Discrete element modelling of ballasted track deformation behaviour

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Railroad ballast layer consists of discrete aggregate particles and Discrete Element Method (DEM) is one of the most suitable ways to simulate the deformation behaviour of particulate nature of ballast materials. An aggregate imaging based DEM simulation platform developed at the University of Illinois at Urbana–Champaign (UIUC) can simulate railroad ballast behaviour through the use of polyhedron shaped discrete elements. These ballast elements are created with realistic size and shape properties from image analyses of actual particles using an Aggregate Image Analyzer. The UIUC railroad ballast DEM model was recently put to test for predicting settlement behaviour of full-scale test sections under repeated heavy axle train loading. Field settlement data were collected from the Facility for Accelerated Service Testing (FAST) for Heavy Axle Load (HAL) applications at Transportation Technology Center (TTC) in Pueblo, Colorado, to validate the DEM model. The ballast settlement predictions due to the repeated train loading indicate that the DEM model could predict magnitudes of the field ballast settlements from both early loading cycles and over 90 Million Gross Tons (MGTs) performance trends reasonably accurately. The settlement predictions were sensitive to aggregate shape, gradation and initial compaction condition (density) of the constructed ballast layer.

Keywords: railroad ballast; aggregate shape; settlement; porosity; discrete element modelling; field validation

1. Introduction

Railroad ballast is uniformly graded coarse aggregate placed between and immediately underneath the crossties. The purpose of ballast is to provide drainage and structural support for the dynamic loading applied by trains. A large portion of the annual budget to sustain railway track system goes into maintenance and renewal of track ballast. Aggregate type, size distribution (gradation) and particle shape, texture and angularity are among the major properties that impact the mechanical behaviour of ballasted railroad track performance. A better basic understanding of the ballast behaviour influenced by aggregate type, gradation, angularity and surface texture (ST) properties is essential for mitigating track problems and failures due to ballast fouling; ballast deformation and degradation due to compaction and repeated loading; and ballast lateral movement and instability causing track buckles. In addition, many railroad track structures that have traditionally supported heavy freight trains in the United States are currently upgraded to also support the much faster passenger service for more complex dynamic loading considerations. These structures are mostly ballasted track, which must be durable, stable

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and able to withstand repetitive dynamic loading without excessive deformation or ride quality degradation. There is an increasing need to better understand the effects of different qualities of aggregate types and properties on ballast layer performance under such demanding dynamic loading scenarios anticipated in joint passenger and freight corridors and develop engineered/optimised ballast specifications for improved track performance and hence increased network safety and reliability. Ideally, proper functioning of the existing ballast layer, ballast strength, modulus and deformation behaviour need to be characterised in the laboratory and then linked to field performance by means of a realistic and robust modelling capability that would establish the basis of a quantitative track performance simulation tool.

This paper presents field validation results of a realistic railroad ballast model, developed recently at the University of Illinois based on the Discrete Element Method (DEM), with ballast settlement data collected from the Facility for Accelerated Service Testing (FAST) for Heavy Axle Load (HAL) applications at Transportation Technology Center (TTC) in Pueblo, Colorado. By addressing adequately the particulate nature of different sized and shaped ballast aggregate particles and their interactions with each other at contact points, the ballast DEM model was used to predict ballast settlement trends of four 30.48 m (100 ft) test sections constructed in early 2010 with four different aggregate materials used as the new ballast layer installed on a curve at the TTC FAST test track. Both field measured ballast settlements and the DEM model predictions are presented and compared in this paper. Based on the results, the potential use of the field validated DEM model with future improvements is also highlighted for engineering ballasted track designs and addressing critical substructure concerns such as those related to variable track stiffness and track transition zones.

2. Development of image-aided discrete element modelling at University of Illinois

2.1. Image-aided discrete element modelling

Due to the particulate nature of ballast materials, the DEM is one of the most realistic modelling techniques for simulating complex particle interaction. Few research studies using the DEM approach have so far dealt with spherical particles or spherical particle clusters to simulate ballast behaviour [1–3]. With the objective to provide better engineering insight into the design of ballasted track for improving railroad safety and network reliability, recent Association American Railroads (AAR) Technology Scanning Program research at the University of Illinois has developed a ballast performance model based on DEM which uses rigid but random shaped three-dimensional (3D) “polyhedrons or blocks” as the basic elements to realistically simulate interactions such as interlock/contact of actual aggregate particles. This aggregate particle imaging based modelling approach utilises a DEM program BLOCKS3D that can simulate true polyhedron particles. The BLOCKS3D program was originally developed at the University of Illinois by Ghaboussi and Barbosa [4] and enhanced more recently with new, fast contact detection algorithms [5,6]. Imaging technology provides detailed measurement of aggregate shape, texture and angularity properties and has been successfully used in the last two decades for quantifying aggregate morphology. Among the various particle morphological indices, the flat and elongated (F&E) ratio, the angularity index (AI) and the ST index, all developed using University of Illinois Aggregate Image Analyzer (UIAIA), are key indices [7,8] used for this research. The UIAIA system features taking images of an individual aggregate particle from three orthogonal views to quantify imaging based F&E ratio, AI and ST
morphological indices. The aggregate particle image-aided DEM approach (see Figure 1) then recreates the 3D aggregate shapes as individual DEM elements based on the UIAIA processed top, front and the side views.

### 2.2. Calibration and application

The aggregate particle image-aided ballast DEM model was calibrated in our early research efforts with laboratory direct shear (shear box) ballast strength test results [9]. The calibration process was accomplished by matching the simulation results with the laboratory results by changing the modelling parameters, such as: Normal Contact Stiffness (K_n), Shear Contact Stiffness (K_s), Inter-particle Friction Angle (\(\phi_\mu\)). After proper calibration, these modelling parameters, needed for simulating direct shear test results with clean ballast materials, were determined to be 20 MN/m for normal contact stiffness, 10 MN/m for shear contact stiffness and 31° for Inter-particle Friction Angle, respectively. The calibrated DEM model was then utilised to predict strength and settlement behaviour of railroad ballast for the effects of multi-scale aggregate morphological properties [10,11]. Ballast gradation [12] and fouling issues [9,13] influencing track performances were also successfully investigated by the calibrated DEM model. More recently, large scale triaxial strength tests have been successfully simulated [14] by using rigid elements to represent triaxial cell membrane [15]. Another suitable area to apply this DEM simulation technique is to study aggregate particle–geogrid interactions. The influence of geogrid aperture size, aperture shape and the location to place geogrid in the ballast layer have been investigated through the DEM simulation platform developed at the University of Illinois with realistic angular particle shapes generated through image analysis [16–18].

### 3. Field testing

#### 3.1. Field testing conditions

To further validate the realistic railroad ballast model developed recently at the University of Illinois based on the DEM, the field ballast performance study was conducted in Section 3 of the TTC FAST High Tonnage Loop (HTL) under heavy axle loading (35.75 metric tons per axle) conditions, as shown in Figure 2.
There were four test zones constructed in early 2010 with different ballast materials donated by AAR member railroads, BNSF, UP, CSX and NS. The ballast materials were randomly designated as Railroad 1 to Railroad 4 (RR1 to RR4) in this paper, installed as new ballast layers on a 5° curved track. Each test section had 24.38 m-long test zone and 6.10 m-long transition zone between two test zones to eliminate the influence of different test zones as configured in Figure 3. Since Section 3 of the FAST track was curved track, an average of 0.108 m superelevation was achieved during construction. The average thickness of ballast layer constructed was around 0.356 m.

The following performance measures, in particular, were of interest: permanent deformation of the ballast layer, track surface degradation and ballast breakdown. The field tests allowed measurement of ballast vertical settlement in each test section over time at two locations using subgrade settlement plates. To more accurately measure the settlements of the ballast layer and the subgrade, respectively, three settlement plates (see Figures 4 and 5) were installed in the middle of the rails, at field side and at gauge side of the track for every location where field measurements were taken.
3.2. Ballast material properties

The ballast materials donated by all four AAR member railroads were clean granite type 100% crushed aggregates as shown in Figure 6. Figure 7 shows size distributions of all the ballast materials studied. The first three ballast materials, RR 1, RR 2 and RR 3, had gradations that complied with the AREMA No. 24 requirements, whereas the RR 4 ballast had a large proportion of the total sample as 3.81 cm (1–1/2 in.) size particles. As a result,
RR 4 had fewer particles smaller than 3.81 cm size than are required for an AREMA No. 24 gradation. This ballast gradation was closest to being a single size. On the other hand, the ballast material donated by railroad 2 (RR 2) had the smallest proportion of 3.81 cm particles and a wider distribution of particle sizes.

Besides gradation, aggregate shape properties, especially the F&E ratio, the AI and the ST index, are key indices quantified by the UIAIA. One full bucket of each ballast material was scanned and analysed using the UIAIA to determine the values of the F&E ratio, AI and the ST index. These shape indices were then used to create the aggregate particles as discrete elements in the ballast DEM model (see Figure 1). Table 1 lists the average values of shape properties of each granite type ballast material.
used in this field test study. The ballast materials donated by RR 1 and RR 4 had both high angularity (AI) and high ST indices. Ballast material from RR 3 had more rounded particles (lower AI) and high ST. Ballast material donated by RR 2 had both high AI and ST; however, this material had the largest F&E ratio.

4. Full-scale track DEM simulations

4.1. Ballast compaction (initial) condition evaluation

The level of field compaction or achieved density influences ballast deformation behaviour significantly. Similarly, the density of the simulated ballast layer in the numerical model dictates the predicted settlement results. It is a required input and establishes initial conditions for the ballast DEM model used in any full-scale track loading simulations. However, an appropriate and convenient method to quantify the ballast compaction level or density in the field is not readily available.

To study the appropriate ballast compaction conditions in the field, preliminary settlement data were obtained from a ballast test section constructed and tested in Section 40 Tangent Line at the TTC FAST track. The ballast material used in the Section 40 test section was the same as RR 1 aggregate. Accordingly, a half-track simulation was established using the ballast DEM model for the known ballast material properties (same as RR 1) and Section 40 Tangent Line track geometry data (see Figure 8). Since the tangent section was symmetric in both geometry and loading conditions with no superelevation, the half-track model was enough to represent the field track condition and saved time and computational resources. The ballast layer in the DEM simulation was compacted and prepared to study how different initial conditions influenced settlement predictions. The different initial conditions were quantified by porosity of the ballast layers. By comparing the predicted settlements obtained from the DEM simulations for up to 1000 train loadings, it was found that an initial porosity of 37% yielded the closest results to the field ballast settlements measured by both the settlement plates and top of the rail measurements.

Figure 9 presents the predicted results and the field measurements of the ballast settlement in Section 40. The ballast in Simulation I was compacted to an initial porosity of 37% and allowed slight rebound of the ballast layer, which caused an aggregate rearrangement and reached porosity of 39% after the compaction force was eliminated. The ballast in Simulation II was compacted to an initial porosity of 36%, which achieved a porosity of 37% after compensation for the rebound when the compaction force was eliminated. Figure 9 shows both predictions from Simulations I and II to be close to the field measurements, especially the initial 200 passes of car loading. When the field test and the numerical simulation had identical ballast compaction (initial) condition and material (gradation and shape) properties, the settlement predictions were quite similar.

Table 1. Ballast material characteristics.

<table>
<thead>
<tr>
<th>Test section</th>
<th>Angularity index</th>
<th>Surface texture index</th>
<th>Flat &amp; elongated ratio</th>
<th>AREMA gradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR 1</td>
<td>584</td>
<td>2.3</td>
<td>2.2</td>
<td>No. 24</td>
</tr>
<tr>
<td>RR 2</td>
<td>590</td>
<td>2.5</td>
<td>3.5</td>
<td>No. 24</td>
</tr>
<tr>
<td>RR 3</td>
<td>461</td>
<td>2.2</td>
<td>2.6</td>
<td>No. 24</td>
</tr>
<tr>
<td>RR 4</td>
<td>509</td>
<td>1.8</td>
<td>2.3</td>
<td>No. 24</td>
</tr>
</tbody>
</table>

Note: *Does not meet all gradation requirements.
However, even slight differences in the initial conditions, i.e., Simulations I and II, were found to significantly influence the particle rearrangement and settlement trends with increasing load passes. Since the DEM simulations did not consider particle breakage or particle size degradation with load passes, the settlement predictions from Simulations I and II, shown in Figure 9, either indicate increasing–decreasing–increasing trends (particle reorientation with no edge breakage) or gradually increasing trends when compared with the field measured values, respectively.

As discussed above, ballast compaction (initial) condition is quite important to know in the DEM simulations for predicting accurately the field settlement magnitudes. However, an appropriate and convenient method to quantify the ballast compaction level or density in the field is not readily available. To overcome this difficulty and evaluate the compaction levels of the ballast layers constructed in the different test zones in Section 3 TTC FAST track, an open metal box, 0.305 m (12 in.) wide, 0.356 m (14 in.)

Figure 8. Half-track simulations for the section 40 tangent line (RR 1 ballast).

![Figure 8](image1.png)

Figure 9. Measured and predicted settlements for section 40 tangent line (RR 1 ballast).

![Figure 9](image2.png)
long and 0.152 m (6 in.) deep, was placed on the subgrade during the construction of the RR 1 ballast layer according to the standard field practice, i.e., compactive effort (see Figure 10). The box was then recovered and the total weights of the ballast materials inside the box before and after compaction were measured. Using this approach, the compacted density of the ballast layer in RR 1 test zone could be computed.

To adequately determine the initial conditions of the ballast layers in other test zones, laboratory compaction tests were conducted. First, the same field-compacted weight amount of RR 1 ballast material in the metal box was again compacted to fully pack in the box using a vibratory compactor in the laboratory. The time it took the vibratory compactor to accomplish this task was recorded. A similar level and duration of compaction (same compactive effort) was then applied by the same operator to compact other ballast materials in the box using the same vibratory compactor. By analysing the aggregate weights packed in the box, the porosities were computed for all the ballast materials to account for any discrepancies in the initial compaction field conditions.

Although the above described approach worked well in general, the calculated porosities still could not be used directly as the input initial conditions for the ballast DEM model. This is because, in the DEM model, all the particles created are solid particles without any fractures or permeable (external) voids. However, many aggregate particles found among the four ballast materials used in the test zones were observed to have fractures and porous surfaces on the outside (see Figure 11). Accordingly, all the calculated void ratios from the laboratory compaction tests had to be adjusted using the measured aggregate specific gravities to account for the porous surfaces. Table 2 lists the void ratios used as initial conditions input for the ballast DEM model.

4.2. Full-scale track DEM model setup

Four full-scale track DEM simulation models were established according to the track geometry data of the field ballast layers built and tested in Section 3 curved line at the TTC FAST track. Each full-scale track DEM simulation had approximately 13,000 individual particles that established the 0.35 m thick ballast layer with around 0.1 m superelevation in the field side of the track structure. The rail direction length was 0.61 m,
which was covering half tie spacing on each side. The aggregate particles used in the DEM models were created according to the sieve analysis results as shown in Figure 7 and the imaging based shape indices of the ballast materials from different test zones as listed in Table 1. Examples of polyhedral elements used in the DEM simulations are also given in Figure 12.

Table 2. Initial compaction conditions used in section 3 curved track DEM simulations.

<table>
<thead>
<tr>
<th>Ballast material source</th>
<th>Porosities in DEM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR 1</td>
<td>37</td>
</tr>
<tr>
<td>RR 2</td>
<td>32</td>
</tr>
<tr>
<td>RR 3</td>
<td>37</td>
</tr>
<tr>
<td>RR 4</td>
<td>45</td>
</tr>
</tbody>
</table>

Figure 11. RR 1 ballast aggregates with porous surfaces.

Figure 12. Examples of polyhedral elements used in the DEM simulations.

which was covering half tie spacing on each side. The aggregate particles used in the DEM models were created according to the sieve analysis results as shown in Figure 7 and the imaging based shape indices of the ballast materials from different test zones as listed in Table 1. Examples of polyhedral elements used in the DEM simulations are also given in Figure 12.

The crosstie used in the simulations was a typical tie size used in North America, 2.591 m (8 ft 6 in.) long, 0.203 m (8 in.) wide and 0.178 m (7 in.) deep. A front view of the DEM track model is given in Figure 13. The ballast layers in the DEM simulations were compacted to the porosity values similar to the field test conditions for each section as determined in Table 2, with a 2:1 slope used for 0.25 m-wide shoulders on both sides.
The DEM model parameters used in these simulations are listed in Table 3. It is worth noting that the model parameters used in the full-scale track simulations were exactly the same as the model parameters calibrated from the direct shear box tests. The ballast DEM model developed could capture the particulate nature of ballast materials to simulate different experiment configurations without further adjustments of the model parameters, which indicates that the developed DEM model is promising and practical.

### 4.3. Loading pattern used in DEM simulation

After the DEM simulations were prepared for the initial compaction conditions, a dynamic train loading pattern, derived recently from “Sandwich Model” by Huang et al., [19] was applied to simulate the dynamic loading caused by the 143-ton (315-kip) rail car with 4-axles travelling at a speed of 73 km/h (45 mph). Figure 14 shows the 4-peak moving wheel pulse loading applied with a rest period which was considered as one load pass in the repeated train loading DEM simulations. One pass considers altogether the two axles from the front car and the two axles from the trailing car.

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**Table 3. Model parameters used in the full-scale track DEM simulations.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-particle friction angle</td>
<td>$31^\circ$</td>
</tr>
<tr>
<td>Normal contact stiffness</td>
<td>20 MN/m</td>
</tr>
<tr>
<td>Shear contact stiffness</td>
<td>10 MN/m</td>
</tr>
<tr>
<td>Global damping</td>
<td>0</td>
</tr>
<tr>
<td>Contact damping</td>
<td>0.4</td>
</tr>
<tr>
<td>Ballast material density</td>
<td>$2.65 \times 10^3$ kg/m$^3$</td>
</tr>
</tbody>
</table>
5. Field test and DEM simulation results

Figure 15 shows the measured ballast settlements accumulated with increased tonnage for each ballast section for up to 580,000 car passes (90 MGTs). Note that the ballast material donated by RR 2, shown with the highest settlements in Figure 13, also had the most flat and elongated particles prone to particle breakage. The ballast material donated by RR 3 is shown with the lowest settlement in Figure 15, which may be primarily attributed to the more rounded (low AI) nature of the RR 3 ballast material having the least tendency to crush particles. The field test results agreed with earlier studies on the influence of aggregate shape properties on ballast performance [11].

![Field test and DEM simulation results](image)

Figure 15. Field test results of ballast settlement graphed with number of passes.
Settlement plates installed on top of the subgrade were used to determine how much settlement was occurring in the foundation below the ballast layer and accordingly, the settlement within the ballast could be computed from the top of rail measurements. Figure 16 indicates that the major contribution of the track settlement was, in fact, from the ballast layer. In this field test, the subgrade accounted for about 10% of the total settlement as presented in Figure 16.

Additionally, the lateral stability performance of each test zone was assessed using a single tie push test. This test gives a measure of the lateral stiffness of the track panel. It measures the lateral force needed to move a crosstie through the ballast. The average of two ties is reported for each test section. The test results are summarised in Figure 17.
zone having the RR 2 ballast had the largest lateral strength despite the largest settlement (see Figure 15). The high lateral strength comes from the angular particles that can form aggregate structure with good interlocking [10]. However, also note that RR 2 is the only ballast material in Figure 17 to indicate reduced lateral stability for up to 700,000 passes due to the breakage of flat and elongated particles.

Note that due to the significantly large amount of aggregate particle contact forces computed and checked for global granular assembly equilibrium at each iterative time step, the full-scale track DEM model could not be loaded with the same number of field load applications in the limited time and computational resources available. Although the field tests applied over 580,000 car passes (90 MGTs), the DEM simulations could only be finished for up to 2000 car passes.

Figure 18 shows the ballast DEM model settlements predicted in each test zone with the number of car passes. The DEM simulations predicted the track with the RR 3 ballast material to have the lowest settlement, which is in agreement with the field observed trends. This can be primarily attributed to the more rounded (low AI) nature of the RR 3 ballast material having the least tendency to crush particles. A similar, more compact ballast layer packing by rounded particles was also observed to yield low settlements in an earlier modelling effort by Tutumluer et al. [11]. The DEM simulations predicted the track with the RR 2 ballast material to have the highest settlement, which is also in agreement with the field observed trends. RR 2 ballast material had more angular (high AI), and flat and elongated (high F&E ratio) particles, which made RR 2 ballast particles with the highest tendency to break. This result also agrees with earlier research findings by Tutumluer et al. [11]. Note that the ballast DEM model could not accommodate particle breakage in simulations and hence could not predict the much higher settlements in the early stage, observed for the RR 2 ballast, which had more flat and elongated particles.

Current research efforts with the DEM model focus on building the capability to characterise ballast degradation with time.

Utilising the predicted settlement data for only up to 2000 car passes, DEM settlement prediction models were developed based on regression analyses to extrapolate the settlement trends and predict the long-term performance of the ballast test zones. Table 4 lists the developed settlement prediction models and the DEM predicted long-term ballast
settlements, which in general compare favourably to the field measurements at 580,000 car passes (90 MGTs).

Figure 19 compares the DEM predicted settlements with the field measurements in two locations for only up to the first 1000 car passes. The predicted settlements increase always gradually in the DEM simulations due to the better control of compaction and loading when compared to the field measurements, which show sudden increases and often heaves due to unstable field shakedown conditions. Note that the field measurements are sometimes in agreement with the DEM predictions, e.g., Figure 19(a) and (c), but also, the field measurements can be quite surprising when compared to the DEM predictions in other cases, such as in Figure 19(b) and (d). For example, Figure 19(d) indicates heave measured in both rail locations; this is somewhat unexpected even on a 5° curved track. In addition to the difficulties in maintaining uniform compaction/

Table 4. Field and DEM settlement prediction results.

<table>
<thead>
<tr>
<th>Test section</th>
<th>DEM settlement prediction models [N = \text{No. of passes}]</th>
<th>Settlement after 580,000 passes (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR 1</td>
<td>[S = 0.74N^{0.29} R^2 = 0.93e = 37%]</td>
<td>34.64 29.72</td>
</tr>
<tr>
<td>RR 2</td>
<td>[S = 0.64N^{0.32} R^2 = 0.91e = 32%]</td>
<td>44.60 38.10</td>
</tr>
<tr>
<td>RR 3</td>
<td>[S = 0.62N^{0.30} R^2 = 0.92e = 37%]</td>
<td>33.14 27.18</td>
</tr>
<tr>
<td>RR 4</td>
<td>[S = 0.84N^{0.29} R^2 = 0.88e = 45%]</td>
<td>39.32 29.97</td>
</tr>
</tbody>
</table>

Figure 19. Detailed ballast settlement results for the initial 1000 car passes (measurements I and II refer to settlements measured at two rail locations). (a) Test section with RR 1 ballast material. (b) Test section with RR 2 ballast material. (c) Test section with RR 3 ballast material. (d) Test material with RR 4 ballast material.
construction for ensuring proper test zone track geometries, the existing superelevation of the curved track would definitely influence the settlement characteristics on both sides of the track due to uneven loading and lateral forces applied in the rails. Meanwhile, in the DEM simulations, the loading was applied evenly onto the two rail seats and there was no lateral force applied to track substructure, which eliminated some random factors and yielded gradual settlement accumulations predicted in the ballast.

6. Summary and conclusions

Numerical simulations of railroad track ballast settlements were conducted in this study utilising a DEM ballast performance model developed at the University of Illinois. The ballast DEM model realistically considers both gradation properties and image analysis results of individual aggregate particles for shape, texture and angularity. To validate the ballast DEM model with the field settlement data, four ballast materials, donated by AAR member railroads, were used to construct ballast test zones at the FAST for HAL applications at TTC in Pueblo, Colorado. The four ballast materials had different imaging quantified aggregate shape indices and accordingly, accumulated settlements differently. Further, the superelevation in the curved track caused uneven measured settlements of the two rails and made it hard to predict ballast settlement behaviour in the initial loading stages, because only vertical loading was considered and the vertical loading was evenly applied in rail seats at both sides.

Using individual ballast particles as discrete elements generated from the four different ballast materials with varying aggregate shape, texture and angularity properties, the ballast DEM model was utilised to perform numerical simulations of the full-scale curved track test zones under realistic heavy axle train loadings. By properly accounting for the initial compaction conditions, the ballast DEM simulations closely predicted the lowest settlement performance of one of the ballast materials with only 2000 car passes investigated. The test section with more flat and elongated particles had the most particle breakage and degradation, which contributed to the highest field settlements. The ballast DEM model currently does not consider particle breakage. This is a current research area to enhance the capability to characterise ballast degradation with time and as a result, fully develop the ballast DEM model as a performance prediction tool.

Results from the dynamic, repeated train loading simulations indicate that the ballast DEM model could predict magnitudes of the field ballast settlements over 580,000 car passes (90 MGTs) performance trends reasonably accurately. The ballast settlement predictions were sensitive to both aggregate shape and gradation. In addition, ballast initial compaction condition (density, porosity or void ratio) played a very important role in ballast performance predictions and it is a key input for DEM simulations. The ballast DEM model has been successfully validated using the field settlement data for predicting ballast deformation behaviour under realistic train loading. The ballast DEM model has the potential use as a tool for engineering ballasted track designs and addressing critical substructure concerns such as those related to variable track stiffness and track transition zones.

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