Aggregate Shape Effects on Ballast Tamping and Railroad Track Lateral Stability

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Aggregate Shape Effects on Ballast Tamping and Railroad Track Lateral Stability

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ABSTRACT

Tamping is a common railroad maintenance activity often used to correct railroad profile. During tamping, tamping arms inserted into the ballast layer raise and loosen aggregates by squeezing and vibrating. As a result, the tamping process may cause serious problems such as derailment due to decreased track lateral stability and track buckle. This paper is aimed at applying discrete element modeling (DEM) concepts to railroad ballast to investigate effects of aggregate shape, texture and angularity on improved ballast compaction, strength, track stability, and resistance to lateral deformations by means of quantifying aggregate morphology from image analysis. An aggregate image analyzer recently developed and readily available for scanning ballast aggregates at the University of Illinois was successfully utilized to establish a library of representative aggregate particles from flat and elongated shapes to more cubical particles ranging from high angularity crushed particles to rounded gravels. A total of 11 aggregate shape libraries established this way with varying shape properties were used to construct ballast layers in a DEM computer program DBLOKS3D, which properly modeled individual aggregate particles as rigid shaped geometric blocks or discrete elements. Tie pull out tests were simulated in the DEM analyses to investigate before and after tamping of ballast compaction, strength and stability conditions. Tamping was found to significantly decrease the shear resistance of angular aggregates for up to 40%. Flatness and elongation of a particle had only a minor effect on lateral stability when aggregate breakdown was not considered.

Keywords: Ballast, Aggregate Shape, Tamping, Discrete Element Modeling, Image Analysis, Track Lateral Stability
INTRODUCTION

Railroad ballast is the aggregate layer usually installed between crosstie and subgrade. It transfers the load impact from the tie and distributes over the low strength subgrade soil. Under repeated wheel loading, railroad ballast is gradually consolidated gaining strength from aggregate interlocking. Meanwhile, the ballast layer accumulates permanent deformation after a certain amount of traffic which often causes rough track profile.

Maintenance activities such as tamping aims to raise the ballast layer and correct the track profile. During tamping, tie is raised followed by inserting the tamping arms; squeezing and vibrating the ballast. Usually the track profile can be corrected by one to several rounds of tamping. However, tamping dramatically decreases the ballast strength and stability by disturbing the consolidated ballast. Tie lateral pull out tests show that ballast could lose up to 60% of its original lateral resistance to tie right after tamping (1). This is believed to be an important cause of railroad derailment often associated with track buckle especially occurring in hot summer months.

Many factors may influence the ballast behavior before and after tamping such as aggregate gradation, shape, angularity, tie surface texture, and ballast compaction level. Among these factors, aggregate type and shape properties have been known to directly affect the compaction of ballast, lateral stability, and the long term performance of the railroad track. According to the American Railway Engineering and Maintenance of Way Association (AREMA), ballast aggregate should be open graded with hard, angular shaped particles providing sharp corners and cubical fragments with a minimum of flat and elongated pieces (maximum 5% by weight over 3 to 1 ratio). Yet, there is so far no standard test procedure to evaluate ballast lateral stability in terms of ballast aggregate shape, texture and angularity properties other than common visual
inspection. As a result, the influence of aggregate shape on ballast strength, lateral stability, and deformation characteristics has not been thoroughly investigated by means of quantifying individually the effects of aggregate morphological properties.

The mechanics of ballast tamping is investigated in this paper using a discrete particle analysis computational technique called Discrete Element Modeling (DEM) combined with digital image analyses of typical ballast aggregate shape, texture and angularity properties. Representative aggregate shapes developed based on image analyses, including aggregates with flat and elongated shapes to more cubical particles ranging from high angularity crushed particles to rounded gravels, are used in the simulations. Realistic ballast tamping maintenance activities are simulated by modeling typical field compaction equipment with tamping arms penetrating into ballast, raising the crosstie. Numerical DEM simulation results from a series of crosstie pull out tests utilizing the representative ballast aggregate shapes are also presented before and after tamping to highlight the impacts of tamping and different aggregate shapes on the track/tie lateral stability. Important conclusions are drawn on the selection of aggregate shapes for improved railroad track lateral stability and manufactured crosstie design.

BALLAST DISCRETE ELEMENT MODELING

Discrete Element Modeling (DEM) techniques are numerical procedures to solve problems that exhibit gross discontinuous behavior. Since its first introduction by Cundall (2), DEM techniques have been successfully used in many areas of civil engineering including geotechnical engineering and transportation/railroad engineering. The DEM method analyzes multiple interacting bodies undergoing large dynamic motions. The principle of DEM calculations is illustrated in Figure 1. The analysis consists of computing dynamically the motion of the
individual discrete elements and the interaction (friction) between the discrete particles and boundary conditions. By modeling the individual particles and computing their motion, the overall behavior of the granular assembly, which may include irrecoverable deformations, dilation, post-peak behavior, and anisotropy, is modeled implicitly. Interaction of granular materials or rock masses can this way be modeled accurately and realistically, since any discontinuous detail can be included in the analysis.

Using discrete particle analysis, the DEM approach can realistically model ballast layer and its interaction with crossties under dynamic loading. In this micro-mechanics based approach, aggregate particles are employed in the ballast to approximately model the load transfer mechanisms of the real particulate nature of granular materials. By representing railroad ballast as assembly of discrete elements, interacting through frictional contacts, the dominant effect that contacts may have on the behavior of the ballast is modeled directly. Both elastic and permanent deformations are solved for the ballast bed and crossties. A better basic understanding of the dynamic interactions and individual factors contributing to ballast lateral stability can be achieved to improve ballasted track design and manufactured crosstie design.

Carrillo (3) developed a DEM program called BLOCKS3D which utilized arbitrarily shaped block elements representing discrete particles. The BLOCKS3D program required rather long execution times due to its contact detection algorithm. Nezami et al. (4) improved considerably the BLOCKS3D by introducing a new, more efficient contact detection algorithm called “Fast Common Plane.” Four realistic contact types were established for corner-to-face, edge-to-edge, edge-to-face, and face-to-face element contacts. The new version of the DEM program named DBLOCKS3D, currently under development at the University of Illinois, was used in this research to generate a model for the mass of typical railroad ballast. The DBLOKS3D program
uses rigid but random shaped three-dimensional (3-D) “blocks” as the basic elements to realistically simulate interactions such as interlock/contact of actual ballast aggregate particles.

**IMAGE ANALYSIS FOR AGGREGATE SHAPE PROPERTIES**

Several studies in the last decade have linked coarse aggregate size and shape properties to pavement performance (5,6). In the pavement unbound aggregate base courses, while compaction is important from a shear resistance and strength point of view, the shape, size and texture of coarse aggregates are also important in providing stability (7). Field tests of conventional asphalt pavement sections with two different base thicknesses and three different base gradations showed that crushed-stone bases gave excellent stability because of a uniform, high degree of density and little or no segregation (8). Rounded river gravel with smooth surfaces was found to be twice as susceptible to rutting compared to crushed stones (9). For the unbound aggregate used in railroad ballast, a recent study by Han (10) developed a computer program and successfully modeled some of the observed trends in aggregate shape effects on railroad ballast performance based on a large amount of test data.

Imaging technology provides an objective and accurate measurement of aggregate profiles and has also been successfully used in the last two decades for quantifying aggregate morphology. A variety of imaging based aggregate morphological indices have been developed and linked to material strength and deformation properties in the recent years (11,12). Among the various particle morphological indices, the flat and elongated (F&E) ratio, angularity index (AI), and surface texture (ST) index developed using the University of Illinois Aggregate Image Analyzer (UIAIA) are key indices that have been recently validated by measuring aggregate properties and successfully relating them to laboratory strength data and field rutting
performances of both unbound aggregate and asphalt mixtures (13,14,15). The NCHRP 4-30A project final report on “Test Methods for Characterizing Aggregate Shape, Texture, and Angularity” has also identified UIAIA and its morphological indices as a viable image processing technique for analyzing coarse aggregate morphology (16).

In a recent national pool fund study, Tutumluer et al. (17) evaluated 48 different coarse aggregate samples obtained from 11 different states throughout the United States for shape, texture and angularity properties using the UIAIA. As a result, four categories were established in terms of angularity and surface texture ranges using statistical clustering techniques. Table 1 lists these categories, which coincided with the typical AI an ST index values identified for the uncrushed gravel, crushed gravel, crushed limestone, and crushed granite. As the surface irregularity levels of the aggregate materials increase from uncrushed to crushed, both the AI and ST indices increase for the 48 different aggregates evaluated. This finding is consistent with the common experience and perception although some special aggregate materials such as obsidian and precious stones may not follow this trend and instead possess rather high angularity and very smooth surface texture properties.

IMAGING AIDED DISCRETE ELEMENT METHODOLOGY

The AREMA specifications were used to select the standard No. 4 ballast gradation to represent uniform sized aggregate materials. In addition to size, aggregate shape properties were also reviewed according to the AREMA material specifications. Accordingly, 11 different shaped ballast aggregates were determined for the DEM study from an imaging based evaluation of various aggregate shapes. This was done by the use of the in-house UIAIA equipment and its F&E shape and AI algorithms already developed for the imaging based aggregate shape
Both the F&E ratio and the quantitative angularity index (AI) was developed based on three orthogonal images of an aggregate particle captured by the UIAIA. The F&E ratio is simply calculated as the ratio of the longest dimension to the shortest dimension of the 6 dimensions obtained from the three 2-D images. The AI methodology is based on tracing the change in slope of the particle image outline obtained from each of the top, side and front images. Accordingly, the AI procedure first determines an angularity index value for each of the three orthogonal 2-D images (13). Then, a final AI value is established for the particle by taking a weighted average of its angularity index determined for all 3 images.

A ballast aggregate shape library was established to include 3 different F&E aspect ratios (1 to 1, 3 to 1, and 5 to 1) and 5 different angularity (AI) classes ranging from nearly rounded river gravel to 100% crushed angular aggregate particles. The different shaped ballast aggregate particles were generated based on the UIAIA processed top, front, and side views. This process was easily performed using available computer aided design software and by changing the shapes of the top, front, and side aggregate 2-D images. Accordingly, each “representative aggregate” with a certain F&E ratio and AI was created from the intersection common volume built by extruding the three orthogonal 2-D images (see Figure 2). For example, Figure 2 illustrates building of a representative aggregate particle from the three 2-D images of each having an AI of 600 and 1 to 1 F&E ratio. Figure 3 shows all of the 11 representative aggregate particles created with AI ranges from 347 to 630 and F&E ratios from 1:1 to 5:1. These user defined element shape libraries were easily implemented into the DBLOCKS3D program for computation of the ballast aggregate contact forces and movement in DEM analysis.
TIE PULL OUT TEST SIMULATIONS AND RESULTS

All of the 11 aggregate particles with different shape properties were used to set up initial conditions for modeling the ballast layer using the DBLOKS3D program. Only one half of the railroad track width was modeled due to symmetry. A typical tie spacing of 508mm (20in.) was chosen in the analyses with the half section of a No. 4 tie used with 178mm x 203mm x 2591mm (7in. x 8in. x 8ft. 6in.) dimensions. The ballast depth was chosen to be 457mm (18in.) considering a typical tamping depth of 305mm (12in.). The whole process was modeled using the DBLOKS3D DEM program for providing geometry and contact force solutions at different loading time steps.

The flowchart of the tie pull out test procedure, also shown Figure 4, consists of the following steps:

1. Generate a layer of aggregates, typically 76 to 127mm (3 to 5in.) using the No. 4 ballast gradation from one aggregate library shape. Let the aggregate particles fall down and generate the second layer after the first layer stabilizes. Repeat the process until enough ballast depth is reached. Assign material and environment constants such as density and surface friction angle.

The approach was first to randomly drop 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. This way, a total of 11 ballast layers were prepared using the 11 aggregate libraries.

2. Compact the ballast layer by first decreasing aggregate surface friction angle to zero, i.e.,
aggregate surface is absolutely smooth, and then by applying down static force through a generated rigid block on top of the ballast until no vertical displacement is recorded. The rigid block above the ballast was created to push downwards and simulate the placement and compaction of aggregates during the layout of the original ballast layer.

3. Push a crosstie into the ballast layer representing the effects of repeated loading from wheels. In the field, the tie is commonly pushed into the ballast to stabilize the layer when the traffic accumulates to a certain point. Meanwhile, the ballast portion under the tie gains maximum interlock strength. In the laboratory, this process is normally checked by monitoring the residual stress in the ballast layer.

It was assumed in this study that the ballast and tie stabilized when the residual stresses reached maximum. Since this process was very time consuming, an alternative method was utilized. After placing the tie on the top of the ballast layer, the gravity constant was increased to 50 m/s² while keeping the aggregate surface smooth from step 2. The tie-ballast structure would this way reach an “equilibrium state” after a certain amount of time. This “equilibrium state” was checked by using the residual stress method (18).

The aggregate surface friction angle related to the aggregate surface texture was then changed back to 35 degrees for a rough textured crushed stone aggregate. A consolidated or shaken down tie-ballast sample was therefore prepared in this manner.

4. Raise the tie and insert tamping arms into the ballast layer at the position of the rail-tie crossing, squeeze and vibrate at a frequency of 35 Hz for 2 seconds.

5. Place the tie back on the top of the tamped ballast layer.

6. Apply 3000N vertical (normal) force on the tie followed by a 25mm (1in.) lateral displacement assigned to the tie.
For the same ballast layer, this was executed once in step 3 and once in step 5. The mobilized lateral resistance forces were recorded for all 11 samples.

Figure 5 shows tie lateral resistance forces before and after tamping from the pull out test DEM simulations for the 11 ballast aggregate shapes. Considering that the actual weight of track (running rail, guard rail, tie plates, spikes, and clips) can be taken as approximately 90kg (200lbs) per lineal foot with a concrete tie weighing about 272kg (600lbs) and timber tie weighing about 90kg (200lbs), the 3000N normal force for the half track was quite reasonable. From Figure 5, ballast samples with angular aggregates, higher AI values, 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 large as 40% for aggregate library 1 with the highest AI of 670 (see Figure 5). However, for aggregates with low AI, tamping had a relatively less significant effect on the lateral stability (see aggregate library 4 in Figure 5), which implies that more rounded aggregates would have weaker interlock. For the ballast samples with more flat and elongated aggregates, the same trends still applied but in a less significant way (for example, see aggregate libraries 5 through 11 in Figure 5). Tamping did even affect shear resistances of some 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 DEM analysis.

The aggregate contact forces predicted in the ballast before and after tamping are plotted in
Figure 7 for aggregate library 5 with AI = 620 and F&E ratio 3:1 (see Figure 3). It is clearly shown 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 (see Figure 7a). However, during and after tamping, these particles were disturbed to transform into a looser state and did not carry the wheel load anymore (see Figure 7b). As indicated with the major contact for 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.

**SUMMARY AND CONCLUSIONS**

A large portion of the annual budget to sustain the railway track system goes into maintenance and renewal of track ballast. A better basic understanding of the ballast behavior is essential for mitigating track problems and failures due to ballast deformation, lateral movement and instability causing track buckle. A realistic ballast maintenance activity was simulated in this paper by modeling typical field compaction equipment with tamping arms penetrating into ballast, raising the crosstie up, squeezing and compacting the underlying aggregate material, and the final positioning of the crosstie.

A discrete particle analysis computational technique called Discrete Element Modeling (DEM) was combined with digital image analyses of typical ballast aggregate shape, texture and angularity properties. The validated image analysis device, University of Illinois Aggregate Image Analyzer, was utilized with its readily available algorithms for establishing a total of 11 aggregate shape libraries, 3 different aggregate flat and elongated (F&E) ratio categories and 5 different angularity index (AI) values ranging from nearly rounded gravel to highly angular
crushed particles. These aggregate shapes established the ballast aggregate particles or discrete element blocks in the DEM computer program DBLOCKS3D analyses of railroad track tie pull out simulations.

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 (as much as 40%) the lateral stability especially when ballast aggregates were very angular and caused 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 DEM analysis at this stage. Research is currently underway to also consider the most realistic fouled ballast conditions and to analyze for settlement due to repeated wheel loading.

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<table>
<thead>
<tr>
<th>Aggregate Type</th>
<th>Angularity Index (AI)</th>
<th>Surface Texture (ST) Index</th>
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<tr>
<td></td>
<td>Range</td>
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<td>Uncrushed Gravel</td>
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<td>Crushed Limestone</td>
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<td>500</td>
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<tr>
<td>Crushed Granite</td>
<td>500-650</td>
<td>550</td>
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