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Breakage and shape analysis of ballast aggregates with different size distributions

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ABSTRACT

Particle breakage usually alters the size and shape of ballast aggregates, which significantly influences the long-term performance of rail tracks. This study reports an investigation on the breakage and shape characteristics of ballast aggregates subjected to monotonic and cyclic triaxial tests with two different load frequencies. The results show that particle breakage is not only influenced by the particle size distribution but also by the relative density. Breakage indices defined by breakage potential and grading entropy fail to characterize the breakage extent of ballast with multiple initial particle size distributions, while the Marsal breakage index exhibits a general decrease with increasing coefficient of uniformity for ballast with similar relative densities. Higher breakage extent is observed in ballast subjected to a higher load frequency. Particle shape varies with load frequency because of breakage. A slightly higher value of each shape index is observed for ballast subjected to a higher load frequency, implying that ballast aggregates become increasingly regular with the increase of load frequency.

Introduction

Particle breakage usually occurs in angular aggregates even at low confining pressures (Agustian & Goto, 2008; Lackenby, Indraratna, McDowell, & Christie, 2007; Lade, Yamamuro, & Bopp, 1996; Liu & Zou, 2013; Sun, Indraratna, & Nimbalkar, 2015). Aggregates become increasingly rounded during monotonic and cyclic loading because of particle breakage. It has been demonstrated that particle breakage significantly influences the strength and deformation behaviors of granular soils, including railroad ballast (Anderson & Key, 2000; Indraratna, Ionescu, & Christie, 1998), rockfill (Fu, Chen, & Peng, 2014; Xiao, Liu, Chen, & Jiang, 2014), and sand (Luzzani & Coop, 2002; Vilhar, Jovičić, & Coop, 2013). To study the influence of particle breakage on the strength and deformation characteristics of granular soils, many theoretical and experimental studies have been conducted. For example, McDowell and Bolton (1998) proposed a fractal theory for particle crushing and suggested that larger particles with high probabilities of internal flaws and particle angularity would increase the extent of particle breakage during monotonic loading. Dilation and shear strength were reduced when particle breakage increased (Indraratna et al., 1998). Unlike clay, particle breakage would also translate vertically and even rotate the critical state line of granular soils (Xiao et al., 2015).

For samples with a given particle size distribution (PSD), particle breakage was observed to shift the initial PSD of the granular soil towards an ultimate PSD in which particles were distributed fractally (Einav, 2007a, 2007b). It has also been recognized that particle breakage increases monotonically with increasing loading stress and strain. Less breakage can be expected as the PSD approaches the ultimate fractal distribution. Aggregates with lower angularity tend to experience less internal breakage. However, until now, most studies on particle breakage have been conducted on samples with the same fixed initial PSD. There have been some studies (Cunningham, Evans, & Tayebali, 2013; Kim, Tutumluer, Little, & Kim, 2007; Sevi & Ge, 2012; Sitharam & Nimbkar, 2000) concerning the influence of PSD on the mechanical response of granular soils. However, fewer studies have been conducted into the variation of particle breakage with varying initial PSDs (Carrera, Coop, & Lancellotta, 2011; Indraratna, Khabbaz, Salim, & Christie, 2006; Indraratna, Lackenby, & Christie, 2005; Li, Liu, Dano, & Hicher, 2014). Sun (2017) performed a series of large-scale cyclic triaxial tests on railroad ballast with multiple initial PSDs and suggested

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Table 1
Physical properties and test conditions of ballast.

PSD No.	e_0	$e_{\min}$	$e_{\max}$	R_d	C_u	d_M (mm)	d_{60} (mm)	d_{50} (mm)	d_{30} (mm)	d_{10} (mm)	d_m (mm)	Cycles (N)
1	0.78	0.71	1.03	0.77	1.2	53	50.3	49.4	46.9	41.9	2.36	500,000
2	0.78	0.67	0.97	0.63	1.5	53	47.2	45.3	40.3	31.4	2.36	500,000
3	0.75	0.60	0.91	0.52	2.0	53	43.4	40.4	33.1	21.6	2.36	500,000
4	0.75	0.55	0.86	0.35	2.5	53	40.7	37.1	28.5	16.3	2.36	500,000
5	0.82	0.71	1.02	0.63	1.2	53	50.3	49.4	46.9	41.9	2.36	500,000
6	0.71	0.60	0.91	0.63	2.0	53	43.4	40.4	33.1	21.6	2.36	500,000
7	0.66	0.55	0.86	0.63	2.5	53	40.7	37.1	28.5	16.3	2.36	500,000
8	0.62	0.51	0.82	0.63	3.0	53	38.4	34.2	24.9	12.8	2.36	500,000
9	0.57	0.45	0.77	0.63	4.0	53	34.4	29.6	19.5	8.6	2.36	500,000
10	0.53	0.43	0.72	0.63	4.5	53	32.4	27.2	17.1	7.2	2.36	500,000
11	0.75	0.58	0.92	0.50	1.9	53	52.3	40.8	40.7	22.3	9.5	500,000
12	0.75	0.61	0.93	0.56	1.9	45	43.7	34.6	33.7	19.5	9.5	500,000
13	0.75	0.62	0.93	0.58	1.9	40	37.1	30.5	28.6	17.2	9.5	500,000
14	0.75	0.62	0.93	0.58	1.9	37.5	32.7	28.4	25.1	16.1	9.5	500,000
15	0.75	0.63	0.94	0.61	1.9	31.5	30.5	22.7	23.4	13.0	9.5	500,000
16	0.76	–	–	–	1.5	53	41.1	39.5	34.2	26.8	16	Monotonic

two breakage zones, namely a high breakage zone and a reduced breakage zone, according to the coefficient of uniformity of the railroad ballast. However, the mechanisms for particle breakage and the applicability of the different breakage indices were not studied comprehensively.

In this paper, the breakage behavior of ballast aggregates with different initial PSDs under both monotonic and cyclic triaxial tests is studied. Samples with different PSDs are prepared based on two categories: similar void ratio and similar relative density. The applicability of nine different breakage indices in evaluating the breakage mechanism for railroad ballast with different initial PSDs is investigated. Variations of the particle shapes are evaluated by using a three-dimensional (3D) laser scanner to study the shape of ballast aggregates before and after testing.

Materials and methods

The railroad ballast used in this study was taken from the Bombo quarry located in New South Wales, Australia. It contained primarily augite, feldspar minerals, and plagioclase (Sun, Indraratna, & Nimbalkar, 2014). The physical attributes of the ballast were evaluated by standard testing procedures according to AS 2758.7 (1996) and can be found in Indraratna et al. (1998). Table 1 lists the details of each PSD in this study, such as the minimum (d_m) and maximum (d_M) particle sizes as well as the coefficient of uniformity (C_u), along with physical properties such as the initial void ratio (e_0) and relative density (R_d).

A large-scale triaxial apparatus (Geolab Ltd, Australia) was used to investigate the effect of PSD on the particle breakage characteristics of ballast under both monotonic and cyclic loading. The ballast aggregates were first sieved and divided into 10 size ranges (Fig. 1) before being carefully washed and air-dried under natural sunlight. After that, the aggregates were weighed separately according to each PSD shown in Fig. 1 and then re-mixed together. Samples were then prepared by placing the mixed ballast aggregates inside a lubricated rubber membrane in four layers to achieve the value of e_0 or R_d given in Table 1. Each sample was prepared by layered compaction to achieve the target thickness as calculated based on each e_0 and R_d value. The prepared sample had a final height of 600 mm and diameter of 300 mm before being tested. The sample was then saturated by allowing water to pass through the base of the triaxial cell and using a top drainage system to remove any air voids.

The confining pressure (σ'_3) was then applied. For the monotonic drained triaxial compression test, an axial strain rate of 3 mm/min was used, during no excess pore water pressure was found to develop. The test data were recorded by a computer-controlled data acquisition system with pressure transducers and a linear variable differential transformer (LVDT). Tests were suspended when the axial strain reached around 30%. Details of the monotonic tests can be found in Table 2. Cyclic tests were carried out by using a harmonic (sinusoidal) cyclic load with a maximum deviator stress ($q_{\max}$) of 230 kPa and a minimum deviator stress ($q_{\min}$) of 45 kPa. These represent the stresses exerted by a 25-ton axle load and an unloaded track superstructure, respectively (Sun et al., 2015). Two different load frequencies (f), 20 and 30 Hz, were used for each PSD. Cyclic loading was applied up to either 500,000 cycles or when the axial strain exceeded 30%. The detailed testing procedures were discussed comprehensively by Indraratna, Sun, and Nimbalkar (2016). Following ASTM C 136 (2006), each sample was sieved by a set of 12

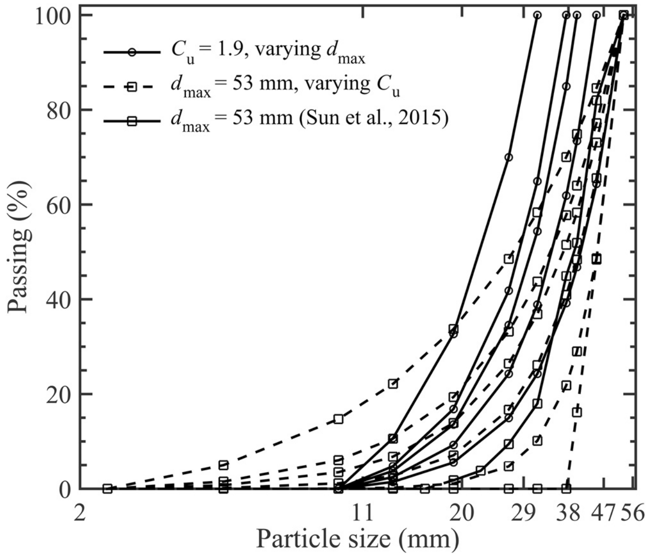

Fig 1. Particle size distributions of ballast.

Table 2
Monotonic triaxial testing program (modified according to Indraratna et al. (2014)).

Test No.	e_0	Confining pressure (kPa)
1	0.76	30
2	0.76	60
3	0.76	180
4	0.76	240
5	0.76	300
6	0.76	360
7	0.76	420
8	0.76	570

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