Effect of Geogrid Inclusion on Ballast Breakage: A Numerical Study Using the Discrete Element Method

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ABSTRACT

Under train loading, ballast particles can undergo significant breakage resulting in overall reduction in ballast shear strength, and deterioration in the drainage properties. Placing geogrids in the ballast layer can significantly improve the mechanical response under loading, manifested through increased shear strength and improved resistance to permanent deformation. An ongoing research study at Boise State University is focusing on numerically studying the effect of geogrid reinforcement on ballast particle breakage under repeated loading. A commercially available discrete element modeling package, PFC3D® is being used for this purpose. The study makes innovative use of the Pavement Design Package, a feature built into the PFC software package. This paper presents findings on how the geogrid placement in the ballast layer affects the amount of ballast breakage and the associated permanent deformation experienced by the ballast layer. Two different geogrid types, with square as well as triangular apertures, have been studied in this modeling effort.

INTRODUCTION

Type of aggregate (in terms of geology), particle angularity, gradation, and relative arrangement of individual particles in the aggregate matrix are the primary factors that influence the elastic as well as inelastic response of railroad ballast layers under loading (Tutumluer et al., 2007). Accumulation of irrecoverable strain or permanent deformation within the ballast layer is caused by rearrangement and breakage of individual ballast particles, and is the main trigger for maintenance activities on railroad tracks (Kwan, 2006). Geosynthetics have been proven in the past to reduce particle degradation and the resulting permanent deformation accumulation in ballast layers, thereby improving the overall track performance (Brown et al., 2007; Indraratna et al., 2006; Indraratna et al., 2013). Geogrids, a type of geosynthetics, can be placed within the ballast layer to improve its strength and modulus. Interaction between individual particles and geogrid apertures restricts excessive lateral movement of ballast particles under loading (Brown et al., 2006; Qian et al., 2013).

The degree of interlock between the geogrid and ballast aggregates is affected by various factors like the aggregate particle shape and size, types and properties of geogrids, loading conditions, and compaction effort during the installation of geogrids (Qian et al., 2015). Researchers have conducted laboratory and numerical studies to study this reinforcement mechanism due to biaxial geogrids having rectangular or square apertures (Indraratna et al., 2006; Brown et al., 2007) and triaxial geogrids having triangular apertures (Qian et al., 2013).
Most of these past research efforts observed increased bearing capacity of the track substructure due to geogrid reinforcement. Biaxial geogrids have high tensile strength properties mainly in two directions, machine direction and cross-machine direction, while triaxial geogrids can provide more uniform reinforcement in all directions (Qian et al., 2013); several research studies have compared the performances of these two geogrid types as far as reinforced ballast response under loading is concerned (Tutumluer et al., 2009a; Biabani and Indraratna, 2015).

Studying the interaction between geogrid and ballast particles at a micromechanical level can enhance the understanding of reinforced ballast behavior under loading. Analysis at the micromechanical level is particularly important when comparing the degree of ballast degradation under unreinforced and geogrid-reinforced conditions. An ongoing research study at Boise State University is using the Discrete Element Method (DEM) to understand the effect of geogrid reinforcement on ballast breakage and the associated vertical permanent deformation of the ballast layer. Particle breakage and permanent deformation accumulation trends were studied for unreinforced ballast specimens along with biaxial and triaxial geogrid-reinforced specimens.

**MODELING APPROACH**

This research study marks an innovative use of the pavement design package (pdPkg) of Particle Flow Code in 3 dimensions (PFC3D). The pdPkg can be used for the creation and triaxial testing of synthetic unsaturated granular material with the geogrid embedment. Detailed explanation about the pdPkg can be found in the technical memorandum prepared by Potyondy (2018). Relevant model parameters for the models created in the current study have been borrowed from Potyondy (2018). The following sections briefly describe the procedure adopted to create the geogrid and ballast materials using the pdPkg.

**Model Generation**

**Geogrid Reinforced Specimen.** One of the primary considerations during numerical modeling involves selection of appropriate model dimensions. This is particularly important in case of discrete element modeling as the relative dimension of the model with respect to the maximum particle size can significantly affect the results. Indraratna et al. (1993) reported that as the value of sample size ratio (ratio of diameter of specimen to the maximum particle size dimension) approaches 6, sample size effects become negligible. Commonly used ballast materials often comprise particles as large as 50-60 mm; accordingly, to minimize size effects while at the same time keeping the computational time requirements within reasonable limits, a cubic specimen box of size 300 mm X 300 mm X 300 mm was selected for this study. Using the pdPkg, a geogrid set comprising one layer of flat geogrid oriented perpendicular to the specimen axis was then created, and placed at the center of the specimen box. Ballast grains represented by simple 4-ball clumps, satisfying the particle size distribution presented in Figure 1 were then distributed in the box. Note that the ballast shape selected in this study was an overly-simplified polyhedral shape and was selected to reduce computational efforts associated with more complex polyhedral particles. Movement of the grid was then fixed during this initial assembly stage such that no rotation or translation of the balls forming geogrid was allowed; and the ballast grains were distributed uniformly in the model until the static equilibrium was achieved. Confinement was applied by moving the specimen box walls to obtain a material pressure of 10 kPa. Note that this confining pressure level was selected as representative initial railroad ballast layer confinement
levels have been reported in the literature to range between 10-60 kPa (Indraratna et al., 2010a). For the current study, the lower range of this confinement pressure was chosen as it would increase the tendency of ballast particles to spread laterally, thereby ensuring mobilization of the geogrid interlocking mechanism. After this step, the grid was freed, and the above step was repeated on the unconstrained grid to allow the grid to move and deform in response to the compressive forces imposed by the grains. Detailed description of this grid embedment process in pdPkg can be found elsewhere (Potyondy, 2018).

![Figure 1. Particle size distribution used in the current study to create the ballast matrix (Inset: tetrahedral ballast clump used in the model).](image)

Finally, at the end of this process, a specimen box consisting of homogeneous, isotropic and well-connected ballast assembly with an embedded and well interlocked grid at the material pressure of 10 kPa was produced. A total of 846 ballast clumps (each clump comprises four balls) were created. One of the primary objectives during the sample preparation phase was to generate ballast assemblies with similar porosity values. The final porosity values achieved for the three different geogrid-reinforced models (biaxial beamed, biaxial parallel bonded and triaxial beamed; details to be provided later), were 0.462, 0.460 and 0.460 respectively. Note that final porosity values in the range of 0.44-0.46 were targeted as it has been reported by researchers to be the realistic porosity value of the railroad ballast layer (Indraratna et al., 1998).

**Geogrid Properties.** Two different types of geogrids, based on the aperture shape, were modeled in the current study: square (biaxial) and triangular (triaxial). Figure 2 shows the DEM-generated geogrid elements used in the current study. Note that each grid consists of strings of overlapping spherical balls joined in a particular manner. For biaxial geogrids, the bonds between individual particles were modeled using parallel bonds or beamed contacts; for triangular-aperture geogrids on the other hand, only beamed contact models were used between individual balls. These contact models provide the behavior of a finite size, linear elastic and bonded interface that carries a force and moment. The interface of the parallel-bonded contact model has a circular cross section, while the interface of the beam contact model has a rectangular cross section. Each grid behaves either as an elastic beam of circular cross section with varying radius along its length (parallel-bonded contacts), or as a prismatic and bisymmetrical elastic beam with varying width and height along its length (beamed contacts).
The grid behaves as an elastic body which does not break, and will return to its original shape when unloaded. More details about the grid modeling approach can be found elsewhere (Potyondy, 2018).

![Image](Biaxial Beamed (BB) Biaxial Parallel-Bonded (BP) Triaxial Beamed (TB))

**Figure 2. Geogrid types used in the study.**

The properties of the square (BB/BP) and triangular geogrids (TB) resemble those of Tensar SS20 biaxial (aperture size 39 mm) and Tensar TX160 triaxial (pitch 40.7 mm) geogrids respectively. Detailed descriptions about the particular types of geogrids can be found elsewhere (Potyondy, 2018). Model parameters assigned within the Pavement Design Package to model the geogrids have been listed in Table 1.

<table>
<thead>
<tr>
<th>Grid Set parameter (Biaxial and Triaxial)</th>
<th>PFC parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Density (kg/m$^3$)</td>
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</tr>
<tr>
<td>Young’s Modulus (GPa)</td>
<td>gd_E</td>
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</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>gd_nu</td>
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<tr>
<td>Grid-Ballast Effective Modulus (GPa)</td>
<td>gd_ggemod</td>
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</tr>
<tr>
<td>Grid-Ballast Stiffness Ratio</td>
<td>gd_ggkrat</td>
<td>2</td>
</tr>
<tr>
<td>Grid Ballast Friction Coefficient</td>
<td>gd_ggfric</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Unreinforced (or Control) Specimen.** Unreinforced (or control) specimens were created in the DEM model targeting the same specimen size as the geogrid-reinforced models; one of the objectives was to ensure the number of ballast particles are similar in the unreinforced as well as geogrid-reinforced specimens. However, upon ‘material generation’ in the model, it was observed that the porosity value for the unreinforced model was much lower compared to that for the geogrid-reinforced model. Significant differences in porosities can lead to significantly different particle interlock, thus resulting in noticeably different response under loading. For example, permanent deformation accumulation in a ballast layer depends mainly on the initial compacted density of the ballast (Selig and Waters, 1994). To facilitate direct comparison between unreinforced and geogrid-reinforced ballast behavior and to adequately isolate the effect of the geogrid reinforcement, it is critical that both specimens be constituted at relatively similar porosity values. Therefore, the current study adopted the following approach to achieve the target porosity values.

First, a relatively larger (compared to that for the unreinforced specimen) box size (310 x 310 x 335 mm) was created, and filled with ballast particles. A total of 847 ballast particles (each particle comprised 4-balls glued together in a pre-established geometric pattern) were distributed
in the specimen box using the same particle size distribution as shown in Figure 1. The side walls of the model were then compressed to achieve an average material pressure value of 10 kPa. The resulting change in dimension of the specimen produced a ballast assembly with a final porosity value of 0.464.

**Contact Models Used.** Five different types of contacts are possible in the models created in this current study. They are: (1) Ballast-Ballast; (2) Geogrid-Geogrid; (3) Geogrid-Ballast; (4) Ballast-Specimen Box; and (5) Geogrid-Specimen Box. Depending on the nature of interaction at these contact points, different contact models were assigned to mechanically define the behavior at these interfaces. For example, the beamed or parallel bonded contact models were used to define the behavior at the contact points between balls constituting the geogrids. Similarly, the Hill contact model (Potyondy, 2016) was used to define the behavior at ballast-ballast contact points. Finally, the linear contact model was used to define the grid-ballast, grid-specimen box, and ballast-specimen box interactions. The primary difference between the ‘beamed’ and ‘parallel bonded’ contact models was described earlier in this manuscript. Detailed information about the principles governing the linear contact model can be found elsewhere (Itasca, 2016).

The Hill contact model defines the behavior of an infinitesimal, nonlinear elastic (no tension) and frictional interface that carries a compressive surface interaction force and may carry a tensile moisture force. It behaves like two locally elastic spheres that may have a ‘liquid bridge’. The liquid bridge is present if the moisture state is wet, and absent if the moisture state is dry. Detailed information on the Hill Contact Model can be found elsewhere (Potyondy, 2016). In the current study, the ballast material was modeled in a dry state, and therefore, the liquid bridge was not modeled. Therefore, the each contact point between ballast particles simplifies to a non-linear elastic (no tension) contact with frictional interface.

**Model Parameters Used.** As already mentioned, one of the objectives of the current research effort was to study the effect of geogrid reinforcement on ballast breakage using DEM. To achieve this objective, it was necessary to first establish the crushing strengths for ballast particles being included in the model. This would help define the bond strengths between individual balls within each clump (remember that ballast particles were modeled as 4-ball clumps). This was accomplished by running the Single Particle Crushing Test (SPCT) in the laboratory. Once the particle crushing strengths were established in the laboratory, similar tests were performed using PFC. The Diametral Compression (DC) or Brazilian test, built into the material modeling package in PFC was used for this purpose. Figures 3-a and 3-b show photographs of the SPCT being carried out in the laboratory. Figures 3-c and 3-d show the same test being carried out in PFC. Note that special care was taken to replicate the exact ballast particle shape for DEM simulation of the SPCT. This was done using the software “Autodesk ReCap Photo” (Autodesk, 2017). Note that the red discs in Figure 3-d represent broken bonds between individual balls. Appearance of the red disc indicates fracture of the ballast particle at that particular point. Three different ballast particles were tested in the laboratory using SPCT and were subsequently modeled using PFC. Bond strengths were assigned within each ballast clump after calibration of the Brazilian test models against the laboratory test results. Table 2 shows the model parameters used in the simulation. Details about the ballast particle generation for SPCT and calibration of the SPCT model are beyond the scope of the current manuscript and
will be published elsewhere. Laboratory specific gravity tests were conducted on the ballast particles, and the resulting values were assigned in the model.

Table 2. Model parameters used in the simulation.

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Effective Modulus</td>
<td>3x10⁹ N/m²</td>
</tr>
<tr>
<td>Ballast Young’s Modulus</td>
<td>8.33x10⁸ N/m²</td>
</tr>
<tr>
<td>Ballast Poisson’s ratio</td>
<td>0.2</td>
</tr>
<tr>
<td>Ballast Friction Coefficient</td>
<td>0.6</td>
</tr>
<tr>
<td>Ballast Density (ρ)</td>
<td>2610 kg/m³</td>
</tr>
</tbody>
</table>

**Parallel Bond Properties**

<table>
<thead>
<tr>
<th>Parallel Bond Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel Bond Normal Stiffness (k_n)</td>
<td>1.48x10¹¹ N/m³</td>
</tr>
<tr>
<td>Parallel Bond Shear Stiffness (k_s)</td>
<td>7.58x10¹⁰ N/m³</td>
</tr>
<tr>
<td>Parallel Bond Normal Strength (σ)</td>
<td>3.83x10⁶ N/m²</td>
</tr>
<tr>
<td>Parallel Bond Shear Strength (τ)</td>
<td>1.57x10⁷ N/m²</td>
</tr>
<tr>
<td>Parallel Bond Radius Multiplier (λ)</td>
<td>1 (fully-bonded)</td>
</tr>
</tbody>
</table>

Figure 3. (a) Photograph of ballast particle on loading platen for single particle crushing test in the laboratory (b) Broken ballast particle after crushing (c) Ballast particle generated in PFC, and oriented for the Diametral Compression test (d) Fractured ballast particle after DC test (red discs represented fragments).

Figure 4 shows screenshots of the DEM-generated ballast specimens (at the end of the initial packed assembly process), under both unreinforced as well as geogrid-reinforced configurations. After this step, a cyclic loading was applied to the specimen (using a wall servo mechanism) in the vertical direction with a mean stress level of 232 kPa. Note that until the start
of the cyclic loading process, the ballast particles (represented by 4 ball clumps) were modeled as non-breakable.

**Figure 4.** Initial packed assembly after ballast distribution and confinement (a) Biaxial Beamed or BB grid (b) Biaxial Parallel-Bonded or BP grid (c) Triaxial Beamed or TB grid (d) No-grid. *(The ballast particles have been made 50% transparent for a, b and c to aid geogrid visibility).*

**Ballast Breakage Simulation under Cyclic Loading.** To allow the ballast particles to undergo breakage under cyclic loading, the ballast clumps were released, and parallel bonds with properties shown in Table 2 (section Parallel Bond Parameters) were applied in between the balls just before initiation of the cyclic loading process. At this state, each ballast particle behaves like a 4-ball cluster joined by the linear parallel bonds which could break when the stresses in the bonds exceeded the predefined bond strength values. Once a bond breaks, the resulting contact between ballast particles is governed by the Hill Contact model.

 Sinusoidal load cycled between two compressive states of $q_{\text{min}}$ (45 kPa) and $q_{\text{max}}$ (419 kPa) was then applied via the top wall of the specimen box. The frequency of the cyclic loading was set to 10 Hz. These values were obtained from the research effort reported by Indraratna et al. (2010b). Detailed description of the cyclic loading and the ballast breakage criteria can be found elsewhere (Dahal et al., 2018). As it would be unrealistic to perform simulations for a large number of cycles due to the limitation in computing times, the current simulations were run for 40 cycles; the number of ballast breakage as well as permanent axial strain accumulations for each model were recorded, and have been discussed below.
RESULTS AND DISCUSSIONS

Comparing the Extent of Ballast Breakage

To quantify the number of bond breakages due to cyclic loading, the number of bonds before and after cyclic loading was counted. As seen from the table in the inset of Figure 5, the total number of bond breakages were very similar for the four different models, with the two extreme values differing by only 3% as far as the total number of bond breakages are concerned. Therefore, based on these results no clear distinction could be made regarding the effect of geogrid reinforcement on ballast breakage. This can be visually confirmed by plotting the particle size distributions for the specimens before and after loading. As seen from Figure 5, there was no significant difference in the particle size distribution after loading between the unreinforced and geogrid-reinforced specimens.

![Figure 5. Ballast particle size distribution before and after cyclic loading (Inset: Table containing number of linear parallel bonds before and after cyclic loading for different models).](image)

Comparison of Permanent Axial Strain or Permanent Deformation (PD)

Axial strain was calculated using the relative distance between the top and the bottom walls before and after cyclic loading. Figure 6 shows a plot of the permanent axial strain as a function of number of load cycles for different geogrid-reinforced and unreinforced specimens. As seen from the figure, for all the ballast layers, the permanent strain accumulation increased rapidly during the initial cycles of loading, and the rate of PD accumulation per cycle gradually reduced thereafter. The PD accumulation during the initial loading cycles is primarily due to ballast breakage and particle rearrangement. The unreinforced specimen showed the highest strain accumulation of approximately 15.4%. The grid-embedded ballast layers were found to accumulate total permanent strain magnitudes of 10.87% for BB grid, 10.71% for BP grid, and 9.99% for TB grid. From these results, the benefits of geogrid reinforcement for permanent strain reduction is clearly evident. Comparing the results for the biaxial and triaxial geogrids, the
triangular-aperture geogrids provided better aggregate interlock than the square aperture geogrids, and resulted in lower permanent strain accumulations. This can be attributed to the fact that the stiffness of triaxial geogrid is nearly consistent in all directions unlike the biaxial geogrids in which the stiffness is greatest in the direction of ribs only (Chen et al., 2012).

**CONCLUSIONS**

Based on the results of the above simulations, following conclusions can be drawn.

1. For both unreinforced as well as geogrid-reinforced ballast specimens, most of the permanent deformation accumulation and particle breakage occurred during the initial load cycles; this rate decreased as the number of loading cycles increased.
2. The use of geogrid in the ballast layer leads to significant reductions in the permanent deformation accumulation.
3. Triangular-aperture geogrids lead to greater reductions in permanent deformation accumulation compared to square-aperture geogrids.
4. No significant effect of geogrid reinforcement on ballast breakage was observed.

**LIMITATIONS OF CURRENT STUDY**

1. A simple polyhedral ballast shape was used in these models to reduce the computational effort requirements. Future publications will focus on models with more realistic ballast shapes.
2. The effect of geogrid reinforcement on lateral movement within the ballast layer was not studied; and will be included in future publications.

**REFERENCES**


Itasca. (2018). *Particle flow code in two and three dimensions*, Itasca Consulting Group, Version 5.0, Minneapolis, MN.


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