior. The total force between the particles can be divided into normal and tangential forces. Spring and damping components are available for both the forces, friction is available only for tangential component and coefficient of restitution is related to the normal force component. This model calculates the normal forces using material properties such as the coefficient of restitution, Young's modulus, Poisson's ratio, size and mass.

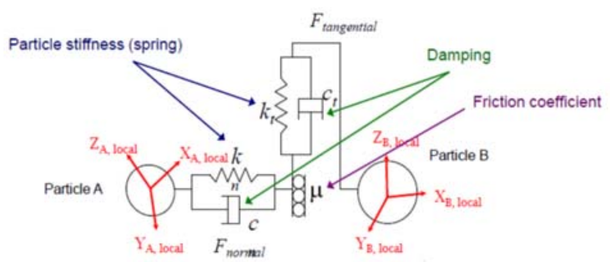

Figure 1. Schematic diagram for Hertz-Mindlin contact model [6]

3 NUMERICAL MODELING

3.1 *Model*

The model domain is the area in which simulation takes place. The EDEM Simulator stops tracking any particle that moves out of the model domain during the course of the simulation. Domain size has an effect on simulation time: the larger the domain, the longer the simulation will take to run.

This simulation was intended to recreate how inter-particle forces evolve when a granular material is subjected to a prismoidal triaxial compression test. The first step was the construction of the simulated rectangular chamber. The simulated chamber had a width of 600 mm, a length of 800 mm and a height of 800 mm (Figure 2).

It is intended to create a true triaxial model in which three major effective principal stresses (σ'_1, σ'_2 and σ'_3) can be measured independently [7-10]. Each vertical wall of the test chamber is restrained in a horizontal direction, the ballast specimen is free to deform vertically under cyclic loading. Mean parameters were used to simulate the triaxial tests (Table 1).

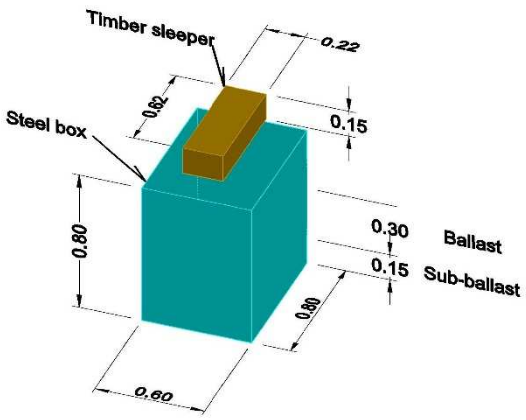

Figure 2. Schematic illustration of triaxial chamber

Table 1: Simulation parameters for the DEM simulations

Parameter	Value		
	Ballast and sub-ballast	Steel	Timber
Solid density (Kg/m^3)	2700	7800	700
Shear modulus (Pa)	2×10^9	7×10^{10}	1×10^9
Poisson´s ratio	0.35	0.3	0.3
Interface	Rock-Rock	Rock-Steel	Rock-Timber
Coefficient of static friction	0.5	0.7	0.4
Coefficient of restitution	0.2	0.25	0.38
Coefficient of rolling friction	0.001	0.001	0.001

3.2 *Particles description*

The ballast and sub-ballast were represented by a set of spheres with different diameters. Two samples were simulated with two different particle size distribution (PSD). One sample was according to PSD recommended by Indraratna et al. [1] entitled as 'Gradation A' and the other sample was prepared in order to Brazilian standard [3] entitled as 'Gradation B' (Table 2, Figure 4).

Table 1: Particle-size-distribution characteristics of materials

Diameter	Gradation A		Gradation B	
(mm)	% Mass	Particles	% Mass	Particles
		Bearing Ballast		Bearing Ballast
63	5,00	33	5,00	33
53	18,06	198	23,23	254
45	11,29	202	14,52	259
40	12,46	317	17,49	445
35	13,64	518	20,45	777
30	12,55	757	15,32	924
25	10,00	1043	3,33	347
20	12,34	2515	0,67	136
15	4,66	2248	0	0
Total		7831		3175

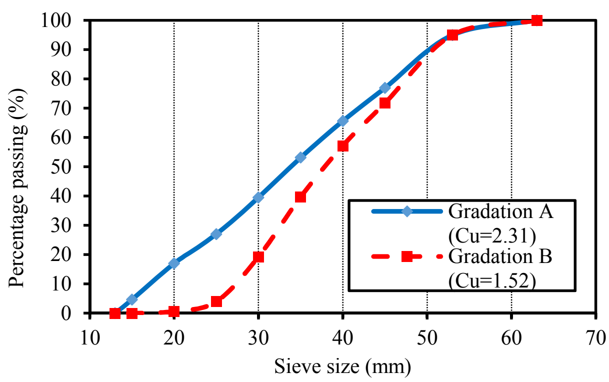

Figure 3. Particle size distribution curve for ballast material

3.3 *Time Step*

For dynamic processes, important factors to consider are the propagation of elastic waves across the particles, the time for load transfer from one particle to adjacent contacting particles, and the need not to transmit energy across a system that is faster than nature [11]. In the non-linear contact model (e.g., Hertzian), the critical time step cannot be calculated beforehand, unlike with the linear contact model in which the critical time step is related to the ratio of contact stiffness to particle density. Miller and Pursey [12] showed that Rayleigh waves or surface waves account for 67% of the radiated energy, whereas dilational or pressure waves and distortional or shear waves, respectively, are 7% and 26% of the radiated energy. The amount of energy dissipation during shearing and associated particle breakage have been discussed elsewhere [13,14,15] and this has been found to be associated with large permanent deformations usually observed in the field due to low track confinement [7].

All of the energy is assumed to be transferred by the Rayleigh waves since the difference between the speeds of the Rayleigh wave and the distortional wave is small and the energy transferred by the dilational wave is negligible [11]. The average time of arrival of the Rayleigh wave at any contact is the same irrespective of the location of the contact point. The Rayleigh time step, therefore, is the idealized DEM time step and is calculated based on the average particle size [5,11]. It is a theoretical maximum time step for a DEM simulation of a quasi-static particulate collection in which the coordination number (total number of contacts per particle) for each particle remains above 1. The detailed equations are given by Li et al. [11] and DEM Solutions [5].

In practice, some fraction of the maximum value of the idealized Rayleigh time step (equation 12) is used. For high coordination numbers (4 and above), a typical time step of 20% of the Rayleigh time step has been shown to be appropriate. However, for lower coordination numbers, 40% is more suitable [11]. The step time used in our virtual tests is 1×10^{-5} seconds, in order to resemble material´s parameters.

$$Tr = \pi r\sqrt{(\rho/G)}/(0{,}163\upsilon + 0{,}8766) \qquad (1)$$

3.4 *Stage I: creation of particles*

Particle factories are used to define where, when and how particles appear in a simulation. Any virtual surface or volume can be turned into a particle factory. For simulating the railway ballast and sub-ballast, some virtual boxes are created to be turned into a particle factory, and some associated parameters are defined. After the construction of the chamber, 22635 spheres with uniform diameter of 15 mm were generated inside to represent sub-ballast. Their positions were randomly chosen by the program, with the limitation of no overlaps between particles. After the spheres were generated, they settled down and reorganized under the action of a normal gravity field (9.8 m/s^2). This process takes 0.4 seconds (virtual time). A steel plate (virtual) settles down to compact the sub-ballast and to achieve 15 cm thickness. The ballast particles were created afterwards similarly, reaching 30 cm height at 1 second. The corresponding initial void ratios (e_0) of the ballast and subballast layers were 0.69 and 0.80, respectively. The deformation of model railroad track was analysed through these tests, whereas the effect of a particle-size-distribution was studied in terms of deformation.

3.5 *Stage II: loading*

After the creation of particles, the sleeper started to move down with a constant velocity of 10 m/s (1×10^{-4} m/step). After some displacement, it made contact with the particles and the vertical compression was started, and then, the velocity of the sleeper changed to 2×10^{-2} m/s (2×10^{-7} m/step), remaining constant until the end of the test at 4 seconds.

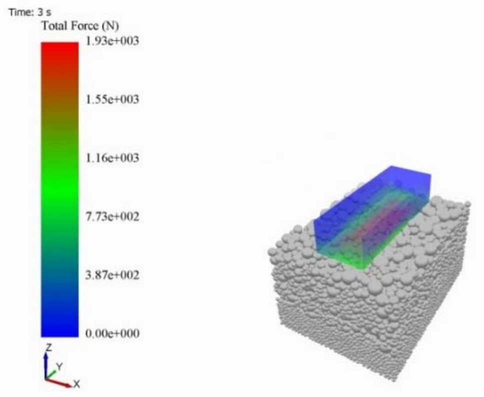

Figure 5. Test at 3 seconds (Gradation A)

4 RESULTS AND DISCUSSION

4.1 *Evolution of deformation*

The loading stage started and the particles rearranged as a result of the applied load. Fig. 6 shows the applied displacement vs. reaction force curves for the bottom face of the sleeper. The first particles with high stress were located in the middle and upper regions of the sample, and in general high stress concentrated in the upper region during the loading (Figure 7). The Figure 8 shows the evolution of contacts number along the time.

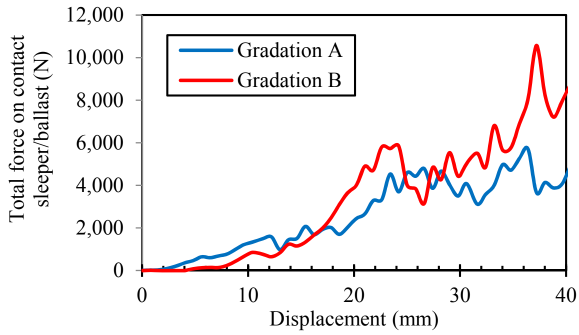

Figure 6. Total contact force acting at sleeper/ballast interface

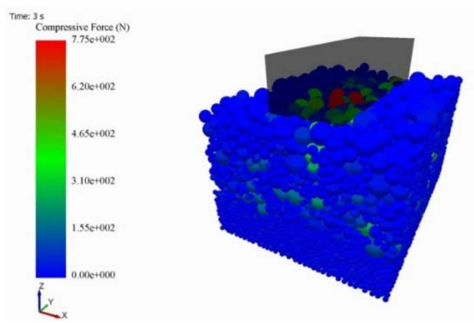

Figure 7. Compressive force of particles at time period of 3 seconds

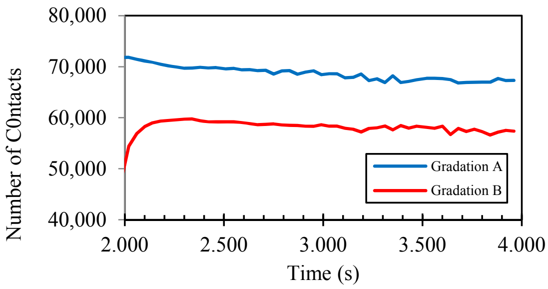

Figure 8. Number of Contacts vs. Time

4.2 *Motion Trends of Ballast Particles*

In the process of loading, stone ballast under the action of vertical force produce motion. In order to qualitatively study the behaviour of railway ballast during loading, in the process of simulation, we extract the motion trend of the stone ballasts as shown in Figure 9. It clearly shows that the stone ballasts below sleepers are moved away of sleepers to fill the voids between sleepers during loading.

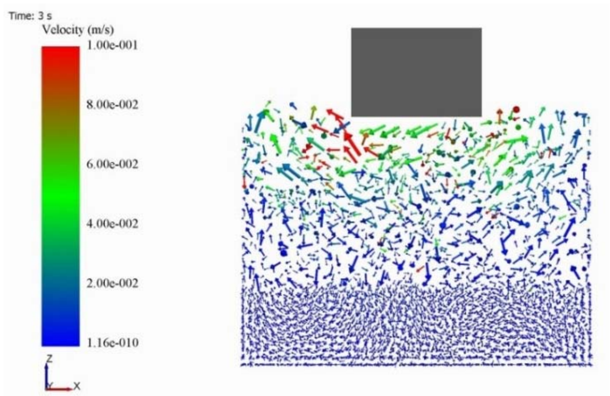

Figure 9. Velocity vectors of railway ballast during loading

4.3 *Normal overlap of particles*

One of the most important parameters in DEM simulations is the normal overlap of particles. It is suggested that average overlaps of 0.1 – 1.5 % are required to ensure most realistic results [16,17]. In these tests the maximum overlap is approximately 0.06 mm, or 0.4 % smallest particle diameter.

5 CONCLUSIONS

The discrete element analysis method has been used to simulate the geotechnical behaviour of railway ballast observed during the triaxial testing. The large-scale prismoidal triaxial apparatus was used for laboratory testing. Three dimensional numerical simulations were performed using discrete element modelling approach. It is found that the DEM predictions are in consistent with laboratory measurements.

6 ACKNOWLEDGEMENTS

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