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Image-aided Discrete Element Modeling of Aggregate Ballast Behavior

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Summary

The University of Illinois Urbana-Champaign recently focused efforts in investigating ballast behavior by the use of an innovative approach referred to as image-aided discrete element modeling (DEM). Use of image-aided DEM will allow the railroads to accurately model the behavior of ballast. Until today, ballast has been modeled as a continuous layer. The continuous layer approximation does not allow for evaluation of the effects of ballast particle size and shape, tie surface texture, or maintenance procedures.

DEM simulations were made to study aggregate shape, texture, and angularity affecting ballast behavior included ballast tamping, tie lateral pull-out test, and repeated loading of tie-ballast structure. The following findings are the highlights of the DEM analyses and simulation results.

- Ballast with angular aggregates is the most stable laterally and the most effected by track maintenance.
- Ballast consolidation rate is affected by loading rate. While railroads have already put this principal into practice using ballast consolidation machines, this is the first ballast theoretical model that is capable of predicting the effects of loading rate on ballast consolidation.
- Ballast shape affects the ballast settlement rates and may affect total settlement. From the model simulations, rounded and cubical ballast will settle less than angular ballast, at least initially. Thus, optimizing lateral and vertical ballast stability requires different gradations.
- Effects of aggregate flatness and elongation on lateral stability could not be evaluated since aggregate breakdown or degradation was not considered in the image-aided DEM analyses at this stage.

A large portion of the annual budget to sustain a railway track system goes into maintenance and renewal of track ballast. Annual industry expenditures for ballast and subgrade construction and renewal are nearing $740 million, with an additional $270 million for maintenance. A better basic understanding of ballast behavior is essential for mitigating track problems and failures due to ballast deformation, lateral movement, and instability causing track buckling. Under sponsorship of the Association of American Railroads' Affiliated Laboratories Program, a railroad specific ballast model that is intended for design of granular track layers for heavy axle load service was developed.

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INTRODUCTION

Image-aided DEM techniques utilize numerical procedures to solve problems that exhibit gross discontinuous behavior as interactions of particulate media under applied loading. They analyze multiple interacting bodies that undergo large dynamic motions. The analysis often consists of dynamically computing the motion of the individual discrete particles (elements) and the interaction (through Coulomb friction and cohesion) between the discrete particles and boundary conditions. By modeling the individual particles and computing their movements in time, the overall behavior of the granular assembly, which may include irrecoverable deformations, dilation, post-peak behavior, and anisotropy, was modeled implicitly.

Traditional DEM programs do not account for the effects of particle or element shape. This is indeed one of the most important factors affecting ballasted track performance. In this research, aggregate imaging technology was successfully combined with the use of a DEM program, BLOKS3D1, to investigate the impact of aggregate shape on ballast layer behavior. Particle shape or morphology was quantified with developed quantifiable indices. The flat and elongated (F&E) ratio, the angularity index (AI), and the surface texture index, developed using the University of Illinois Aggregate Image Analyzer (UIAIA), were used to generate a wide range aggregate shape properties.

The UIAIA system features taking images of individual aggregate particles from three orthogonal views with which morphological indices are quantified. Representative aggregate particles were generated based on those UIAIA processed 2-D images. This process was easily performed using available computer aided design software and by changing the shapes of the top, front, and side 2-D aggregate images. Accordingly, each representative aggregate with a certain F&E ratio and AI was created from the intersected common volume by extruding the three orthogonal 2-D images. Figure 1 illustrates building of a representative aggregate particle from the three 2-D images of each with an AI of 600 and a 1-to-1 F&E ratio.

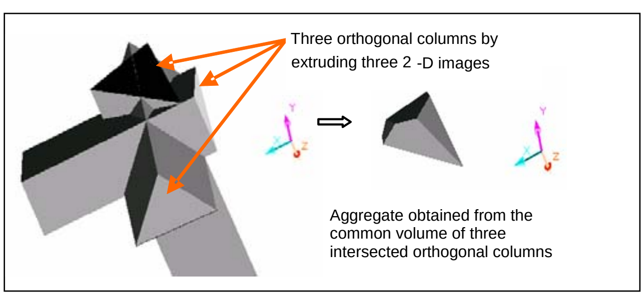


Figure 1. Construction of an Aggregate Particle

TIE PULL-OUT TEST

The image-aided DEM approach allows us to construct actual ballast aggregate shapes and sizes to investigate their impact on ballast performance.

Eleven typical aggregate shape categories (libraries) ranging from round and cubical to angular and elongated were generated. Eleven ballast samples were prepared with aggregates that come from these 11 libraries, respectively, to study the ballast shape effect by conducting tie pull-out tests. Only one half of the railroad track width was modeled due to symmetry. The first step was dropping particles to a rigid ground to achieve gravity equilibrium for each particle shape analyzed. This process was repeated until the ballast depth was large enough for the load capacity and tamping depth. Typically, three to four thousand aggregate particles were used to establish a ballast layer. After compaction, a tie was pushed into the ballast layer to simulate the tie settlement after a certain amount of traffic. The tie was then raised and tamping arms were inserted into the ballast layer followed by vibration and squeezing. Afterwards, the tie was placed back and a normal force of 667 pounds (3,000 Newton) was applied on the top of the tie followed by 1 inch (25 millimeters) lateral displacement (pull-out) assigned to the tie.

The same pull-out test procedure was also applied to the tie-ballast assembly before tamping. Figure 2 shows the ballast sample before tamping arms were inserted. Figure 3 shows tie lateral resistance forces before and after tamping from the pull-out test image-aided DEM simulations for the 11 ballast aggregate shapes.

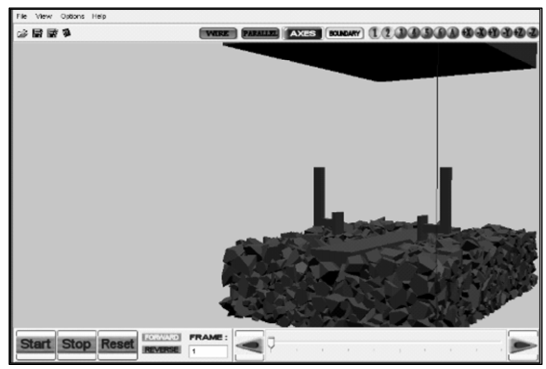


Figure 2. Tie-ballast Assembly Showing Tamping Arms

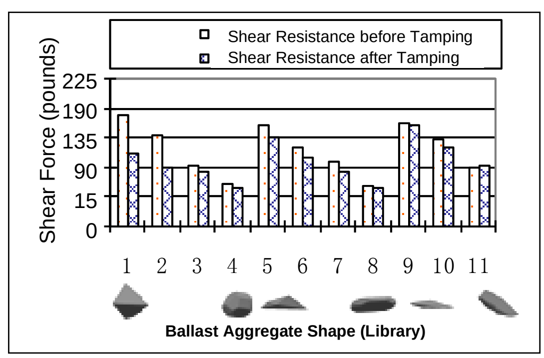
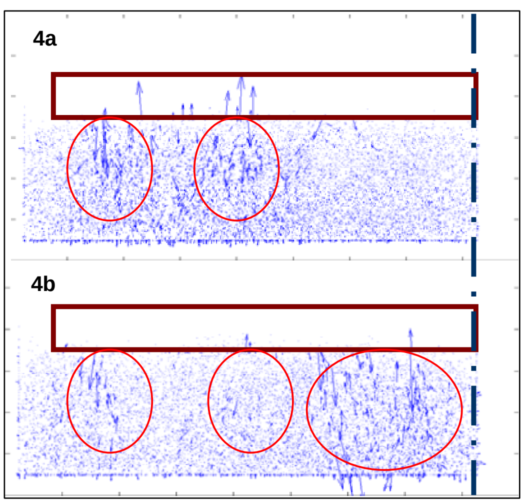


Figure 3. Tie Lateral Resistance from Tie Pull-out Test for 11 Aggregate Shapes

The actual weight of track (running rail, guardrail, tie plates, spikes, and clips) can be taken as approximately 200 pounds (90 kilograms) per lineal foot with a concrete tie weighing about 600 pounds (272 kilograms) and timber tie 200 pounds (90 kilograms). Therefore, the 667 pounds (3,000 Newton) normal force for the half-track was quite reasonable. From Figure 3, ballast samples with angular aggregates, higher AI values for libraries 1, 5, and 9, clearly resulted in significantly higher shear forces or lateral resistance than those ballast samples with low AI values both before and after tamping. Tamping had a large impact on the shear resistance especially for highly angular aggregates. The lateral stability decreased as much as 40 percent for aggregate library 1 with the highest AI of 670 (Figure 3). However, for aggregates with low AI, tamping had a relatively less significant effect on the lateral stability (aggregate library 4 in Figure 3), which implies that more rounded aggregates would have weaker interlock. For the ballast samples with more flat and elongated aggregates, the same trends still apply significantly less (for example, see aggregate libraries 4 through 11 in Figure 3). Tamping also affected shear resistances of flat and elongated particles. However, this should not suggest that flat and elongated aggregates would perform better than cubical ones. These slender particles are often very susceptible to breaking and degradation although this aspect was not addressed in this study because only rigid and unbreakable discrete elements were used at this stage of the image-aided DEM analysis.

The aggregate contact forces predicted in the ballast before and after tamping are plotted in Figures 4a and 4b for aggregate library 4 with AI = 620 and F&E ratio 3-to-1. Figure 4a shows that much greater contact forces or force chains to carry the wheel load were mainly provided before tamping by those particles immediately underneath the wheel loading position. However, during and after tamping, these particles were disturbed to transform into a looser state; thus, no longer carrying the wheel load (Figure 4b). As indicated with the major contact force chains, the new load carrying location was moved to the center of the tie. This phenomenon is often referred to as the center-bound tie, which can considerably decrease the tie service life.



Figures 4a and 4b. Aggregate Contact Forces under the Tie (4a) before and (4b) during and after Tamping

BALLAST REPEATED LOADING

Figure 5 shows a half-ballast section that developed for image-aided DEM simulations. A half-length tie was generated and placed on top of the ballast layer and the loading profiles were derived from track dynamic solutions.[2] Different combinations of image-aided DEM simulations were performed to consider a total of three loading magnitudes and three loading frequencies (1, 5, and 10 Hertz (Hz) corresponding to train speeds of 17.5, 87.5, and 175 miles per hour or mph, respectively), and three ballast aggregate shapes.

Figure 5. Half-tie Ballast Section –– Profile View

Ballast settlement: that is, permanent deformation or settlement depth, was recorded with the number of load cycles for all the image-aided DEM simulations. Each repeated loading test was performed up to 100 cycles but not up to commonly tested three log cycles due to intense computational time needs of image-aided DEM simulations. Results of repeated loading simulations that considered 22-kip (120-kN) normal loading are presented. For the ballast layer with cubical and angular shaped aggregates, simulation results showed that train speed had a significant impact on ballast settlement. The faster the train (higher loading frequency or shorter pulse durations), the lower the permanent deformations accumulated under the same load magnitude for the same ballast aggregate material.

Kim and Tutumluer reported similar findings on unbound aggregate permanent deformation trends from both laboratory repeated load triaxial testing of compacted aggregate specimens and full-scale field testing of thick airport granular layers.[3] It is encouraging to see similar trends obtained here from the image-aided DEM simulations. For the cubical and angular aggregate shape permanent deformations produced by a static loading and the same magnitude dynamic loads applied at different frequencies, the settlement produced by the static load is lower than the permanent deformation due the 1-Hz dynamic loading. Figure 6 shows these permanent deformations. As the loading frequency increased, the settlement is estimated to peak at a frequency between 1- and 5-Hz loadings, then, it decreased to a settlement accumulation less than the starting value due to the static loading. Therefore, there exists a frequency analogous to a natural frequency, possibly of the track structure simulated here, which could produce the maximum settlement. This kind of a trend in peak permanent deformations was found for two other aggregate shapes.

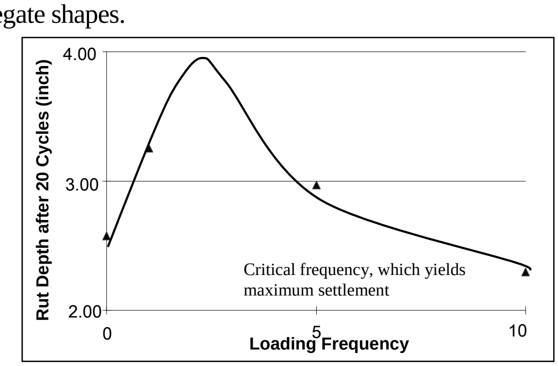


Figure 6. Permanent Deformations Produced by the Static Load and the Same Magnitude Dynamic Loads Applied at Different Frequencies

Figure 7 compares the performances of two cubical ballast aggregate shapes; however, library 1 was cubical and angular and library 8 was elongated and rounded. Note that the ballast layer with the rounded particles yields much less settlement than the ballast with angular aggregate. This is in general against the common belief and what is normally expected. Angular aggregates have been known to be always better than rounded aggregates in the sense of higher strength properties and improved stability due to better interlock. Nevertheless, when it came to permanent deformation trends, this was not the case from image-aided DEM simulations.

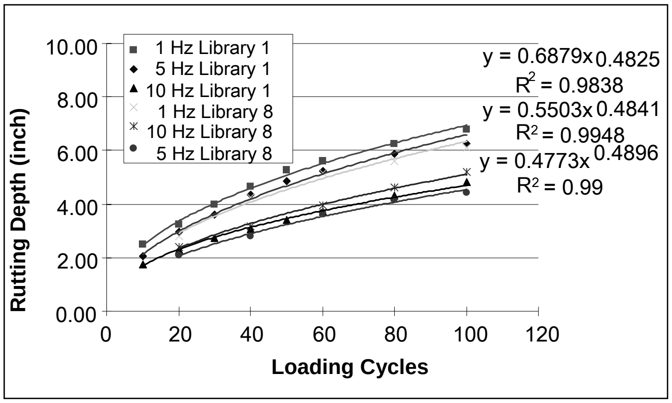


Figure 7. Comparisons of Ballast Settlement between Aggregate Shape Library 1 and 8

Two explanations in relation to what was simulated in this study are possible. One explanation is that during ballast aggregate particle packing, angular particles will result in larger air voids, e.g., consider uncompacted voids tests performed for determining angularity of fine and coarse aggregate. This is due to less efficient packing, which allows each aggregate particle more room to move, shakedown, and consolidate. The other explanation is that only one tie is simulated in the moving train direction. Because of this, the interactions between ties are not considered in the image-aided DEM simulations and the ballast aggregate movement along the traffic direction is limited by the transverse plane in the middle of the two adjacent ties. The ballast layer with the rounded aggregates has larger residual force on this middle plane than the force created by the angular aggregate. It suggests that, lateral confinement in the test setup for the rounded aggregate particles is higher than the angular one, this would help reduce the permanent deformation tendency of the library 3 rounded aggregate particles.

CONCLUSIONS

An innovative aggregate image-aided DEM approach was introduced to study ballast properties during railroad maintenance activities. These activities include before and after tamping and the accumulated settlement due to repeated train loading. The validated image analysis device, UIAIA, was utilized with its readily available algorithms for establishing a total of 11 aggregate shape libraries, three different aggregate F&E ratio categories, and five different AI values ranging from nearly rounded gravel to highly angular crushed particles.

The aggregate contact forces predicted during and after the compaction, or before and after the tamping activity were studied to quantify the effects of aggregate shape on the track lateral stability.

Ballast with angular aggregates (with high AI) resulted in the highest shear resistance or lateral stability. However, tamping dramatically decreased the lateral stability (as much as 40 percent) especially when ballast aggregates were very angular and caused the wheel load to be carried by aggregates closer to the center of tie, known as the center-bound tie.

Flatness and elongation of a particle had only a minor effect on lateral stability since aggregate breakdown or degradation was not considered in the image-aided DEM analysis at this stage.

From the image-aided DEM simulations, for up to 100 repeated load applications, it was found that reducing the train speed, such as slow orders or decreasing the applied loading frequency by increasing the load pulse durations, resulted in a significant increase in the settlement accumulation. However, static loading induced smaller permanent deformations than the 1-Hz loading. Therefore, a critical loading frequency to give maximum settlement was found to be between 1- and 5- Hz loadings. Effects of ballast aggregate shape was also found to influence ballast settlement. The image-aided DEM simulations that considered single tie tests resulted in lower ballast settlements for rounded aggregate particles possibly due to a lesser tendency to shakedown and consolidate.

For future ballast settlement simulations, it will be worthwhile to consider a modified ballast box for the half-tie and half-ballast width railroad track geometry with at least three ties included to model longitudinal confinement and movement of ballast aggregate.

Future work in image-aided DEM ballast simulations should also include the effects of different ballast gradations and breakage of flat and elongated aggregate particles.

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