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Investigation of the gradation effect on ballast mechanical behaviors by means of discrete element modeling - part 1

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Investigation of the gradation effect on ballast mechanical behaviors by means of discrete element modeling - part 1

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Abstract. The ballast gradation has a strong influence on the mechanical behavior of ballast aggregates. Discrete Element Method (DEM) based simulations are performed to investigate the gradation effect of ballast aggregates on their settlement, ballast position rearrangement, breakage rate and void ratio. This is the first part of two papers. In this article, a newly developed ballast random form generator is described. With this generator five form databases of different ballast gradations are established. A box test and its corresponding DEM simulation are usually performed to calibrate and to investigate the mechanical behavior of small-scaled ballast aggregates with different gradations. The ballast stones are simulated by the Bonded Particle Models with the Flat Joint contact model to enable the investigation of the breakage behavior of each ballast stone.

1. Introduction

The ballast layer of a ballast track is ballast aggregate, which is a group of well compacted ballast stones. The size distribution of the stones, also known as the ballast gradation, has a strong influence on the mechanical behavior of ballast track such as its stability, degradation and hydraulic conductivity [1, 2]. To regulate the gradation for the practical usage, the specifications of ballast forms, including the size and shape of ballast stones, are elaborated in railway related standards according to engineering experiences [3–6]. However, the reason of these specifications has not been sufficiently studied. Such design should be able to fulfill the need of ballast track of having lower plastic settlement, breakage rate, as well as maintaining an eligible hydraulic conductivity. How the changing gradations affect the above-mentioned mechanical behaviors needs to be further investigated.

The plastic settlement is the most important mechanical behavior of ballast aggregate. It causes an unevenness of the rail and an increased dynamic loading derived from the wheel-rail contact. Consequently, the degradation of ballast layer is accelerated, which causes a decreased maintenance cycle, and even worse, a complete renewal of the track. The reason for the plastic settlement is a combination of ballast breakage (ballast degradation) and ballast position rearrangement (ballast movement). Under traffic loadings, the two factors act not sequentially but iteratively. The breakage of a ballast stone generates smaller pieces of rock, which fill the voids inside a ballast aggregate and causes the ballast position rearrangement. Meanwhile, this position rearrangement changes the loading pattern of the ballast aggregate, causes excessive local stress, and thus more breakages. Obviously, these mechanical behaviors of ballast aggregate are interconnecting. However, the current studies mainly take

them individually. A comprehensive study of the gradation effected mechanical behaviors of ballast aggregate should be performed.

Discrete Element Method (DEM) based simulation is an appropriate modeling approach for such type of research. DEM is a numerical method, which specializes on investigating the mechanical behavior of granular materials such as ballast stones [7]. In DEM simulations, the ballast stones can be treated individually. They can have their own shapes and sizes, which enables the representation of ballast gradation and the calculation of their volumes, and then the void ratio of the ballast aggregate. Furthermore, the relative motions of ballast stones are obtainable in a DEM model, which means the position rearrangement under loading can be studied. Last but not the least, the breakage behavior of ballast stones can be investigated in DEM simulations by using the Bonded Particle Model (BPM), which is a cluster of balls bonding together to a predefined form to represent a single ballast stone [8]. The breakage of the stone is represented by invaliding the bonds under a certain condition (e.g., the stress of a bond exceeds its tensile strength).

In this article, the gradation effect on ballast mechanical behaviors is comprehensively investigated by means of discrete element modeling of the box test. A newly developed ballast random form generator is implemented to create five ballast form databases, which are quantified based on the railway standards [3–6] from engineering practice. Based on these databases, five types of ballast aggregates, in which each ballast stone is simulated by the BPM, are created. The settlement, the void ratio, the breakage rate and the ballast position rearrangement of these ballast aggregates are investigated.

2. The box test

In this article, the simulation model is calibrated by the settlement of the ballast aggregate in a box test, which is performed by the Material Testing Institute (MPA) at the University of Stuttgart, in collaboration with the Institute of Railway and Transportation Engineering (IEV). The box test is a small-scaled test comparing to the full-scaled test for the investigation of the mechanical behavior of a ballast aggregate [9]. In the test, ballast stones are dumped into a container, which can be made of different materials and with different shapes, and acted upon by static or dynamic loading. The test is usually performed to investigate the change of the mechanical behavior of different ballast aggregates under the same loading pattern. Furthermore, the test also serves as a calibration tool for simulation models due to its convenience and low cost.

In this article, a steel cylinder, which is with a height of 22 cm and a diameter of 34 cm, is manufactured and employed as the container (see figure 1, a). The ballast samples investigated in the test are obtained from the Stuttgart public transport operating company SSB AG. Based on the specifications of the European standards [3–6], several properties of a ballast aggregate should be tested and a report should be generated to identify the aggregate. The report contains information such as gradation, shape distribution, raw density, Los-Angeles coefficient of the ballast aggregate. However, for this study, only the research-related information, i.e., the geometrical categorizes and raw density, is taken into consideration (see table 1).


Figure 1. The box test setup (a) the empty cylinder (b) without the pressing plate (c) with the pressing plate.

Table 1. The geometrical categorizes and the raw density of the ballast test sample.

Grading category (-)	Shape index (-)	Particle length category (-)	Flakiness index (-)	Raw density (kg/m^3, soft / hard)
G_{CRB} B	SI_{RB} 5/30	L_{RB} B	FI_{RB} 35	2620 / 2850

In table 1, the grading category G_{CRB} B indicates that the test sample matches the size distribution B. The shape index SI_{RB} 5/30 means that the proportion of the mass of the non-cubic ballast stones to the total mass of the sample falls into the range of 5% to 30%. The particle length category L_{RB} B shows that the mass of the long ballast stones with a length bigger than 100 mm is less that 6% to that of the whole sample in mass. The flakiness index FI_{RB} 35 means that there are 35% of ballasts stones in mass, which pass through grid sieves with slot widths determined by the ballast stone size groups. The raw density is the density of the rough stone, which is used to produce the ballast test sample. For more detailed explanations of the geometrical categories and the indexes see also [3–6].

200 ballast stones are randomly selected as the test sample from the aggregate, and manually placed in the cylinder one by one in order to form a compacted packing. Some of the ballast stones are painted in yellow so that their breakage behavior such as abrasion and crushing can be studied after the loading process (see figure 1 b and c). The selected ballast stones are composed roughly of 70% hard rock (e.g., basalt, granite) and 30% soft rock (e.g., limestone). To further compact the test sample, three pre-loading processes with the static loading of 10kN, 20kN and 30kN are firstly performed. Afterwards, the test sample is acted upon by a sinusoidal dynamic force for 10,000 steps. The dynamic force varies from 15kN to 45kN while the sample settles during the force (see figure 2, a. Note that only 100 steps are demonstrated, otherwise the curve would be too crowded to be seen). In order to better demonstrate the relationship between the settlement of the test sample and the loading steps, the position of the pressing plate by 30kN of every loading step was extracted (see figure 2, b). This settlement of ballast aggregation will be used for the calibration of the DEM model. Note that the loading element and the pressing plate are not rigidly coupled in the test (see figure 1, c). It enables the pressing plate to rotate, so that a uniform contact between the plate and the ballast aggregate can be found during the loading process. In this way, the contact force is well distributed and the unrealistic exaggerated local stress of the ballast stones, which arouses extra breakages of them, can be avoided.

a. The dynamic loading   b. Settlement of the test sample
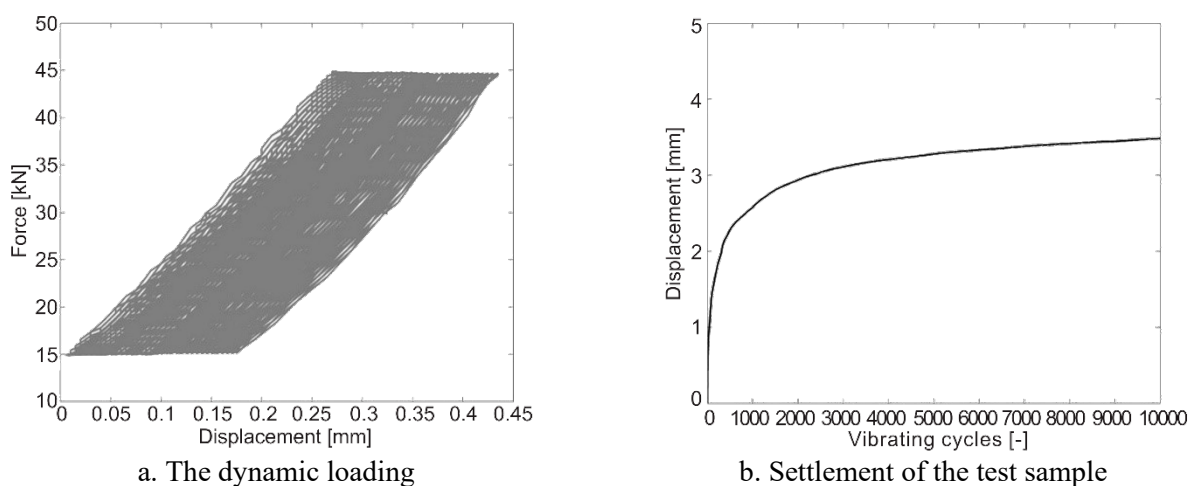
Figure 2. The dynamic loading and accumulated settlement of the test sample in the box test.

3. The random form generator for ballast stones

In order to simulate a ballast aggregate, the geometrical forms of the ballast stones should be firstly represented. The random form generator creates ballast form databases, which match the geometrical

specifications regulated by the railway related standards [3–6]. By giving the parameters such as the grading category, the shape index, the particle length category, the flakiness index and the raw density, the generator creates .stl files, where every file contains geometrical information of one single ballast stone. The database of the ballast aggregate is thus the generated files putting together (see detailed information about the generator in [10]), which can be used in further ballast form related DEM simulations and studies.
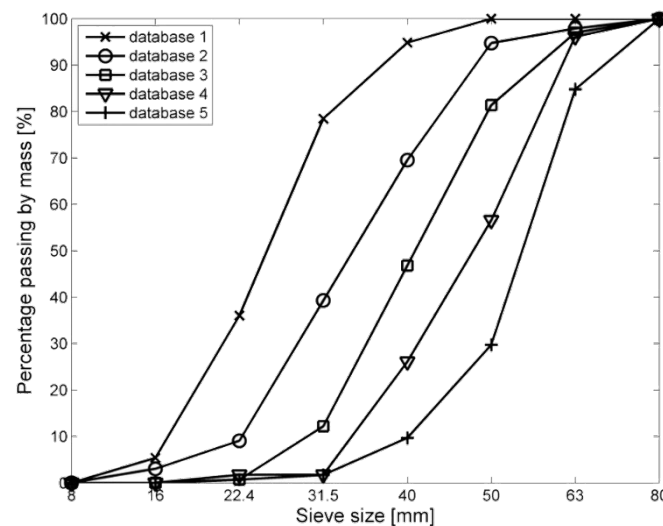

Figure 3. The size distribution curves of the generated form databases.

Even through the generator is able to create form databases with different shape distributions, in this article, the generated form databases are only differed in the respect of gradation. Five form databases with the size distribution curves shown in figure 3 are created. 25 randomly picked forms from each database are illustrated in figure 4. The form databases' shape index, particle length category and flakiness index are set to be the same as the ballast aggregate in the box test. Generally speaking, the average sizes of the generated forms in the five databases increase with the database index number. Database 1 has the smallest average size of forms, while database 5 has the largest one. Note that the database 4 is generated with the geometrical parameters of the test sample. Therefore, the calibration of the DEM model is performed by using this database.
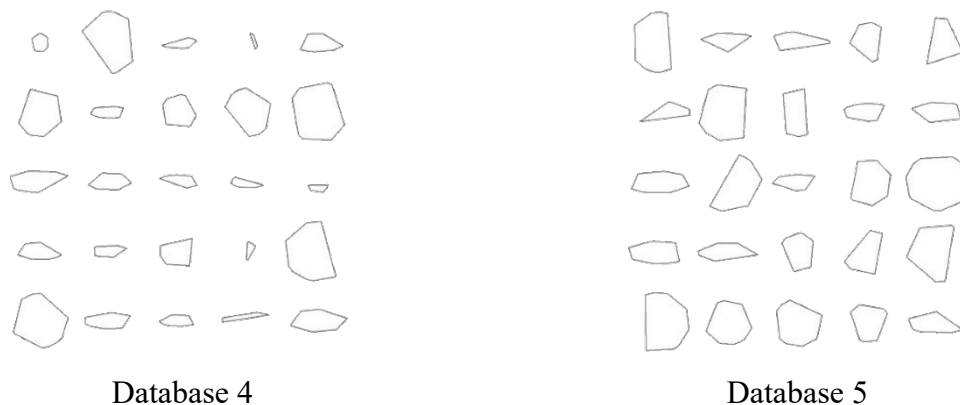

Database 1   Database 2   Database 3

Database 4　　　　　　　　　　　　　　Database 5
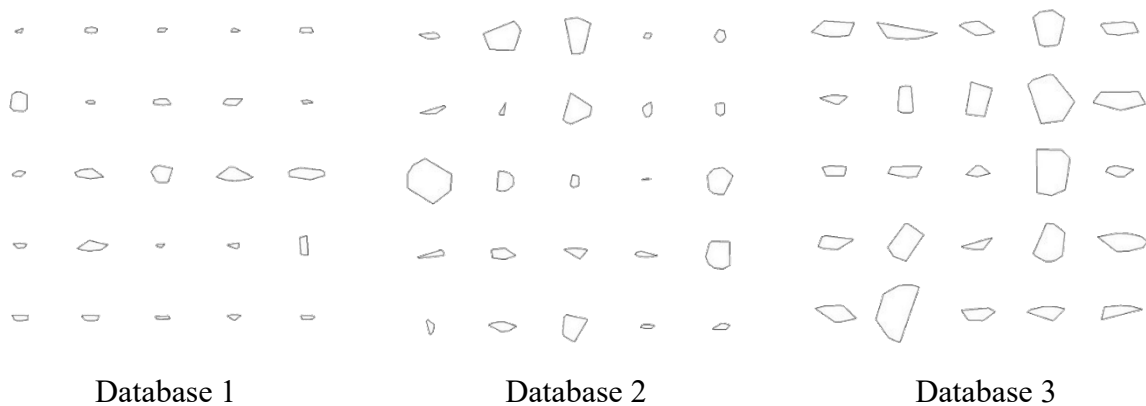
Figure 4. The generated form databases (only 25 randomly picked forms are demonstrated).

4. Model establishment and its calibration

With the generated ballast form databases, the simulative ballast stones can be created. In this article, using the DEM based commercial software Particle Flow Code (PFC), the ballast stones are simulated by the Bonded Particle Model (BPM) [11]. The BPM is firstly proposed by Potyondy and Cundall [8]. It is a cluster of balls bonding together to a predefined form to represent a single breakable rock (in this article, a ballast stone). Using the BPM, the breakage behavior of ballast stones under loading can be studied.

The bonds of a BPM can be described by several of contact models. In PFC, the contact models can be linear Contact Bond (CB), linear Parallel Bond (PB) or Flat Joint (FJ) models. The bond in the CB model can be seen as a couple of elastic springs (or a point of glue) with constant normal and shear stiffness acting at the contact point. The bond in the PB model can be envisioned as a set of elastic springs, which are distributed over a cross-section lying on the contact plane and centered at the contact point. These springs are of the parallel-bond component, resist rotation between particles and can carry a moment. They act parallel to the springs of the linear component of the PB model. The bond break is embodied by deleting the parallel-bond component. If the two pieces are once again in contact, the interaction will be determined by the remaining linear component. The FJ model describes the bond as an interface, which exists between the bonded notional surfaces of the contacting particles and is discretized into elements, with each element being either bonded or unbonded. If all the elements are unbonded, the bond will be considered as broken, and the interface is removed. If the two particles come back into contact, the interaction will be dependent on the unbonded notional surfaces.

If the contact of particles remains after the breakage of the bond, the normal and shear stiffness of the CB model remain the same. This indicates that, in the CB model, the bond breakage, which mimics a crack inside a rock specimen, may not influence the macro-stiffness of the BPM as significantly as it does in reality [12]. The PB model solves this problem by using both the parallel bond and linear components for the bonded state. The removal of the parallel-bond component to simulate the bond breakage will directly reduce the stiffness of two contact particles, thus affecting the macro-behavior of the BPM. However, the removal also eliminates the moment between particles, which means that the relative rotations between two broken particles can no longer be resisted. This results in a much lower estimation of unconfined compressive strength (q_u) of the BPM when the tensile strength of the bond is chosen to match the Brazilian strength (r_t). In the FJ model, since the notional surfaces will not be deleted even though a fully broken state is reached (only the interface for bonding will be deleted), the notionally polygonal particles can still carry a moment. With a reasonable choice of the tensile and shear strength of the bond, q_u and r_t can be simultaneously matched [13].

In this article, the bonds of the BPM are described by the FJ model. Except for the simulation of one single breakable ballast stone, the simulation of interaction between ballast stones is also crucial. The Linear Model (LM), which provides linear and dashpot components to simulate the linear elastic (no-

tension) frictional behavior and viscous behavior between ballast stones, is employed [7]. Using the form database 4, which is with the same geometrical properties and hard-soft rock ratio of the testing sample, the calibration of the model parameters is performed by matching the settlement of the aggregates from the test and simulation. The calibrated parameters are listed in table 2 and the matched settlement curves are illustrated in figure 5. Considering the computational intensity of the simulation, all the models are established in 2D and only 1000 loading steps are performed in the simulation instead of 10,000 loading steps in the test.

Table 2. The calibrated modeling parameters.

	Parameter	Description	Value (hard rock / soft rock)
FJ parameter:	F_{str-co}	strength and cohesion scaling factor	3.5 (-) / 3.5 (-)
	σ_c	tensile strength	F_{str-co} * (5.4e5 (Pa) / 3.0e5 (Pa))
	c	cohesion	F_{str-co} * (6.0e5 (Pa) / 5.0e5 (Pa))
LM parameter:	μ	friction coefficient	0.7 (-) / 0.7 (-)

It is shown in figure 5 that the simulated settlement curve (the red dashed curve) matches greatly with the one from the test (the solid blue curve). However, it is important to point out that the simulated settlement curve is the average value of 10 simulation cases[1] (the gray curves), where the modeling parameters are exactly the same, while the results vary greatly. The reason for this difference is that the ballast forms, which are from the same form database, are randomly picked and vary from time to time. Besides, even though the material distribution of the database is fixed, the one of the selected ballast stones for simulations can change (see figure 6). In this case, the modeling parameters can be considered as calibrated only if enough cases (10 cases in this article) are performed and their mean value of results matches the test result. Only in this way can the randomness be statistically reduced.

[1]Simulation models with the same modeling parameters and use the same form database, but vary due to the random pick of the forms and the materials from the database.
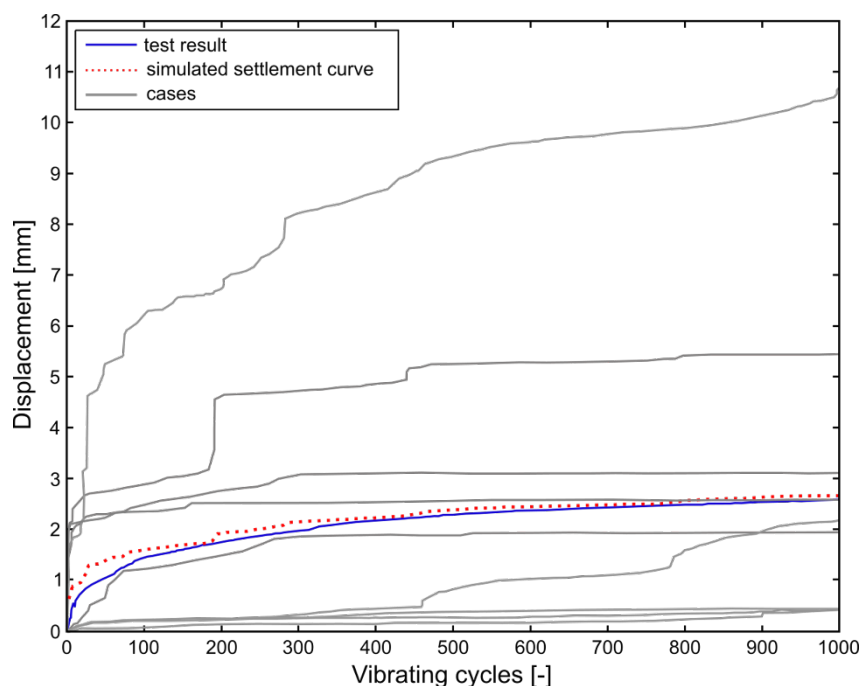

Figure 5. Ballast settlements of simulation cases, their mean value and the test result.
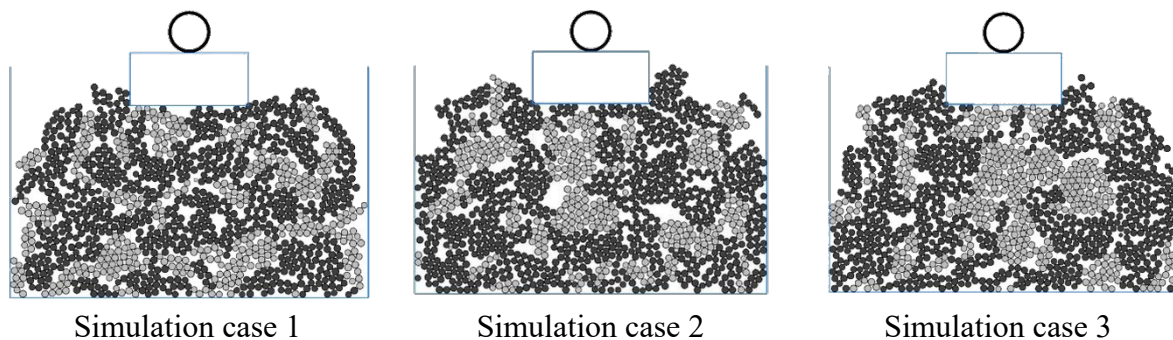
Figure 6. Three simulation cases with different selected ballast forms and materials (black: hard rock, gray: soft rock) from the same ballast form database.

Furthermore, there is also randomness caused by the packing process of the ballast aggregate. In this study, in order to get a compacted ballast aggregate, a tamping-like process is performed (see figure 7). The tamping process in railway engineering is performed by a tamping machine, which inserts two vibrating tines into a ballast layer and pushes them together until the ballast aggregate between them is well packed and lifted. This process ensures a more stable railway track. In the simulation, the simulated ballast stones are applied with centripetal speeds, so that they can assemble at the axis of symmetry. The tamping-like process also serves for the purpose of eliminating the incomplete contact between the pressing plate and the ballast stones. By fixing the pressing plate, during the process, the ballast stones will rush against to the plate. However, some void will still show up from time to time, which will cause an excessive settlement of the pressing plate (see figure 8). Unlike in the test, where the ballast stones are manually placed and the ones under the pressing plate can be manually rearranged to find a balanced and firm contact to the pressing plate, in the simulation, the void is hard to be avoided and adjusted. It is another reason for running multiple cases and getting the mean value as the final result, so that this randomness can be reduced as much as possible.
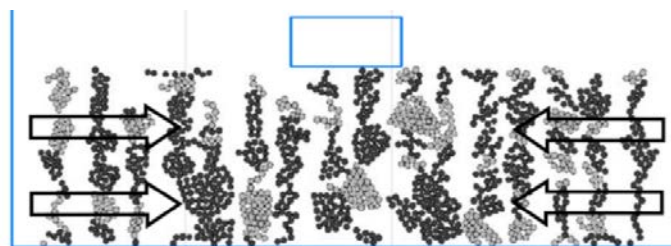

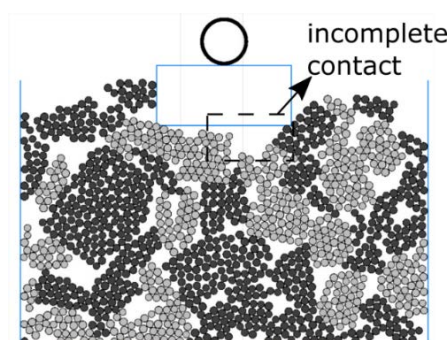**Figure 7.** The tamping-like process in the simulation to get a compacted ballast aggregate.

Figure 8. The incomplete contact (the void) between the pressing plate and the ballast stones.

5. Conclusion

The box test and its corresponding simulation are usually performed to investigate the mechanical behavior of small-scaled ballast aggregates with different gradations. In this article, using a newly developed ballast random form generator, five form databases of different ballast gradations are established. Discrete Element Method (DEM) based simulations are performed, where the ballast stones are simulated by the Bonded Particle Models (BPMs) with the Flat Joint (FJ) contact model to enable the investigation of their breakage behaviors. The simulation model is calibrated based on the box test performed together with the Material Testing Institute (MPA) at the University of Stuttgart. To reduce the randomness caused by random ballast form selection from a certain form database and random packing of the ballast stones in the box, every simulation scenario with the same parameter set is performed 10 times and the mean value of the results is considered as the final result of the simulation scenario. Based on this procedure, a parametric study is carried out in the second part of the paper.

Declaration of Conflicting Interests

The author(s) declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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