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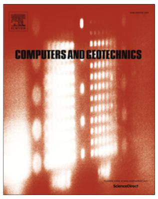

Research Paper

Discrete element modeling of the single-particle crushing test for ballast stones

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ABSTRACT

In this paper, a discrete element modeling approach for the single-particle crushing test for irregularly shaped ballast stones is presented. Bonded spherical particles are used to represent test specimens. Parametric studies focusing on particle size, axial strain rate, particle aggregate size and number of bonds are performed. The selection criteria of these parameters are discussed from the perspective of railway engineering. The results indicate that the proposed modeling approach is reliable for simulating railway ballast stones and can thus be further used for simulations of ballast aggregations.

1. Introduction

The ballast track degrades under the influence of continuous traffic loads. The degradation induces settlement of the ballast layer and a reduction of the hydraulic conductivity, which is an inducement of mud pumping, consequently causing a loss of track elasticity and obligatory maintenance work. To comprehend the mechanism of the ballast track degradation, the mechanism of single-ballast breakage should be first investigated. On the one hand, the single-particle crushing test is usually enforced. The test applies a uniaxial compression force to the specimen via two flat steel plates. Consequently, tensile stresses are introduced to the specimen, and breakage is caused [1–3]. The force necessary to break the specimen and the breakage behavior depend on the material and form (size and shape). On the other hand, simulations based on the Discrete Element Method (DEM) are often used due to its superior capability to simulate granular materials and their ruptures. Within the simulation, the pressing plates are usually represented by rigid walls, which are either speed or force controlled, while the specimen is simulated either by a Bonded Particle Model (BPM), which is an aggregate of particles with removable bonds [4], or by geometries (i.e., polyhedrons, spheres, etc.), where the breakage is embodied by replacing the original geometry with several smaller pieces [5,6]. The BPM is more straightforward because it does not need a complex algorithm to decide the direction and sizes of fragments of the breakage. Nevertheless, the method can be computationally expensive since it calculates the motions of numerous particles at every time step. Meanwhile, multiple tests need to be performed to find an appropriate particle size. However, with a high-performance computer, the problem of computational burden can be eased.

Several DEM simulations of the single-particle crushing test have been performed by researchers using the BPM. Lim studied the Weibull survival probability of granodiorite ballast samples with hexagonal close packing [7]. On the basis of Lim's research, Ergenzinger researched the Weibull survival probability of ballast DEM representations with random polyhedral packing [4]. Wang investigated shielding and the size effect of sand stone [8]. However, these research studies either had a lack of experimental verification or used a geometrically regular-shaped packing of particles, which is not the realistic shape of a ballast stone. A test-verified model using a realistic form of packing has not yet been investigated.

In this paper, the single particle crushing test for ballast stones is simulated by using BPMs with polyhedral packing, which have forms identical to the specimens used in the test. The simulation is calibrated with the test performed by the Material Testing Institute (MPA) at the University of Stuttgart, in collaboration with the Institute of Railway and Transportation Engineering (IEV). The DEM software Particle Flow Code (PFC) is chosen to perform the simulation. Three basalt ballast stones are chosen as specimens for the calibration. The modeling is accomplished on the basis of the material-modeling support in PFC, with necessary improvements to fit the simulation needs of the irregularly shaped ballast stones. Using one of the three calibrated models, parametric studies with respect to particle size, axial strain rate, BPM size and number of bonds are performed. The results of these studies are discussed in detail.

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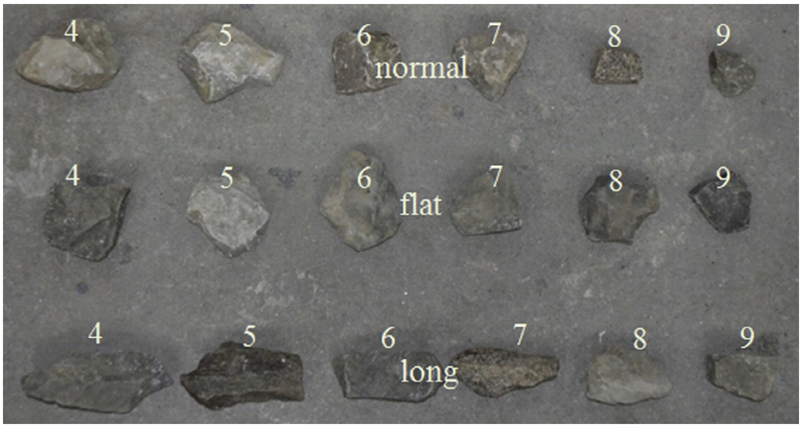


Fig. 2.1. Used ballast stones selected for the crushing test (the top three largest ballast stones with coloring are not included).

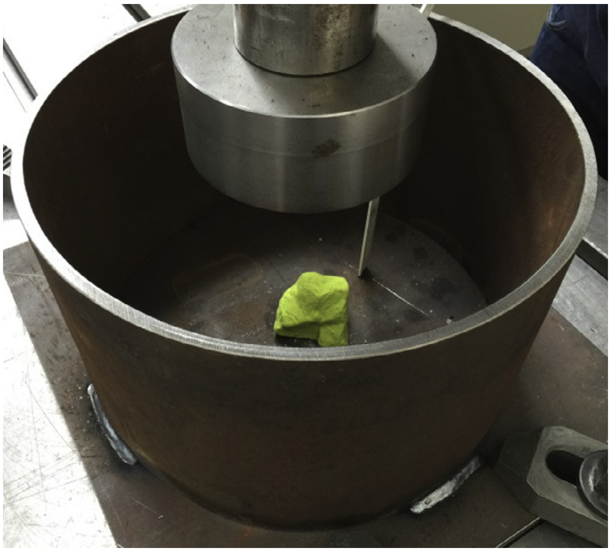
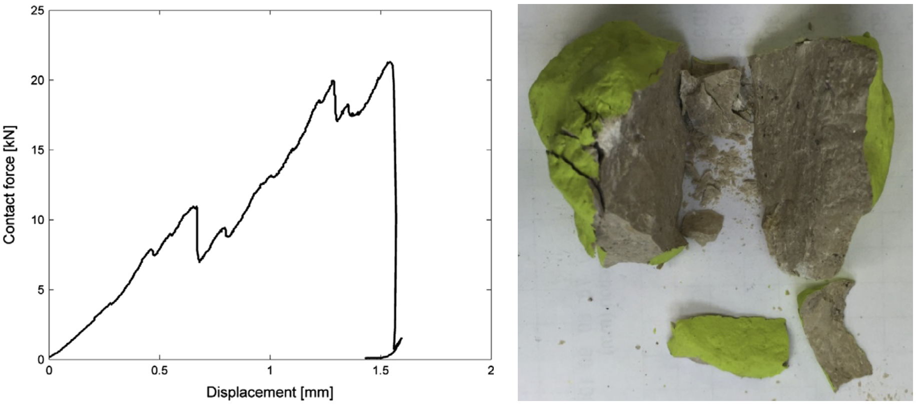


Fig. 2.2. Single-particle crushing test setup.

2. The single-particle crushing test for ballast stones

Two criteria were set for selecting the samples in the test: (1) the sample should be generally convex so that the influence of multiple contacts can be reduced as much as possible; (2) the sample should not tilt before the test, which means that the upper contact (usually a point) and the bottom contact (usually a notional face formed by three points) are vertically aligned. The specimens were categorized into six groups according to their service conditions and shapes (service conditions: new and used; forms: normal, long and flat). Each group had nine ballast stones, arranged and numbered by size (see Fig. 2.1). The ballast stones were first placed individually in a steel cylinder and then crushed by a pressing plate at a speed of 0.5 mm/min (see Fig. 2.2). The largest three ballast stones of each group were colored (used ballast stones were colored in blue, while new ballast stones were colored in yellow) so that a clear behavior of breakage and the contact point could be seen after the test (see Fig. 2.4, a1 and b1).

It is important to note that the surfaces of ballast stones are coarse; a perfectly smooth face cannot be found for the placement of the sample. Even though convex samples are used, multiple contacts cannot be eliminated totally. From the test result, it was noted that there were several non-linear force-displacement curves, indicating an excessive displacement of the pressing plate (see Fig. 2.3). This was caused by the occurrence of tilting of the ballast stone during the compression (caused by crushing of the surface and rebuilding of vertically asymmetrical contacts, even though the initial asymmetrical contacts were already avoided) or infirm contact originating from the roughness of the surface of the ballast stone. Both of these reasons relate to the shape of the ballast stone. Because the exact tilting behavior of a ballast stone



(a) a non-linear force-displacement curve

(b) corresponding crushed ballast sample

Fig. 2.3. A ballast sample with a non-linear force-displacement curve.