Behavior of Geogrid Reinforced Ballast at Different Levels of Degradation

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Abstract: Geogrids have been successfully used in highway applications for stabilization and reinforcement purposes. Recent research efforts have also been dedicated to study geogrids in railway applications, especially for ballast reinforcement. Ballast typically containing large sized aggregate particles with uniform gradation is an essential layer in railway substructure to facilitate load distribution and drainage. However, the reinforcement effect of geogrids in ballast has not been thoroughly investigated yet. Especially with accumulation of tonnage, ballast will get fouled increasingly due to aggregate degradation or contamination by other materials, affecting aggregate-geogrid interlock mechanism at different levels of degradation. In this study, monotonic triaxial strength tests performed on both clean and fouled ballast specimens have been reinforced by geogrids and tested using a large scale triaxial test device recently developed at the University of Illinois specifically for ballast size aggregate materials. Two different geogrids with square and triangular shaped apertures are used in comparison. To further investigate the geogrid reinforcement mechanisms, an imaging based Discrete Element Modeling (DEM) approach was also adopted with the capability to create actual ballast aggregate particles as three-dimensional polyhedron blocks having the same particle size distributions and imaging quantified average shapes and angularities. By addressing adequately the particulate nature of different sized and shaped ballast aggregate particles and their interactions with each other at contact points, and through the innovative use of membrane elements surrounding the cylindrical ballast specimen, the ballast DEM model accurately captured the strength behavior of both clean and degraded ballast specimens reinforced by geogrids with different aperture shapes.

Keywords: ballast aggregates, geogrids, triaxial testing, discrete element method, fouling

INTRODUCTION

Geogrid reinforcement of ballast layer can provide significant benefits to railroad track engineering. Through effective geogrid-aggregate interlocking, geogrids can improve strength and modulus properties of the ballast layer, limit lateral movement of aggregate particles, and reduce vertical settlement. The interlocking between geogrids and aggregate particles depends on many factors, such as aggregate size and shape properties, geogrid types and properties, compactive efforts during installation, and loading conditions.

Previous studies on clean ballast materials have already investigated different factors affecting the interlock between geogrids and aggregate particles through laboratory tests and numerical simulations (Bathurst and Raymond 1987, Raymond and Ismail 2003, Indraratna et al. 2006, Brown et al. 2007, Tutumluer et al. 2009, Qian et al. 2011, Qian et al. 2013a, b). However, with accumulation of tonnage in the field, ballast layer is progressively fouled with finer materials filling the void space commonly due to the ballast aggregate breakdown, which results in changing considerably aggregate size and shape properties and affecting aggregate-geogrid interlock mechanism at different levels of fouling. Effects of ballast degradation on ballast strength and aggregate-geogrid interlock have not been thoroughly studied.

This paper describes preliminary findings from an ongoing research study at the University of Illinois focusing on triaxial testing of geogrid-reinforced ballast specimens using a large scale triaxial test device and modeling the micromechanical interlock behavior of geogrid-aggregate systems with the Discrete Element Method (DEM). Clean and degraded ballast specimens reinforced with geogrids having triangular or square apertures were tested to evaluate the reinforcement benefits through improved stress-strain behavior and strength properties. Unreinforced ballast specimens were also tested as the control samples for evaluation. To simulate the triaxial tests and investigate geogrid reinforcement mechanisms, a numerical modeling approach based on the DEM was adopted with the capability to create actual ballast aggregate particles as three-dimensional polyhedron elements having the same particle size distributions and imaging quantified average shapes and angularities. Both the triaxial strength tests and the DEM simulation results are presented to evaluate the reinforcement benefits and mechanisms governing behavior of the ballast specimens, which were reinforced with different aperture geogrids.

TRIAXIAL TEST DEVICE

A large scale triaxial test device (The University of Illinois Ballast Triaxial Tester or TX-24) was recently developed at the University of Illinois for testing specifically ballast size aggregate materials. The test specimen dimensions are 30.5 cm (12 in.) in diameter and 61.0 cm (24 in.) in height. An internal load cell (Honeywell Model 3174) with a capacity of 89 kN (20 kips) is placed on top of the specimen top platen. Three vertical LVDTs are placed around the cylindrical test specimen at 120-degree angles between each other to measure the vertical deformations of the specimen from three different side locations. Another LVDT is mounted on a circumferential chain wrapped around the specimen at the mid-height to measure the radial deformation of the test specimen. Fig. 1 shows a photo of the TX-24 setup having an instrumented ballast specimen ready for testing.

Considering realistically the influence of traffic induced rather high loading rates on the ballast material behavior, laboratory triaxial strength tests were conducted at a rapid shearing rate of 5% strain per second at an applied constant confining pressure of 138 kPa (20 psi) (Qian et al. 2013c). Considering the 61.0-cm (24-in.) high ballast specimens, these loading rates correspond to vertical ram movements of 30.5 mm (1.2 in.) per second. Due to the large movements of the loading ram causing instant bulging and shearing of ballast samples, the LVDTs were not used during the ballast strength tests.

FIG. 1. The University of Illinois ballast triaxial tester (TX-24)

BALLAST MATERIAL AND GEOGRIDS

The ballast material used in the triaxial strength tests was a clean oven-dried limestone having 100% crushed aggregates. The degraded ballast samples for the triaxial shear strength characteristics were generated from Los Angeles (LA) abrasion testing. A 10-kg oven-dried clean ballast sample having the same gradation and shape properties was placed in the LA abrasion test drum to run approximately 1,500 turns, which was necessary to achieve a Fouling Index (FI) of 40, which corresponds to a heavily fouled or degraded ballast condition certainly requiring maintenance activities in the track (Selig and Waters 1994). All particles with sizes above 9.5 mm (3/8 in.) were collected as the degraded ballast material for conducting the strength test later on. The generated fine materials with sizes below 9.5 mm (3/8 in.) were saved for future research. This LA abrasion test procedure was repeated until enough degraded ballast material was generated. More details on the steps followed to generate the degraded ballast through the LA abrasion testing have been provided elsewhere (Qian et al. 2014). Fig. 2 shows the size distributions of the clean ballast material, which adequately met the US AREMA No. 24 gradation requirements, and the degraded ballast material. Besides the grain size distribution, aggregate shape properties, especially the flat and elongated (F&E) ratio, the angularity index (AI), and the surface texture (ST) index, are key indices quantified by the University of Illinois Aggregate Image Analyzer (UIAIA) (Rao et al. 2002). The two types of ballast materials were scanned and analyzed respectively using the recently enhanced image analyzer (E-UIAIA) to determine the values of the F&E ratio, AI, and ST index, which were then used as the essential morphological data to generate ballast aggregate particle shapes as three-dimensional (3D) polyhedrons, i.e., individual discrete elements utilized in the ballast DEM model (see Fig. 3). The shape properties and some gradation information of the ballast materials are listed in Table 1.

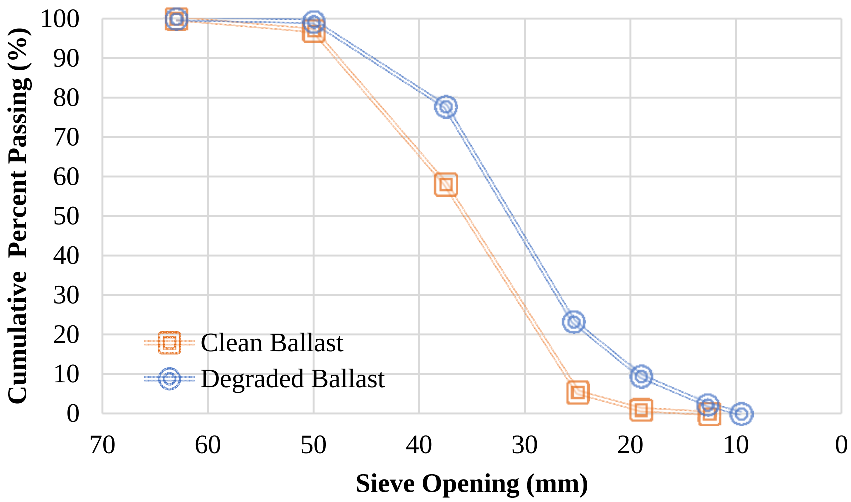


FIG. 2. Particle size distributions of clean and degraded ballast aggregates

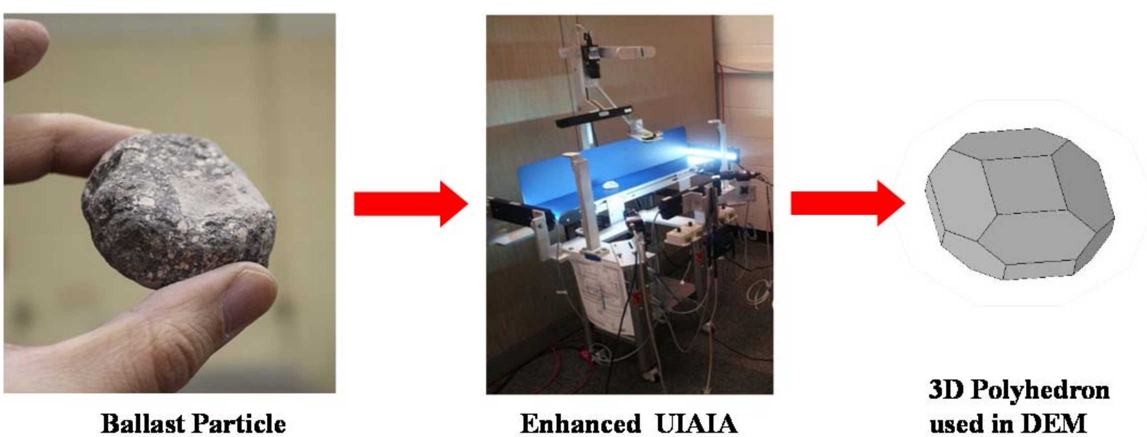


FIG. 3. Conceptual approach for aggregate imaging based railroad ballast particle generation for discrete element method (DEM) simulations

TABLE 1. Properties of Ballast Aggregates Used

Ballast Material (Limestone) Properties					
Ballast Type	Angularity Index (AI in degrees)	Flat & Elongation (F&E) Ratio	Surface Texture (ST) Index	Cu	Cc
Clean	440	2.3	2	1.46	0.97
Degraded	278	1.9	1.3	1.79	1.13

Approximately 70 kg of clean ballast material or 73 kg of degraded ballast material was poured into an aluminum split mold in four lifts, and compacted using a 27.2-kg (60-lb.) electric jack hammer for 4 seconds for each lift (16 seconds in total). After compaction of the first two lifts, one layer of geogrid was placed carefully in the middle of the test specimen for reinforced specimens. At the end of placing all four lifts, each test specimen was checked for the total height and leveling of the top plate. The void ratios computed were 0.68 for clean ballast and 0.61 for degraded ballast, respectively. Fig. 4 shows the photos of the geogrids tested and corresponding properties of the geogrids are given in Table 2.

TABLE 2. Properties of Geogrids Used

	Square Aperture	Triangular Aperture	
	Side	Longitudinal	Diagonal
Aperture Dimensions (mm)	65	60	60
Ultimate QC Strength (kN/m)	30		
Junction Efficiency (percentage)		93	
Radial Stiffness (kN/m@0.5% strain)		350	

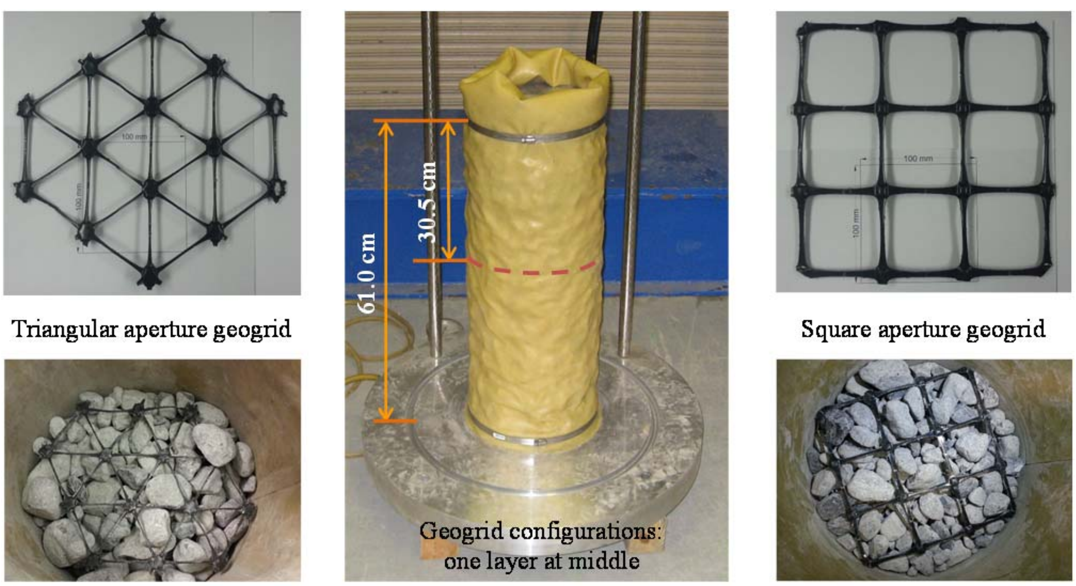


FIG. 4. Triangular and square aperture geogrids used in triaxial tests

DEM SIMULATIONS OF THE TRIAXIAL STRENGTH TESTS

Discrete Element Method (DEM) has been successfully applied in simulating ballast behavior recently (Tutumluer et al. 2009, Indraratna et al. 2010, Lu and McDowell 2010). The DEM simulation approach developed at the University of Illinois adopts real polyhedral particles and has the capability to create actual ballast aggregate particles as 3D polyhedron elements having the same particle size distributions and imaging quantified average shapes and angularities. This DEM approach was calibrated by the laboratory large scale direct shear test results (Tutumluer et al. 2006), validated by field track settlement predictions (Tutumluer et al. 2013), and has been successfully utilized to simulate complex ballast behavior, especially large scale triaxial tests with or without geogrid reinforcement. (Qian et al. 2013a, b, c).

Qian et al. (2013c) recently used rigid rectangular cuboid discrete elements positioned in a cylindrical arrangement to simulate a flexible membrane and "incremental displacement shearing method" to simulate triaxial strength test with the BLOKS3D DEM program. A similar approach was used in this study. Fig. 5 provides the overview of the DEM model. Details of simulating flexible membrane by rigid discrete elements and application of "incremental displacement shearing method" in triaxial strength test simulation are provided elsewhere (Qian et al. 2013c).

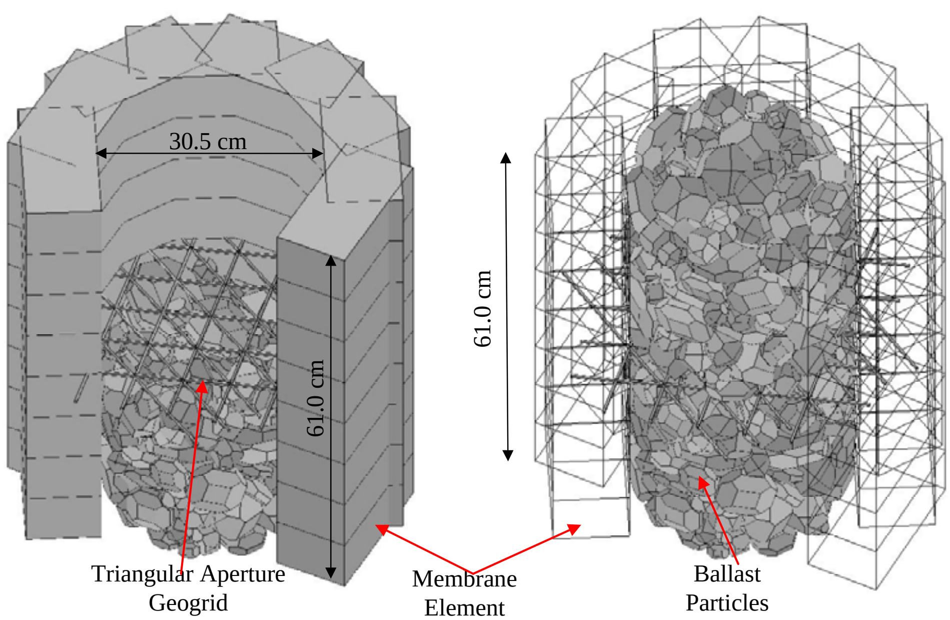


FIG. 5. Flexible membrane shown on left to model one layer geogrid reinforced triaxial ballast specimen established as a DEM simulation

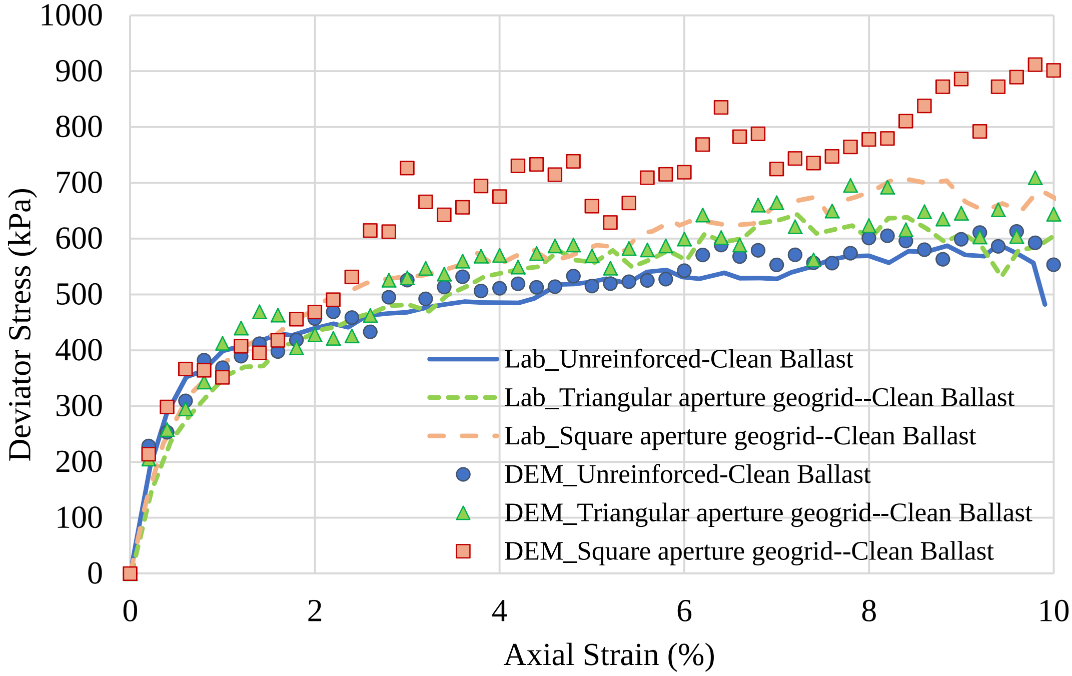
LABORATORY TESTS AND DEM SIMULATION RESULTS

Fig. 6 presents the results of the large scale triaxial strength tests on the clean and degraded limestone ballast cylindrical specimens for up to 10% axial strain. The maximum strength values for different ballast materials from the experiments and the DEM simulations are listed in Table 3. All the test specimens showed similar stress-strain behavior at the initial small strain stage of the strength tests and this was primarily due to the fact that geogrids were not yet fully mobilized early on. When axial strain levels increased, the geogrid was mobilized and the interlock between geogrid and aggregate particles prevented lateral movement or specimen bulging. The zigzag shapes of the stress-strain curves at high axial strain levels indicate sudden strength drops. This can be explained by damaged geogrid due to observed broken ribs and/or particles reorienting themselves from the interlocked positions. Immediately afterwards, the geogrid-reinforced ballast was back to fully restrained condition again with new interlocks formed between aggregate particles and the geogrid and accordingly, the strength of the specimen was restored upon completion of the particle rearrangement. The DEM simulation results presented in Fig.6 showed generally good agreement with the observed trends in the experiments. In some cases, the DEM simulations overestimated the strength of geogrid reinforced specimens; this is due to the fact that the geogrid ribs in the DEM simulations were not allowed to break.

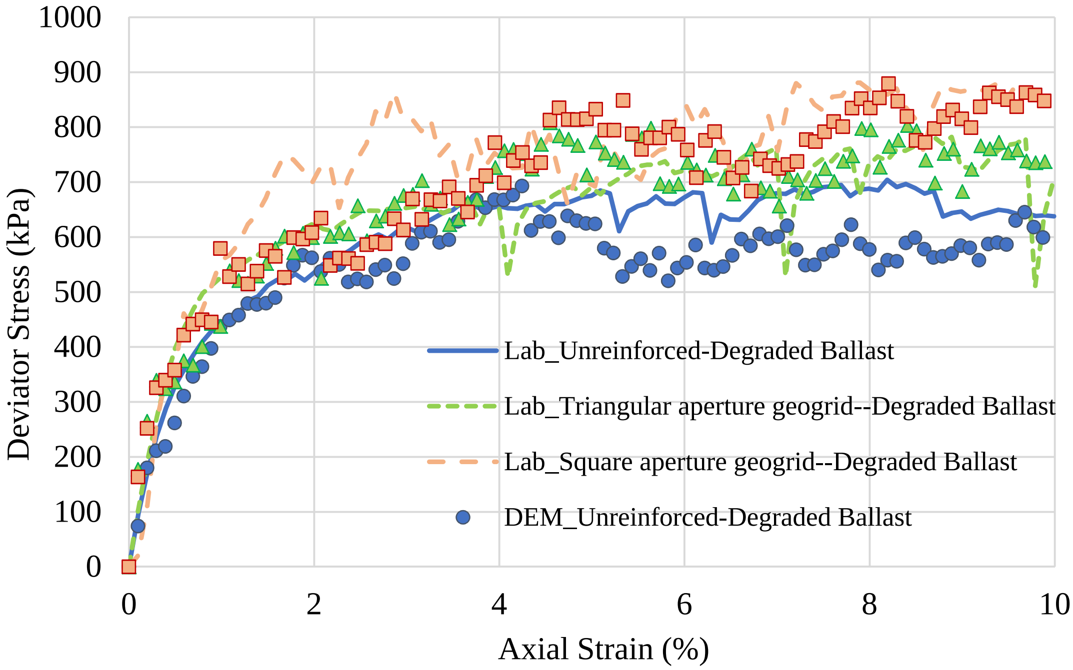
Another interesting phenomenon observed from both the experiments and DEM simulations is that the degraded ballast presented even higher strength than the clean ballast material. Note that the degraded ballast material used in this study was generated by LA abrasion tests and only used particles sizes above 9.5 mm (3/8 in.). Comparing the gradations of the two ballast materials used in this study (see Fig. 1), the degraded ballast materials had higher amounts of finer particles and were more “well” graded as compared to the clean ballast materials satisfying AREMA No. 24 uniform gradation specification. The finer particles of degraded ballast could help to stabilize the aggregate skeleton and therefore, result in higher strength. Also, from the imaging based shape properties listed in Table 1, the degraded ballast particles have significantly lower Angularity Index (AI). The shape properties of degraded ballast aggregate particles tend to be more cubical and smoother, i.e., less susceptible to abrading sharp corners and edges when compared to clean ballast particles. Accordingly, the degraded ballast particles created an improved packing and a well-graded and higher density specimen, which led to higher peak strengths during shearing. This was a similar trend to what was observed in the field when ballast with lower angularity yielded less settlement due to better packing (Tutumluer et al. 2013).

TABLE 3. Peak Strength Values from Laboratory Tests and DEM Simulation Predictions

Ballast Type		Unreinforced (kPa)	Triangular Aperture Geogrid Reinforced (kPa)	Square Aperture Geogrid Reinforced (kPa)
Lab	Clean	593	643	705
	Degraded	709	786	894
DEM	Clean	604	709	912
	Degraded	693	813	880



(a) Strength tests and DEM simulations results with clean ballast



(b) Strength tests and DEM simulations results with degraded ballast

FIG. 6. Laboratory triaxial ballast strength tests and DEM simulation results

CONCLUSIONS

This paper focused on the shear strength results of geogrid reinforced ballast specimens obtained from a large scale triaxial test device in the laboratory. Triangular and square aperture geogrids were used for reinforcing both clean and degraded ballast samples. Numerical simulation was performed with an aggregate image analysis based Discrete Element Method (DEM) modeling approach to demonstrate the capability of studying geogrid-aggregate interlock reinforcement mechanism. The following conclusions can be drawn from this study:

- Both triangular and square aperture geogrids were found to effectively increase maximum strength of both clean and degraded ballast materials. The square aperture geogrid reinforced ballast specimen in this study provided the best performance. More studies are needed to fully investigate aperture shape effects on the overall geogrid reinforcement mechanism.
- The degraded ballast samples (with sizes above 9.5 mm or 3/8 in. in this study) from heavily fouled ballast material, did not necessarily exhibit lower peak strengths than those of the clean ballast material under dry moisture states. From the preliminary test results presented in this study, the degraded ballast exhibited even higher strength values in dry moisture conditions than the clean ballast material when reinforced using the same geogrid and under similar loading conditions.
- The aggregate imaging based DEM simulation platform developed at the University of Illinois could model the stress-strain behavior of ballast specimens under monotonic triaxial tests. The DEM simulation successfully captured the stress-strain behavior of the geogrid-reinforced ballast specimens by addressing adequately the initial condition of the laboratory tests. The DEM simulation platform currently being further developed has the potential for quantifying individual effects of various geogrid properties, such as aperture shape and size and rib dimensions, on the aggregate assembly.

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