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3D LASER SCANNING TECHNIQUE COUPLED WITH DEM GPU SIMULATIONS FOR RAILWAY BALLASTS

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Abstract. Spheres with complex contact models or clumped sphere models are classically used to model ballast for railway applications with the Discrete Element Method (DEM). These simplifications omits the angularity of the actual ballast by assuming the ballast is either round or has rounded edges. This is done by necessity to allow for practically computable simulations that may consist of a few hundred particles. This study demonstrates that an experimentally validated DEM simulation environment, BlazeDEM-3DGPU, that computes on the graphical processing unit (GPU) is able to simulate railway ballast with a more realistic shapes that includes angularity for railway applications. In particular, a procedure is developed that extracts polyhedral shaped ballast geometries digitized from 3D-laser scanning for use in DEM simulations. The results show that much larger number of particles can be successfully modelled allowing for new possibilities offered by the GPUs to investigate model railway problems using DEM. Specifically, in this study a typical experimental ballast box that contains up to 60 000 polyhedral particles have been simulated with the BlazeDEM-3DGPU computing environment within reasonable computing times.

1 INTRODUCTION

France has the second largest European railway network that accounts for a total of 29 901 km of railway. The French railway network is comprised of 16 445 km of double track railway, 15 140 km electrified railway and 1 876 km can accommodate high-speed trains. The main track gauge and high-speed track gauge are both 1 435 mm. In 2014 a freight of 32 billion tonne-km was hauled and a passenger distance of 84 billion passenger-km serviced in France alone. The integrity of the railway relies significantly on the integrity of the railway ballast that supports the railway with failure proving disastrous [**?**, **?**]. The deterioration of superstructure ballast and sub-ballast is amplified by train-track vibrations of high speed trains inadequate water drainage that may cause subsidence of the superstructure ballast and track. As a consequence a number of countries have limited the maximum speed of high speed trains which include China that reduced speeds from 220 mph to 185 mph, Eurostar in Britain runs up to 185 mph and the TGV Est in France reaches only 200 mph.

Particle shape is a key parameters that influences the performance of railway ballast in particular the settling of railway ballast. Specifically, railway ballast depends strongly on the particle shape, surface roughness and wear characteristics of the ballast. As a consequence railway industries have imposed standards to define quality requirements regarding railway ballast.

In parallel, researchers are developing simulation methodologies to tackle the problematic settling of ballasts as freight is hauled within an infrastructure. In particular, the discrete element method (DEM) is classically used to better understand the settling of ballasts under repeated cyclic loading and train-track vibrations. The computational demands of DEM often limits these studies to 2D simulations [2] with limited 3D simulations that at most consider clumped spherical particles [2] with neglects the effect of particle angularity. This is unfortunate as one of the critical geometric aspects of ballast and ballast degradation is particle angularity. This is poorly represented using clumped spherical representations [2, 3] or using a modified rolling contact model adapted from simple individual spheres [4].

This study investigates the potential of BlazeDEM-3DGPU [5] code to model

1. realistic ballast particle shapes,
2. large number of particles in 3D ballast simulations,
3. ballast using GPU based simulations.

In this study preliminary simulation results are presented but in future studies aim to validate simulations against experimental results to assess the importance of accurate and realistic particle representations when modeling ballast. The GPU that makes highly efficient parallelized hardware available is essential for our study towards ii) increasing the number of particles in a ballast simulation within reasonable computing times on multiple

GPUs [5, 6, 7], while the specific DEM environment BlazeDEM-3DGPU [5] is crucial i) to model polyhedral convex and non-convex shaped particles that allows for accurate and efficient incorporation of both angularity and interlocking of the ballast. The GPU by design a highly parallelized hardware architecture as a typical CPU node can launch 12 threads per cycle, a GPU node can launch 53284 threads per cycle. This allows for particle scale simulation to be explored when modeling balast as parallelism at particle level allows one thread per particle which significantly decreases the computational times. In addition, to the particle shape the contact model in BlazeDEM-3DGPU [5] is based on the overlapping volume between particles for a better assessment of the strain energy involved between contacting particles.

The ballast particle shapes are captured using a 3-D laser scanner to obtain accurate digitized ballast particle shape representations of high-speed track ballast for use in the DEM simulations in this study. The detail of the digitized ballast particles are controlled by the number of vertices and faces used to approximate the ballast particle samples. A significant benefit of this approach is that the critical geometric features could be investigated by conducting DEM simulations using varying detailed ballast samples. In addition, the simplified the ballast samples allows for larger number of *angular particles* to be simulated during loading and unloading and vibration studies of the ballast.

The remainder of this study is dedicated towards demonstrating that the developed laser scanning strategy is effective, efficient and practical to quantify the shape properties of the ballasts towards constructing digitized ballast samples for use in DEM simulations. Secondly, that GPU-enabled DEM can efficiently model typical large scale box representative of a typical laboratory ballast experiments to test the cycling compressive loading.

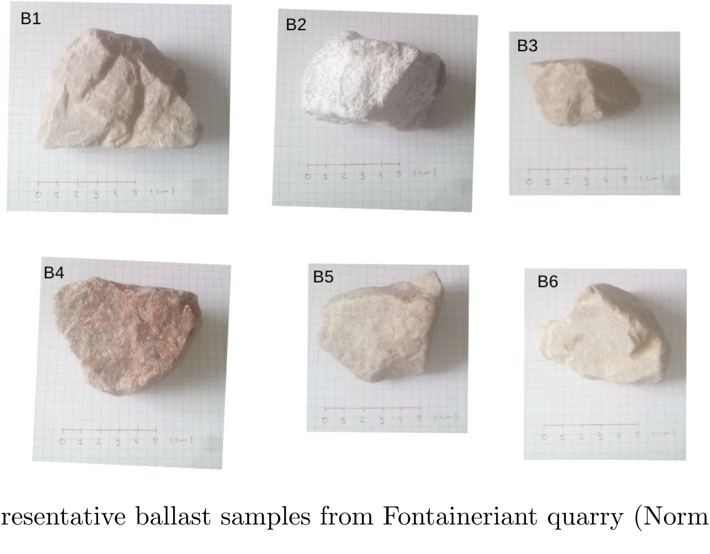

Figure 1: Representative ballast samples from Fontaineriant quarry (Normandy France).

2 3D Laser Scanning Procedure

The 3D laser scanning procedure consists of mounting the particles appropriately to be accurately scanned as outlined in Section 2.1. Thereafter the particle is digitized by approximating the high resolution representation by fitting vertices and planes to cover the surface of the particle as discussed in Section 2.2. the process is repeated for all six selected ballast particles whereafter they are used in DEM simulations of ballast as detailed in Section 3.

The ballast considered in this study are from the ballast used for the new French high-speed rail LGV Bretagne-Pays de la Loire (LGV LN 10, to be completed in 2017). The ballast were extracted from Fontaineriant quarry (Normandy France) which is a quartzite (locally called also in French grès amoricain). The classical designation range for ballast used for French high-speed railway is 31.5/63. The 6 representative ballast samples used in this study are presented in Figure 1.

2.1 3D-Laser scanning device and initial digitization

The shape of ballast particles are classically obtained by particle image processing or X-ray computed tomography (CT). The particle image processing allows for fast and inexpensive processing of the ballast particles allowing for large numbers of particles to be processed. However, the 2-dimensional images obtained by image processing and stitched volume objects are sufficient for the overall particle geometry and aspect ratios while additional detail is seldom well resolved. Improved accuracy is obtained using X-ray CT that allows 3-D shapes to be captured more accurately as demonstrated by Ahmed et al. [11] for ballast applications. However, X-ray CT measurements are expensive, sophisticated and laborious which limits the number of particles that can be processed.

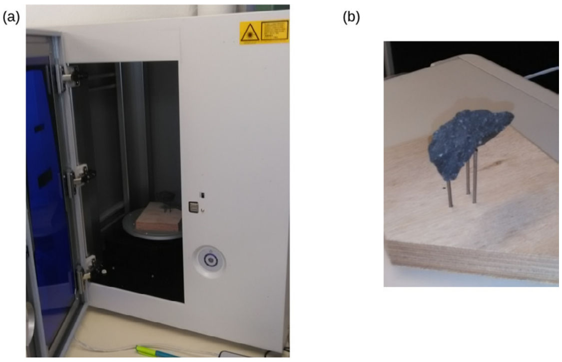

Figure 2: (a) 3D-laser scanning device (b) ballast with scan support

This study considers the 3D-Laser scanning device depicted in Figure 2(a), which can be considered intermediate to the particle image processing and X-ray CT scanning. A 3D-Laser scanning device has already been employed with sufficient accuracy to characterize aggregate shape [10]. In this study, a modern 3D-laser scanning device is used to obtain a scan of the ballast. As shown in the Figure 2(b), the ballast samples are scanned sequentially with the sample being supported by wire supports. The samples are rotated as they are only scanned from the top, this allows for a full digitization of the particle geometry in which there is no effect of the wire supports. The 3-D laser scanning device requires several rotations to scan a sample to finally obtain a digitized ballast particle. The number of rotations to complete planar scans can reduce or increase the precision of the scanned sample. In our case, the times to scan and digitize a ballast sample varied between 10 and 20 minutes depending on the scanning parameters and selected representative planar element i.e. triangle or parallelogram. Table 1 shows that the number of initial polygons of the detailed digitized representations depend of the size and complexity of the ballast as the scanning parameters of the device are the same for each sample.

Table 1: Digitized ballast data before and after mesh reduction operation : number of geometrical elements

	After Scanning		After Mesh Reduction	
Ballast	Triangle	Point	Facet	Vertex
B1	24964	12470	12	8
B2	89980	44856	12	8
B3	25212	12606	12	8
B4	100246	50111	12	8
B5	69096	34517	12	8
B6	71876	35873	12	8

2.2 Ballast digitization to reduce geometrical detail

Once the ballast samples have been scanned they need to be digitized into DEM particles ready for simulation. The scanned particles are digitized with high detail and stored in the `STL` data format, which represents the the particle surfaces as triangles. The geometric detail of the highly detailed digitized samples are then reduced using MeshLab [12], which is open-source and freely available. In this study, the mesh reduction function was utilized to reduce the number of triangular facets to avoid excessive storage requirements as particles in the DEM simulation environment. For this study we chose number of final facets to be 12 for all particles as outlined in Table 1.

Future investigations will adapt the number of facets according to the complexity of the particle which was not the main objective of this study. The originally scanned high detailed particles (left) and digitized DEM particles (right) are depicted in Figure 3. The results highlights that the particle elongation and flatness are globally well represented, while the angularity could be more better defined using more detailed particle in future. The surface texture (roughness) captured by the detailed digitization as well as the non-convexity of the particles are not present in the final particle representations although

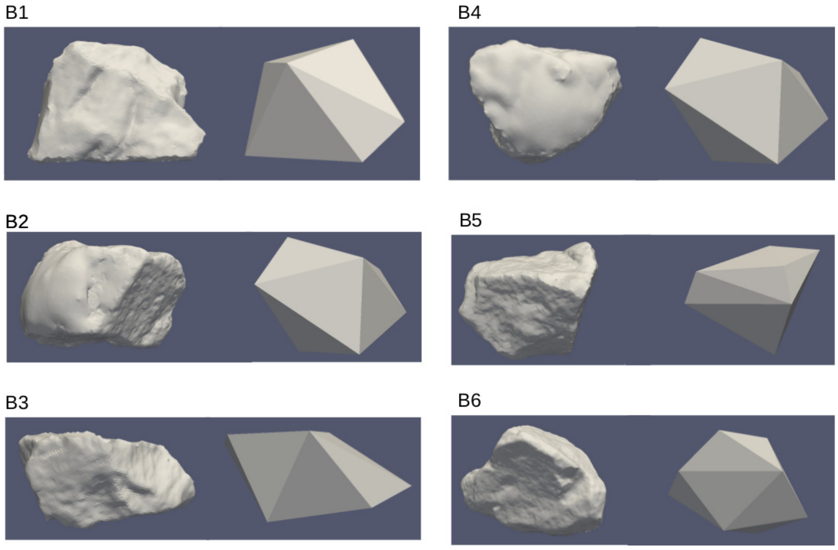

Figure 3: Detailed digitized ballast after the scanning (left) and after reducing the geometrical detail for DEM representation (right)

the detail reduction process is capable of generating both convex or non-convex particle shapes.

3 GPU Discrete Element Simulation

3.1 Ballast considerations during DEM

Both the time computational time and realistic particle shapes are currently the two main limiting factors to use DEM on a regular basis to tackle large scale ballast railway problems. Typically CPU based DEM environments simulate at most a few thousand of ballast particles using the clumped sphere representations that ignores the angularity of actual ballast [3, 4]. It is expected that this kind of DEM simulations can give qualitative assessments but the effect of angularity is expected to be a crucial factor for ballast simulations but this is yet to be investigated in greater detail.

3.2 BlazeDEM-3DGPU

As outlined previously this study considers uses the BLAZEDEM-3DGPU framework developed by Govender et al. [5, 6, 7, 8, 9]. This numerical framework has been validated for silo discharge and power consumption of milling operation simulations that allows for large number of particles to be simulated within reasonable computing time. BlazeDEM-3DGPU is able also to model more complex shapes that include regular and irregular polyhedra (non-convex particles) [8].

In the case of selected scanned ballasts, the `STL` file format is converted to the BlazeDEM-3DGPU format. In particular, the faces and vertices are extracted to define the polyhedral geometries. Note also that the python library `numpy-stl` was used to obtain the Inertia tensor, volume and centre of mass for each digitized ballast particle. In particular, the inertia tensors plays an important effect for the stability of the final packing. The BlazeDEM-3DGPU depicted particle geometries are shown in Figure 4.

All simulations conducted in this study are done using a linear spring dashpot model and Coulomb Criterion are used : $COR_{pp} = 0.25$, $COR_{pw} = 0.1$, $\mu_{pp} = 0.6$, $\mu_{pw} = 0.5$, density $= 1.8 g/cm^3$ for a time-step of $1.10^{-4} s$.

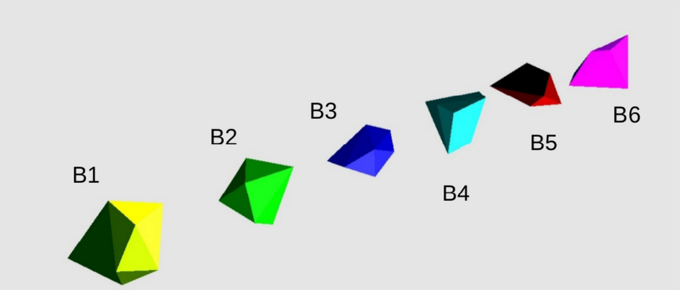

Figure 4: DEM Ballast particles for the 6 selected digitized ballasts

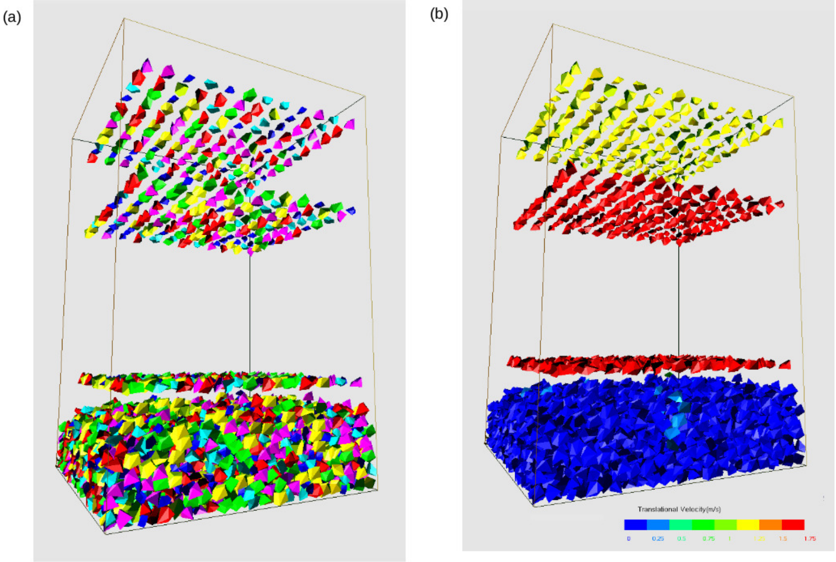

Figure 5: Filling stage of box BOX1 after 7.5 s of filling time (a) coloured by particle geometry and (b) coloured by linear velocity

3.3 Ballast box filling simulations

Two boxes were considered in this study. The first box is 128 cm by 128 cm (BOX1) and the second box is 248 cm by 248 cm (BOX2). These sizes have been chosen to be similar at the scale of experimental devices used classically for the ballast studies during cyclic compaction tests. Figures 5 depicts the ballast filling stage of BOX1. As shown in Figure 5(a) the ballast particles were sequentially filled by slice with random packing of the different particle geometries as well as their orientations, since each colour represents a different geometry in Figure 5(a). The linear velocities in turn are depicted in Figure 5(b) depicting stability during ballast formation. In this study two ballast packings are filled as summarize in Table 2. The final packings are shown in the Figure 6 for the two boxes. The computing time for around 20 s of filling for the packing 1 is around 0.8 hour for two GPUs TITAN X cards.

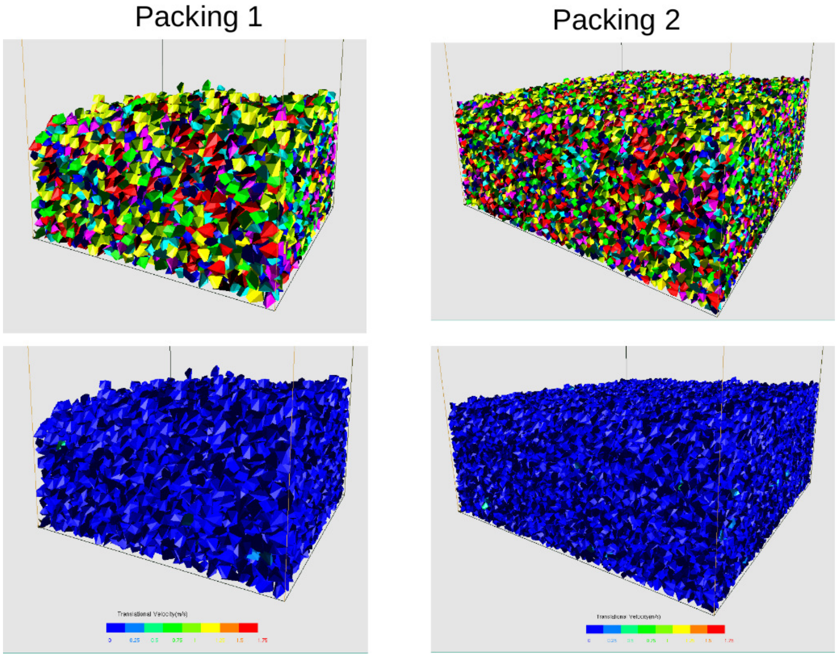

Figure 6: Ballast packings after the filling stage in box BOX1 (a) and box BOX2 (b) (top - coloured by particle geometry and down - coloured by linear velocity)

Table 2: Ballast packing characteristics

Number of ballasts	Total	B1	B2	B3	B4	B5	B6
Packing 1 (BOX1)	10000	2000	1500	1500	2000	1500	1500
Packing 2 (BOX2)	60000	12000	9000	9000	12000	9000	9000

4 Conclusions

Time computation and realistic particle shape (classically clumps of spheres) are actually the principal limitations to apply Discrete Element Method to large scale ballast railway problems. In this paper, two typical experimental ballast boxes were filled by up to 60 000 thousand convex polyhedral-shaped ballast particles using BlazeDEM-3DGPU that efficiently utilizes the GPU to conduct discrete element simulations within reasonable computing times. A simplified experimental procedure has been developed in this work to reduce detailed digitized ballast samples obtained scanning actual samples using 3-D laser scanner to typical polyhedron geometries that can be used in DEM simulations. This study highlights the promising prospects that GPUs can bring to model railway problems more precisely within reasonable time frames. One of the ambitious perspectives of this work will be to test the methodology developed here for the digitized ballasts for the non-convex polyhedra shape, a particle shape that has already been tested with the BlazeDEM-3DGPU platform [8].

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