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Identification of ballast grading for rail track

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ABSTRACT

Grading has long been recognised to critically influence the mechanical behaviour of ballast. To identify the ballast grading for heavy-haul rail track, monotonic and cyclic triaxial tests are conducted to assess the performances of different gradings. Permanent deformations, aggregates degradation, resilience, shear resistance, maximum and minimum densities are recorded and analysed. The grading is found to affect the behaviour of ballast in that coarser gradings exhibit relatively better strength, resilience and therefore less permanent deformation. However, ballast degradation increases with the overall aggregate size. Therefore, to identify the grading for ballast with different performance objectives, a grey relational theory is used to convert the multi-objective into single-objective, i.e. grey relational grade. A relatively optimal grading that provides the highest grey relational grade is thus suggested for the improved ballast performance.

1. Introduction

The foundation of Australian railroad mainly consists of uniformly graded ballast placed between and underneath the sleepers. The purpose of using ballast is to ensure fast drainage and reduce the magnitudes of vertical stress distributed to the underlying weak subgrade from heavy loading trains (Suiker et al., 2005). In recent years, increasingly faster and heavier trains have been used which inevitably compromise the stiffness and drainage capacity of ballast due to significant aggregate degradation and mud pumping (Indraratna et al., 2013). Increased track differential settlements and fouling were thus often encountered in ballast with uniform gradings adopted from the Australian Standard DR 05328 (1996).

To improve the ballast performance for modern high-speed tracks, a variety of methods have been used, such as the application of winged sleepers or intermittent lateral restraints to provide higher restriction of ballast aggregates (Lackenby et al., 2007; Esmaeili et al., 2016), polyurethane polymer reinforcement of ballast to increase track resilience (Kennedy et al., 2013), and the utilisation of geosynthetics to increase particle interlocking within ballast (Yang and Han, 2013; Biabani and Indraratna, 2015). As can be seen, most of these methods were aimed to improve the confinement existing ballast aggregates and substructures. Limited attention (Bian et al., 2016; Indraratna et al., 2016) has been paid to fundamentally modifying the ballast aggregates themselves, i.e. the gradings for better track performance. However, grading has long been recognised as one of the most important characteristics that directly influence the mechanical performance of ballast, e.g. the drainage (Bian et al., 2016), shear resistance (Indraratna et al., 2016), stiffness (Indraratna et al., 2009), deformation (Sevi and Ge, 2012), and particle breakage (Yin et al., 2017). A proper design of the grading for railroad ballast should not only take into account the large voids for providing adequate drainage but also consider the structural stability for track operation. According to Thom and Brown (1988), an increase in the coefficient of uniformity (C_u) of granular aggregates would result in increases of the sample density and friction angle; but it would also significantly decrease the drainage capacity and stiffness of the sample. In addition, Indraratna et al. (2016) observed a reduced breakage with the decreasing particle size and increasing C_u while the permanent deformation was shown to have an opposite trend. Therefore, optimisation of ballast grading should not merely rely on a single objective and factor, for instance, particle breakage or coefficient of uniformity. To avoid unfavourable outcomes, it should consider as many main controlling factors (coefficient of uniformity, C_u;

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maximum and median particle sizes, d_M and d_{50}; etc.) and objectives (permanent radial and axial strains, ε_3 and ε_1; particle breakage ratio, B_g; resilient modulus, M_r; shear strength, ϕ_f; density, ρ_d; etc.) as possible.

Ideally, an optimal grading for railroad ballast should be determined by testing all the potential combinations of different particle fractions. The optimum grading is the one that has proper factors to provide the best balance among different objectives. However, due to the complicated interactions of different particle fractions (Tutumluer et al., 2009) and time-consuming processes through either experimental or numerical approaches, it is unlikely that one can perform a complete study of every possible grading encountered. In fact, this incompleteness of available test results can be regarded as a fundamental characteristic of an unascertained system that can be described by using specific mathematical approaches, e.g. fuzzy mathematics, probability approach, genetic algorithm (Levasseur et al., 2008), and grey system theory (Liu et al., 2012). Fuzzy mathematics concentrates on investigating problems with cognitive uncertainty by making use of experience or membership function. Probability approach studies the phenomena of stochastic uncertainty with emphasis placed on the historical statistical laws. It requires the availability of large number of reliable samples to satisfy a typical form of distribution, which may be unfavourable in geotechnical engineering. The focus of grey system theory is on the uncertainty problems of samples with small discrete data and multi-objective that are difficult for probability or fuzzy sets to handle. No typical distribution of samples is needed. Due to the impossibility for one person to perform a large number of reliable large-scale triaxial tests on ballast with different gradings (>30 for each factor) in a reasonable time, the grey system theory is employed in this study to optimise the grading for railroad ballast. However, it should be noted that the genetic algorithm proposed by Levasseur et al. (2008) and later comprehensively modified by Jin et al. (2016, 2017) can be also applied to optimising the ballast grading. This method is based on Darwin's theory of evolution (Yin et al., 2016). It enables the convergence of a set of solutions close to the best one even with a flat or noisy error function. Undoubtedly, this algorithm is more advanced when compared to the grey system theory employed in this study. However, as pointed out by Levasseur et al. (2008), the calculation cost of this method is high. "*It is necessary to perform a lot of finite element calculations at the beginning of the optimisation process in order to have a good view of the error function in the search space. This sweep, which is essential for the genetic algorithm efficiency, makes this method very expensive if there is only a few parameters to identify*" (Levasseur et al., 2008). Therefore, in this study where three grading parameters (C_u, d_M, d_{50}) are evolved for optimisation, the grey system theory is preferred.

This paper is a follow-up study of the authors' previous work (Sun et al., 2014, 2017; Indraratna et al., 2016). More analyses and discussions on the experimental results by Sun (2017) are presented in 5 sections. In Section 2, laboratory investigation of the influences of different factors on several main objectives is summarised. Section 3 deals with the implementation of the grey relational analysis (GRA) in optimising the grading of railroad ballast. In Section 4, several modifications are suggested for reduced ballast breakage and deformation. Finally, Section 5 concludes the paper.

2. Laboratory investigation

2.1. Test materials

The ballast aggregates were collected from a quarry located in Kiama, New South Wales, Australia with coordinates of 34°40′15″S and 150°51′15″E. Its physico-mechanical properties were measured according to ASTM D2434-68 (2006a), ASTM D4254-14 (2014a), ASTM D4253-14 (2014b) and can be found elsewhere in Sun (2017) and Indraratna et al. (1998). Table 1 lists the different grading alternatives used in this study. As can be seen, the grading alternatives can be divided into two different groups, i.e. constant C_u with varying d_M and constant d_M with varying C_u.

2.2. Sample preparation and test procedure

The effect of grading on the deformation and degradation behaviour of ballast was studied by using the large-scale triaxial apparatus (Sun, 2017). Aggregates with different particle sizes but similar shapes (Sun et al., 2014) were firstly washed and then sieved separately. They were remixed together according to the target weight being calculated. After that, a 5 mm rubber membrane was lubricated and wrapped inside a split cylindrical mould. Aggregates were then put inside and compacted by four equal layers to the target sample height and diameter (600 mm × 300 mm). Then, the sample was placed inside a cell pressure chamber where water was slowly injected from the base of the cell under a back pressure of 10 kPa and air voids were all removed from the top of the cell to saturate the sample.

All the monotonic compression tests were carried out under the fully drained condition at a constant axial strain rate (0.05 mm/s). By doing this, no excess pore water pressure was observed during the test. Test data were collected by using installed pressure and displacement transducers as shown in Sun et al. (2015), thus not repeated here for simplicity. Triaxial compression was stopped until the axial strain (ε_1) arrived at 0.3. Moreover, cyclic tests were carried out by using the fixed minimum and maximum deviatoric stresses, i.e. q_{min} = 45 kPa and q_{max} = 230 kPa (Sun et al., 2017). A sinusoidal cyclic stress with two different frequencies (f = 20 Hz and 30 Hz) was used. Note that the frequency was determined by $f = V/L$, where V (=144 km/h and 212 km/h) was the train speed and L (=2.02 m) was the characteristic length between axles (Sun et al., 2015). Cyclic test was suspended until the number of load cycles equal to 500,000 or stopped at ε_1 = 0.3. Permanent deformation data were recorded at the end of each test. Membrane correction was used when measuring the current stress and strain according to ASTM D4767-11 (2011). Particle breakage before and after the

Table 1
Properties of different samples.

Alternative no.	e_0	R_d	C_u	d_M (mm)	d_{60} (mm)	d_{50} (mm)	d_{30} (mm)	d_{10} (mm)	d_m (mm)
1	0.75	0.5	1.9	53	52.3	40.8	40.7	22.3	9.5
2	0.75	0.56	1.9	45	43.7	34.6	33.7	19.5	9.5
3	0.75	0.58	1.9	40	37.1	30.5	28.6	17.2	9.5
4	0.75	0.58	1.9	37.5	32.7	28.4	25.1	16.1	9.5
5	0.75	0.61	1.9	31.5	30.5	22.7	23.4	13	9.5
6	0.78	0.77	1.2	53	50.3	49.4	46.9	41.9	37.5
7	0.78	0.63	1.5	53	47.2	45.3	40.3	31.4	4.75
8	0.75	0.52	2	53	43.4	40.4	33.1	21.6	2.36
9	0.75	0.35	2.5	53	40.7	37.1	28.5	16.3	2.36
10	0.75	0.23	3	53	38.4	34.2	24.9	12.8	2.36
11	0.72	0.16	4	53	34.4	29.6	19.5	8.6	2.36
12	0.7	0.07	4.5	53	32.4	27.2	17.1	7.2	2.36
13	0.82	0.63	1.2	53	50.3	49.4	46.9	41.9	37.5
14	0.71	0.63	2	53	43.4	40.4	33.1	21.6	4.75
15	0.66	0.63	2.5	53	40.7	37.1	28.5	16.3	2.36
16	0.62	0.63	3	53	38.4	34.2	24.9	12.8	2.36
17	0.57	0.63	4	53	34.4	29.6	19.5	8.6	2.36
18	0.53	0.63	4.5	53	32.4	27.2	17.1	7.2	2.36

Note: e_0 is the initial void ratio; R_d is the initial relative density; d_{60}, d_{30} and d_{10} are the aggregate diameters at 60%, 30% and 10% passing, respectively; d_m is the minimum aggregate diameter.