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Abstract

In this paper, an attempt has been made to investigate the effect of particle breakage on densification behaviour of ballast under cyclic loading using Discrete Element Method (DEM). Numerical simulations using PFC2D have been carried out on an assembly of angular particles with and without incorporation of particle breakage. Two-dimensional projection of angular ballast particles were simulated using clusters of bonded circular particles. Degradation of the bonds within a cluster was considered to represent particle breakage. Clump logic was used to make the cluster of particles unbreakable. DEM simulation results highlight that the particle breakage has a profound influence on the cyclic densification behaviour of ballast. The deformation behaviour exhibited by the assembly with breakage is in good agreement with the laboratory experiments. In addition, the evolution of particle displacement vectors clearly explains the breakage mechanism and associated deformations during cyclic loading.

Keywords

ballast, dem, approach, cyclic, effect, breakage, particle, densification

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Effect of particle breakage on cyclic densification of ballast: a DEM approach

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Abstract. In this paper, an attempt has been made to investigate the effect of particle breakage on densification behaviour of ballast under cyclic loading using Discrete Element Method (DEM). Numerical simulations using PFC^{2D} have been carried out on an assembly of angular particles with and without incorporation of particle breakage. Two-dimensional projection of angular ballast particles were simulated using clusters of bonded circular particles. Degradation of the bonds within a cluster was considered to represent particle breakage. Clump logic was used to make the cluster of particles unbreakable. DEM simulation results highlight that the particle breakage has a profound influence on the cyclic densification behaviour of ballast. The deformation behaviour exhibited by the assembly with breakage is in good agreement with the laboratory experiments. In addition, the evolution of particle displacement vectors clearly explains the breakage mechanism and associated deformations during cyclic loading.

1. Introduction

Ballast layer is one of the major components of a railway track and is often subjected to complex cyclic loads. The cyclic loads from heavy hauling trains degrade and foul the ballast which directly contributes to track settlement, densification, and frequent maintenance [1]. Indraratna et al [2] reported that maintenance and rehabilitation costs of rail tracks due to problems associated with ballast performance is substantial, and several millions of dollars are being spent annually to cope with this problem worldwide. Therefore, it is important to understand ballast behaviour for optimizing the performance of ballast under all operating conditions to reduce maintenance costs.

Limited studies have been carried out using Discrete Element Method (DEM) to simulate the ballast behaviour under cyclic loading incorporating breakage under railway environments [3-6]. Most DEM softwares do not allow particle breakage as it is originally developed by Cundall and Strack [7]. Therefore various modeling techniques have been adopted by researchers, in the recent past, to simulate particle breakage:

First method is to treat each particle as agglomerate made by bonding smaller particles. Disintegration of agglomerate during cyclic loading is considered as breakage [Lim and McDowell [3], Lu and McDowell [5], Harireche and McDowell [8], Cheng et al. [9], Bolton et al [10], Indraratna et al [11]].

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Second method of simulating particle breakage is to replace the original particles with an equivalent set of smaller particles, when the original particle satisfies predefined failure criteria [Lobo-Guerrero and Vallejo [4], Hossain et al [6], Ben-Nun & Einuv [12]].

As real ballast particles are angular and of various sizes, an attempt has been made to model angular ballast particles in the current study to investigate the ballast behaviour under cyclic loading. The modeled angular particles in PFC^{2D} resemble the true shape and size of 2-D projection of field size ballast particles. The angular ballast particles were simulated using clusters of bonded circular particles and degradation of the bonds within a cluster was considered to represent breakage. These clusters were made clumps (a group of particles which behave like a rigid body and have deformable boundaries [13]) for making particles unbreakable. DEM simulation results carried out on an assembly of angular ballast particles with and without ballast breakage during cyclic loading has been reported and discussed.

2. Ballast Particle Modelling in DEM

A novel approach has been used to model an identical two dimensional (2-D) projection of the field size ballast particles. Fifteen representative ballast particles (3 from each sieve size range) of different shapes (almost rectangular, circular and triangular) were selected. The sieve sizes considered were: (i) passing 53 mm and retaining 45 mm, (ii) passing 45 mm and retaining 37.5 mm, (iii) passing 37.5 mm and retaining 31.5 mm, (iv) passing 31.5 mm and retaining 26.5 mm, and (v) passing 26.5 mm and retaining 19 mm. These are the recommended sieve sizes for railway ballast by Standards Australia [14]. The photographs of each of the selected ballast particles were taken and the images were imported into AutoCAD in a single layer. The images were then filled with tangential circles in another layer and every circle was given an identification number (ID). Identification number (ID), radius and central coordinates of each circular particle were extracted from AutoCAD in order to generate 'Balls' in PFC^{2D}. Table 1 shows the picture of some typical ballast particles created for the DEM simulations. These irregular particles were assigned name such as R1, R2, and R3 etc. as shown in Table 1.

Table 1. Representative ballast particles (after Indraratna et al [11]).

Sieve size	Ballast Particles	PFC Particles
Passing 53 mm and retaining 45 mm sieve		R1

R2

R3

3. Sample Preparation

Subroutines were developed (using the FISH Language) in PFC^{2D} after gathering the ID, radius, and coordinates of the centre of each circular particle representing angular ballast particles. These subroutines were used to generate breakable and unbreakable ballast particles for cyclic biaxial testing program. A 300 mm wide $\times$ 600 mm high biaxial cell, similar in the size to the laboratory equipment, was generated for the DEM simulations. A typical assembly considered for the cyclic biaxial tests is shown in Figure 1.

Figure 1. Initial assembly for cyclic biaxial tests (after Indraratna et al [11]).

Table 2 lists the micromechanics parameters adopted for the DEM simulations. Yang et al [17] studied the influence of parallel bond normal strength (σ_b) and shear strength (τ_b) on the strength of the bonded particles. They reported that strength of the bonded particles is influenced significantly if $\tau_b/\sigma_b < 1$. In case of modeling ballast as a bonded particle, it is unlikely to have $\tau_b/\sigma_b < 1$. Therefore, $\tau_b/\sigma_b = 1$ has been adopted in this study. A linear contact model was used for the numerical simulation program. The biaxial sample generated was given a confining pressure of 60 kPa. In order to prevent the particle breakage during compaction and isotropic stress installation for even breakable particles, the ballast particles were treated as clumps.

Table 2. Micromechanics parameters used in the DEM.

Micromechanics parameters	Values
Particle density (kg/m^3)	2500
Radius of particles (m)	$16 \times 10^{-3} - 1.8 \times 10^{-3}$
Interparticle & wall friction	0.25
Particle normal & shear contact stiffness (N/m)	3×10^8
Side wall Stiffness (N/m)	3×10^7
Top & bottom wall stiffness (N/m)	3×10^8
Parallel bond radius multiplier	0.5
Parallel bond normal & shear stiffness (N/m)	6×10^{10}
Parallel bond normal & shear strength (N/m^2)	5×10^6
Acceleration due to gravity, g (m/s^2)	9.81

After the isotropic stress state of 60 kPa, the clumps were released and parallel bonds (PB) were installed to simulate breakable particles. A parallel bond (PB) approximates the physical behaviour of a cement-like substance joining the two particles. In the current study, the ballast breakage is defined when the induced maximum tensile and shear stresses acting on the periphery of the bond exceeds or equal to the normal & shear strength of parallel bonds [13].

4. Cyclic Biaxial Tests

A subroutine was developed to apply a stress-controlled cyclic biaxial test at the desired frequency (f) and amplitude of cyclic loading. Figure 2 shows a typical sinusoidal loading curve [11] used in the DEM simulations. The minimum cyclic stress (q_{min}) was kept at 45 kPa which represents the unloaded state of the track (such as the weight of sleepers and rails) [15]. The cyclic deviatoric stress (q_{cyc}) applied to the ballast were estimated in accordance with Esveld [16]. Cyclic biaxial tests at a frequency of 20 and 40 Hz were simulated on an assembly consisting both unbreakable and breakable particles. Data such as settlement (s), bond breakage (B_r) were recorded every number of cycles (N).

Figure 2. Applied cyclic loading in the biaxial tests (after Indraratna et al [11]).

5. Results and Discussions

Figure 3 explains the role of particle breakage on cyclic densification behaviour of ballast with number of cycles (N) at 20 and 40 Hz frequencies (f). It can be seen that the maximum densification observed in case of unbreakable particles is 12 and 17 mm at $f = 20$ and 40 Hz while for breakable particles they are around 45 and 67 mm, respectively, at the end of 1000 cycles (Figure 3). Also, it is to be noted that the number of cycles required to reach stable permanent deformation depends on the breakability of the particles. For example, for unbreakable particles the stable zone is reached around 100 cycles whereas in case of breakable particles, it is around 400 cycles.

Figure 4 illustrates the effect of particle breakage, expressed in terms of broken bonds (B_r), on cyclic densification of ballast. Broken bonds (B_r) has been defined as a percentage of bonds broken compared to the total number of bonds present in the initial assembly. It can be seen that the shape of the densification curve and breakage curve is very similar which signifies that particle breakage has direct and significant effect on cyclic densification behaviour of ballast. Rapid deformation of the assembly in the initial cycles of loading in case of unbreakable particles (Figure 3) is mainly governed by rolling and sliding of particles, however, in case of breakable particles, it is largely dominated by breakage. Once the particles are broken, they roll, slide and fill the nearby voids causing more densification and as a consequence more sample deformation. When particles breakage is seized ($N > 400$), permanent deformation of the sample is almost stable. At $f = 20$ Hz, it is almost constant after $N = 400$, however, it is still increasing for $f = 40$ Hz.

Figure 3. Comparison of cyclic densification (breakable and unbreakable particles).

Figure 4. Effect of bond breakage on cyclic densification (data from Indraratna et al [11]).

Figure 5 illustrates the evolution of displacement vectors for both assemblies of unbreakable and breakable particles during cyclic loading. It is evident from the Figure 5 that cyclic densification is more pronounced for assembly having breakage. During cyclic loading the unbreakable particles tend to move along the direction of major principal stress direction (Figure 5a). However, for assemblies with breakage, degradation of bond, has concentrated in the direction of particles movements (Figure 5b). This may be attributed due to the decrease in coordination number of the particles due to the rearrangement of the particles, which might have created high tensile stresses in the ballast particles. The particle breaks when the induced tensile stress exceeds the tensile strength of the particle.

Figure 5. (a) Displacement vectors for unbreakable particles (b) Displacement vectors and position of bond breakage for breakable particles.

Figure 6 shows the comparison between the cyclic densification obtained from the DEM simulations and the large-scale laboratory experiments carried out by the authors at the University of Wollongong. It can be seen that the cyclic densification behaviour observed in the DEM considering breakable particles is similar to that has been observed in the laboratory.

Figure 6. Comparison of DEM results with the experiment.

6. Conclusions

In this paper, DEM simulation results on the influence of ballast breakage and associated deformation during cyclic loading are presented. DEM simulations were carried out on an assembly of angular ballast particles with and without breakage. A novel approach has been developed to model 2-D shape of real ballast particles using DEM. It has been observed that particle breakage has a profound influence on the cyclic densification behaviour of ballast. Unbreakable particles modeled to simulate the cyclic densification often underestimate the permanent deformation experienced by real ballast

particles. However, breakable particles exhibit the densification behaviour similar to that observed in the laboratory experiments. The rapid initial deformation exhibited by the breakable ballast sample can be attributed due to particles breakage, rolling and sliding into the adjacent voids. Moreover, the decrease in coordination number of the particles due to the movement of the particles during cyclic loading creates high tensile stresses in the ballast particles and ballast breaks when the induced tensile stress exceeds the tensile strength of the particle.

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