Investigation of the gradation effect on ballast mechanical behaviors by means of discrete element modeling - part 2

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Abstract. The ballast gradation has a strong influence on the mechanical behaviour 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. In the second part of this article, DEM based simulations are performed to investigate the gradation effect of ballast aggregates on their settlement, ballast position rearrangement, breakage rate and void ratio (Part 2). The results indicate that the settlement and the ballast position rearrangement increase with the decrease of the averaged ballast size of a ballast aggregate, whereas the void ratio decreases. Besides, the breakage and the ballast position rearrangement occur mainly with the dynamic loading rather than the static loading. Based on the simulation result, appropriately enlarged ballast stones will benefit not only the stability, but also the hydraulic conductivity of ballast aggregates. The gained result can be used for the optimization of ballast aggregate regarding to its gradation, so that its service cycle can be prolonged.

1. Parametric study

The plastic settlement of a ballast aggregate under loading is a result of iterative ballast degradation and position rearrangement. In the simulation, the degradation is governed by the tensile strength and the cohesion of the bonds of the BPMs, while the position rearrangement is controlled by the friction coefficient between the simulated ballast stones. In this section, parametric study of these two modelling parameters is performed to investigate their influence on the settlement of ballast aggregate. 10 simulation cases of each simulation scenario with the same parameter set is performed and their mean value of result is considered as the final result of the scenario so that the randomness discussed in section 4 (article Part 1) can be reduced.

Since there are two types of materials (soft and hard rock) and two strength related parameters (tensile strength and cohesion) in the simulation, a strength and cohesion scaling factor $F_{\text{str-co}}$ is proposed to simplify the parametric study. By multiplying the factor to each tensile strength and cohesion, the simulated ballast stones are proportionally strengthened or softened (see table 2, article Part 1). Simulation scenarios$^5$ with five values of the factor are performed and the result is illustrated in figure 1. It is shown in the figure that the accumulated settlement of ballast aggregate increases with the decreasing value of $F_{\text{str-co}}$. It fits the common sense that softer stones will break easier and thus yield higher settlement.

$^5$Simulation scenarios: simulation models with different parameter sets or different used form databases.
On the other hand, four simulation scenarios with the changing friction coefficients \( \mu \) are performed. The higher the friction coefficient is, the higher resistant shear force will be produced, which reduces the lateral relative motion between two simulated ballast stones. The simulation result shown in figure 2 proves this standpoint, where the model with lower friction coefficient yields higher settlement and vice versa. It is proven by the parametric study that the strength and cohesion scaling factor \( F_{str-co} \) and the friction coefficients \( \mu \) have great influence on the settlement of a ballast aggregate. They should be selected carefully in such type of research.
2. Gradation effect
The gradation of ballast stones affects the mechanical behavior of ballast track greatly. In this section, based on the five generated ballast form databases, DEM simulation models with different gradations of simulated ballast stones are established. The mechanical behaviors of ballast aggregate such as its settlement, breakage rate, ballast movement and void ratio are studied. Similarly, the illustrated simulation result of each scenario is the mean value of results of 10 simulation cases with the same parameter set. For the reason please refer to the discussion in section 4 (article Part 1).

2.1. Settlement

![Figure 3. Gradation effect on ballast settlement [1].](image)

As illustrated in figure 3, the change of ballast gradation affects clearly the settlement of ballast aggregate under loading. The smaller the ballast stones are (e.g., the scenario 1 using the form database 1), the higher settlement will be created. As discussed in section 1 (article Part 1), the plastic settlement of ballast aggregate is a combination of ballast breakage (ballast degradation) and ballast position rearrangement (ballast movement). Therefore, to better explain the trend shown in figure 3, the influence of the above-mentioned two factors is discussed in the following sections.

2.2. Ballast position rearrangement
In this article, the ballast position rearrangement is expressed as the ball movement. Since the movement of the balls on both sides of the ballast aggregate (see figure 4, ignored area) has relatively less impact on the settlement of the pressing plate, and their movement is actually higher than the one of the balls direct under the pressing plate because of the unrestricted shoulder areas, only the balls direct under the pressing plate (see figure 4, concerned area) are taken into consideration for the study of the ballast position rearrangement.
In the box test, the loading process is consisted of pressing (static loading) and vibrating (dynamic loading). The same loading process is applied in the simulations. For each simulation case, there will be three simulation statuses: before pressing, after pressing(before vibrating and after vibrating). The average ball movement of the balls in the concerned area at each simulation status of every simulation case is calculated. The positions of the balls before pressing is noted as original values and the movement of the balls is considered as the position change comparing the original values and the position at the following two statues. Since the simulation scenarios with different gradations may arouse different degrees of void, which results different number of balls in the concerned area, the sum of displacement of the balls is not comparable. Hence, the average ball movement, which is the sum of displacement divided by the number of balls in the concerned area, is used to reveal the degree of ballast position rearrangement.

**Figure 4.** Division of ignored and concerned areas [1].

**Figure 5.** Gradation effect on ballast position rearrangement [1].
It can be seen from figure 5 that the average ball movement decreases with the increase of the simulated ballast size (from scenario 1 to scenario 5), especially at the status of after vibrating, i.e., at the end of simulation. It fits the trend shown in figure 3, where the settlement of ballast aggregate decreases with the increase of the simulated ballast size. Besides, it is noted that the average ball movement is generally smaller than the settlement shown in figure 3 (e.g., for scenario 1, the average ball movement is near 5 mm, while the settlement is 9 mm). It is because that the upper part of the concerned area contributes the most to the settlement of the ballast aggregate, where the average ball movement is relatively higher than the lower part. If the ball movement is averaged in the whole concerned area, it is decreased due to the low movement at the lower part. Furthermore, the vibration process yields more ball movement than the pressing process. It indicates that the settlement of a ballast aggregate happens mostly under dynamic loading rather than static loading.

2.3. Breakage rate
Using the BPM, the breakage behavior of ballast stones under loading can be studied. The breakage of a bond can be either in tension or in shear. In this article, the breakage rate is proposed to describe the degree of breakage of ballast stones under loading. The breakage rate is defined as the ratio of number of breakage and the total bonds, so that the difference caused by the different number of bonds in different simulation scenarios can be eliminated. Again, since the breakage happens in the ignored areas is irrelevant to the settlement of the ballast aggregate, only the breakage occurs in the concerned area is considered (see figure 4).

![Figure 6. Gradation effect on breakage rate [1].](image)

Figure 6 illustrates the breakage rates of ballast aggregates with different gradations. It is shown in the figure that the breakage in tension constitutes the main part of the whole breakage. Furthermore, the breakage mainly occurs in the process of vibrating rather than pressing. Since the breakage of ballast stones arouses their position rearrangement, which increases the average ball movement, the higher breakage rate in the vibrating process is one of the reasons that the average ball movement in this process is higher (see figure 5).

It is important to point out that even though it is assumed that the ballast aggregate with smaller ballast stones (scenario 1) would yield more breakage while the one with bigger ballast stones (scenario
5) would produce less breakage, in figure 6, this trend is inconspicuous. The reason is the very few bond breakages (nearly 5 averaged bond breakages in each simulation case) caused by, firstly, the low ballast breakage under the dynamic loading; secondly, the limited number of total bonds in the simulation model, which is negatively correlated with the size of ball, which is relatively large in the simulation since the computation load must be considered. Besides, the ballast stones in each simulation case are not enough. If a full-scaled ballast track is simulated, the number of bond breakages should be increased, and thus the statistically instable breakage rate should be eased.

2.4. Void ratio
The voids created by discrete ballast stones provide hydraulic conductivity of a ballast aggregate. On the premise of maintaining the load carrying ability and structural performance of the ballast layer, the voids should be as large as possible to provide adequate drainage. In DEM simulations, the degree of voids can be expressed as the void ratio, which is defined as the ratio of the voids area and the total area. Again, for the sake of continuity of this study, only the concerned area is taken into consideration for the calculation of the void ratio (see figure 7).

Figure 7. Gradation effect on void ratio [1].

Figure 7 illustrates the void ratios of ballast aggregates with different gradations. Generally speaking, the void ratio is proportional to the size of ballast stones. Ballast aggregates with bigger ballast stones tend to yield more voids and vice versa. Furthermore, the pressing and vibrating loading processes compress the ballast aggregate, and thus slightly lower the void ratio. However, the impact is relatively small comparing to the one caused by different ballast gradations. The reasons of the small change of the void ratio between loading processes can be, firstly, the simulated ballast aggregations are already well compacted during the tamping-like process shown in figure 7 (article Part 1); secondly, the 1000 dynamic loading steps are not enough to make a significant change; thirdly, since the breakage rate discussed in section 2.3 is relatively low, there are not enough chances, especially for the big ballast stones (scenario 5) with high initial void ratio, to break and then to fill the void, and thus to decrease the void ratio. The result of this section indicates that, unless the ballast aggregate is addressed with a long-term dynamic loading, its breakage does not play a dominant role in term of its void ratio. As long as the ballast aggregate is well compacted, the void ratio is relatively stable. It is more crucial to wisely choose a suitable ballast gradation in order to assure the hydraulic conductivity of the ballast layer.
3. Conclusion
In the first part of the paper, 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, in the second part of the paper, a parametric study of the strength and cohesion scaling factor and the friction coefficient is carried out. The gradation effect on the settlement, ballast position rearrangement, breakage rate and void ratio of the ballast aggregates is investigated.

The result of parametric study shows that the settlement of a ballast aggregate decreases with the increase of tensile strength and cohesion of the BPM bonds, since strengthen the ballast stones will reduce the possibility of their breakages. Meanwhile, the settlement is negatively correlated with the friction coefficient, since a higher friction coefficient will provide better engaging force between ballast stone, and thus assure a better structural performance of the ballast aggregate.

The study on the gradation effect on the mechanical behaviors of the ballasts aggregates shows that, firstly, the settlement of ballast aggregate decreases if the size of the ballast stones increase. Secondly, the settlement of ballast aggregate is proportional to the ballast position rearrangement, of which the dynamic loading (vibrating process) yields more than the static loading (pressing process). Thirdly, the breakage rate of ballast stones decreases with the increase of the ballast size. However, the trend is not so clear because there are only very few breakage occurred in the loading process, which results in the statistically instability of the result. It fits the reality, where the breakage of ballast stones happens either after a long service time of the track and considerable dynamic loading steps, or not in the operation of railway at all, but in the tamping procedure of the track at the construction or maintenance process. Finally, the void ratio is proportional with the size of ballast stones, while the loading can only slightly reduce the void ratio. From the research findings of this article, it is reasonable to draw the conclusion that, under the precondition that the ballast aggregated is well compacted, using appropriately enlarged ballast stones will reduce the settlement, the ballast movement and the breakage rate, and at the meantime, increase the void ratio. That is to say, in this case, the stability and hydraulic conductivity of the ballast aggregate can be maintained at the same time. The modeling process of a small-scaled ballast aggregate can be taken as a reference for DEM simulation of a full-scaled ballast track. The results of the gradation effect of ballast stones on their mechanical behavior can be used for the mechanical optimization of ballast track.

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