Application of PFC3D to Study Railroad Ballast Response under Train Loading

Session D2-3B: Damage Mechanics - 1
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Outline

- Introduction and Background
- Research Tasks
- Results and Discussion
- Summary and Conclusions

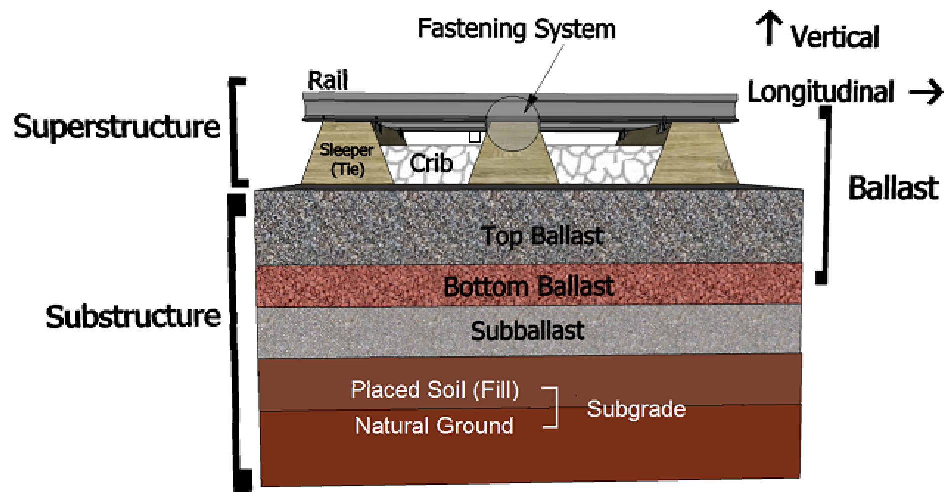
Ballasted Railroad System

Ballasted Railroad System

Ballast particles

Railroad Ballast Layer

- Comprises coarse-grained unbound aggregates
  (often as large as 63 mm)
- Primary load-bearing layer
- Transfers train-induced stresses from the cross ties to the subgrade soil
- Provides rapid drainage, and helps maintain a smooth track profile



Railway Track Structure Components

Problem Statement

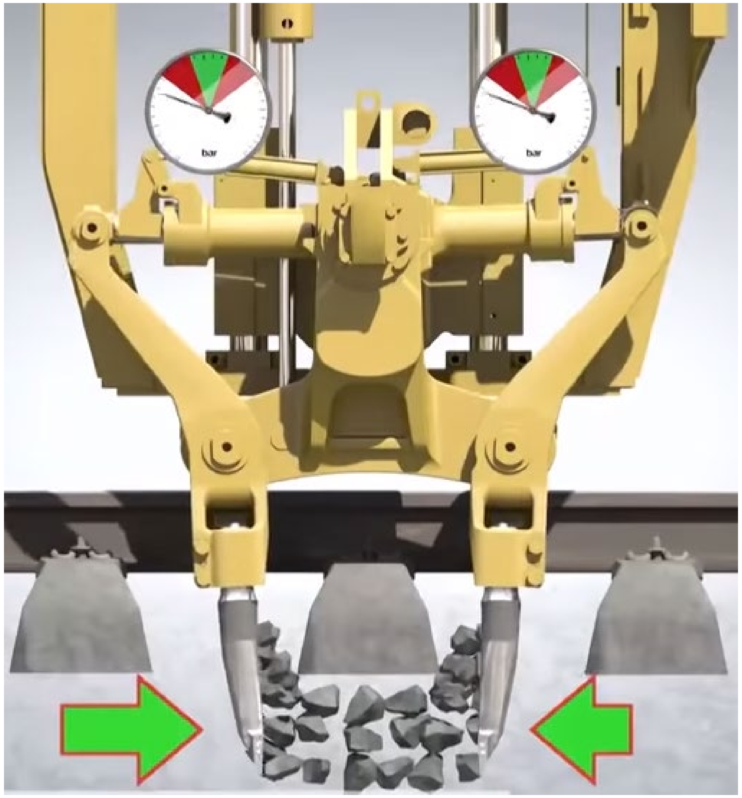
Ballast particles undergo significant breakage due to

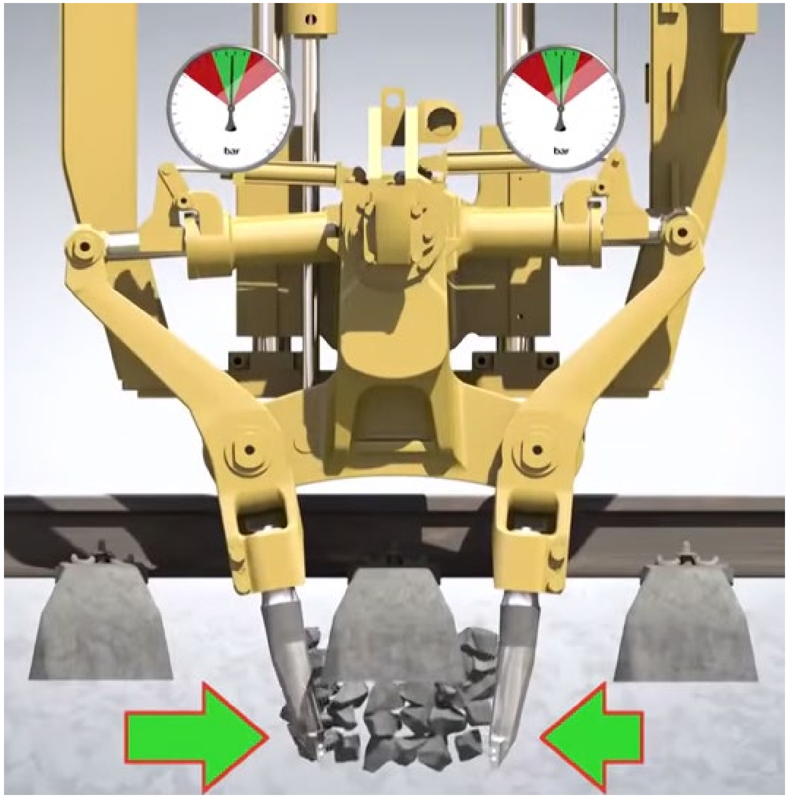
- ✓ Repeated train loading
- ✓ Aggressive maintenance processes such as tamping

What is tamping?

Tamping

Eliminate voids under the cross ties





Problem Statement

Ballast particles undergo significant breakage due to

- ✓ Repeated train loading
- ✓ Aggressive maintenance processes such as tamping

All this eventually

- ✓ Degrades quality of the ballast layer
- ✓ About 76% fouling fines originate from ballast breakage
- ✓ Leads to speed restrictions and poor drainage
- ✓ Causes rapid deterioration of track geometry
- ✓ Increases maintenance costs
- ✓ In extreme cases, can lead to derailment

Understanding Ballast Breakage

Laboratory and Field Experiments

- Can simulate actual field conditions
- Expensive and requires significant time
- Cannot give complete picture of particle breakage
- Cannot isolate effects of individual variables

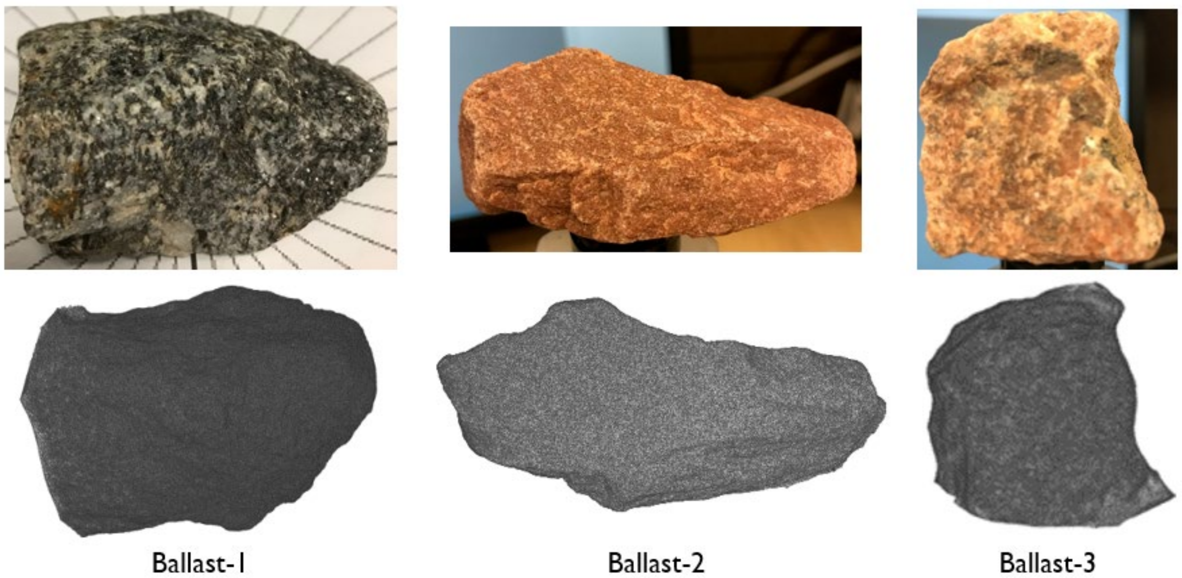
Discrete Element Method

- Considers the particulate nature of ballast
- Effects of individual variables can be studied
- Evolution of breakage can be studied

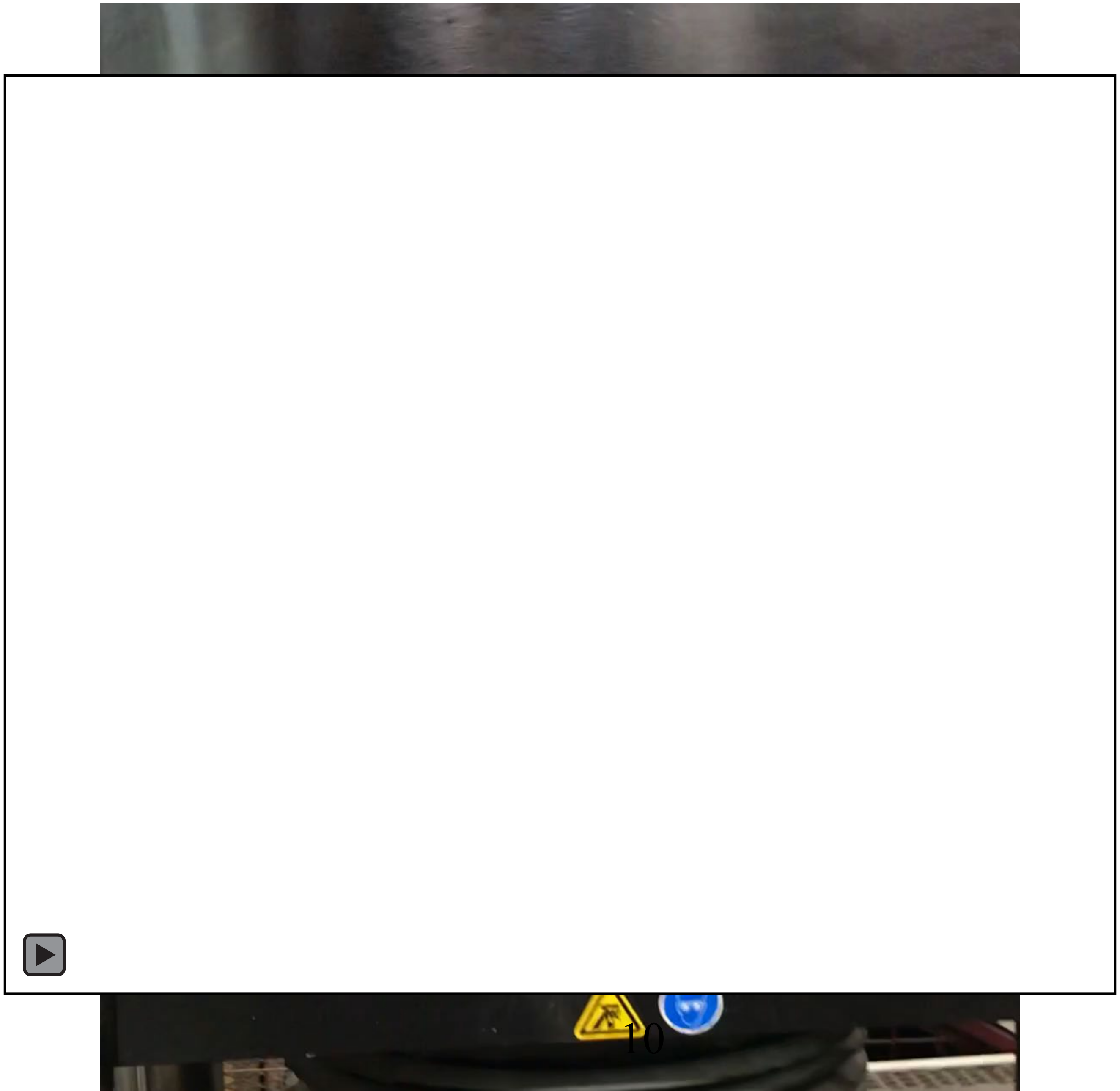
Particle Flow Code (PFC3D) as a Discrete Element Tool to study ballast breakage under train loading

Acquisition of Polyhedral Ballast Shape

- Researchers use expensive and complex image analysis approaches to capture the shapes of ballast particles
- Modern smartphone cameras are used to capture high-resolution images
- Autodesk® ReCap software used to digitize images and then import to PFC model

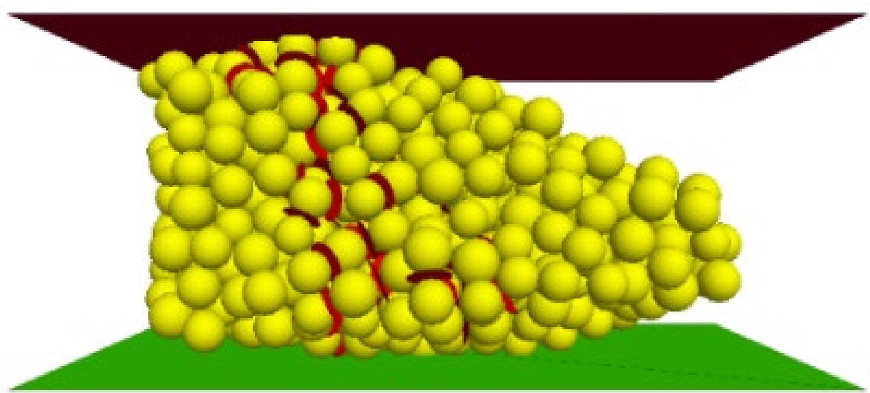


Single Particle Crushing Test (SPCT)



Single Particle Crushing Test (SPCT)

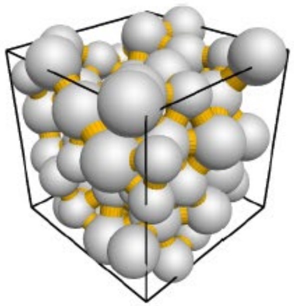
Broken Ballast after Lab Test



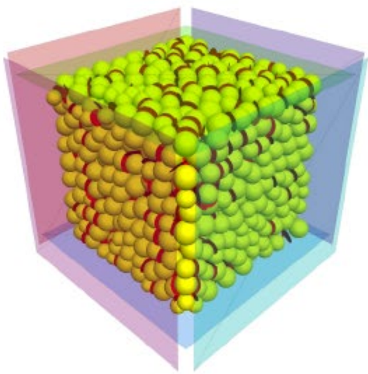
Broken Ballast after DE Test

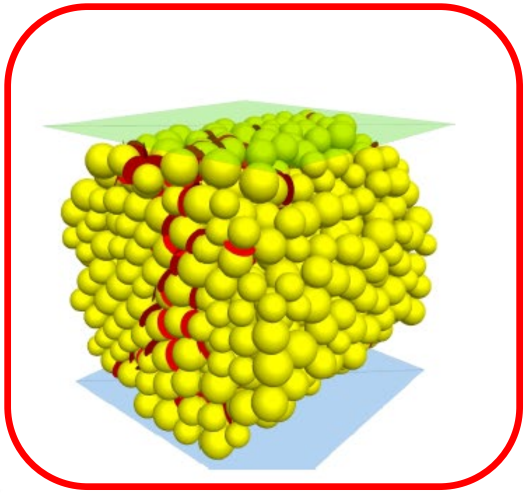
DEM Simulation of SPCT

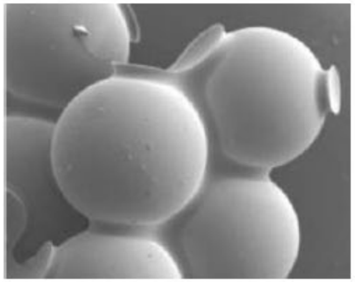
- Used material modeling support package in PFC to perform the Discrete Element simulation of SPCT



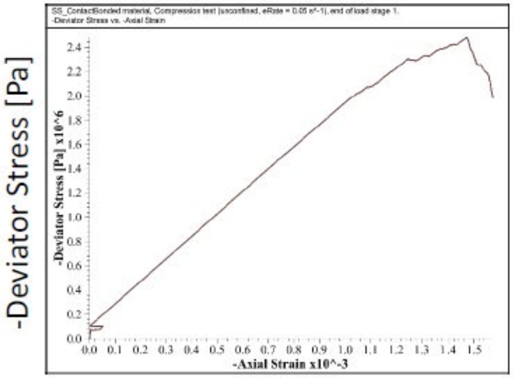
parallel-bond cement



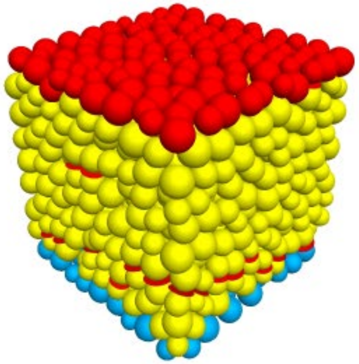




Glass beads
cemented with epoxy



- Axial Strain



DEM Simulation of SPCT

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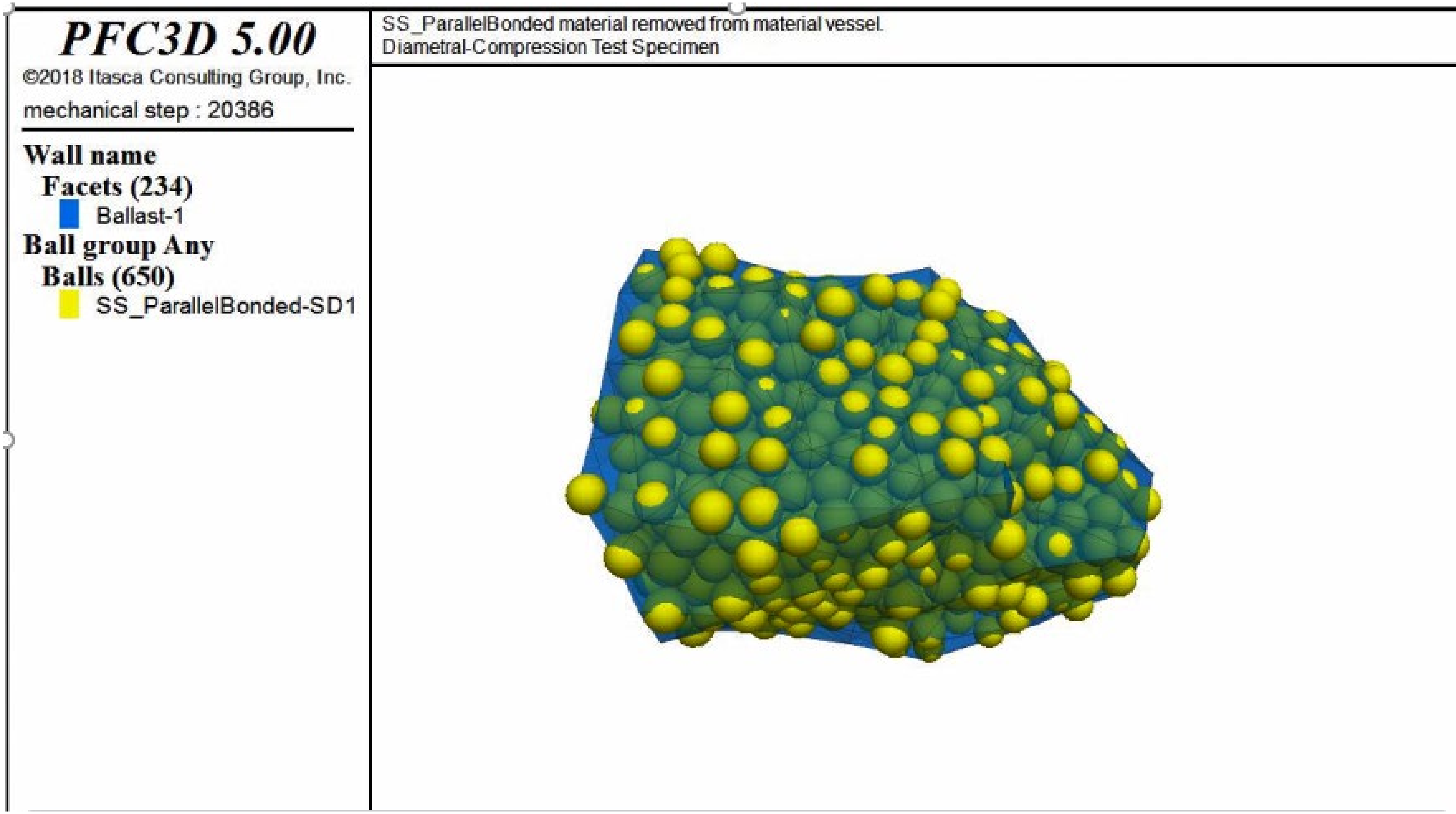


DEM Simulation of SPCT

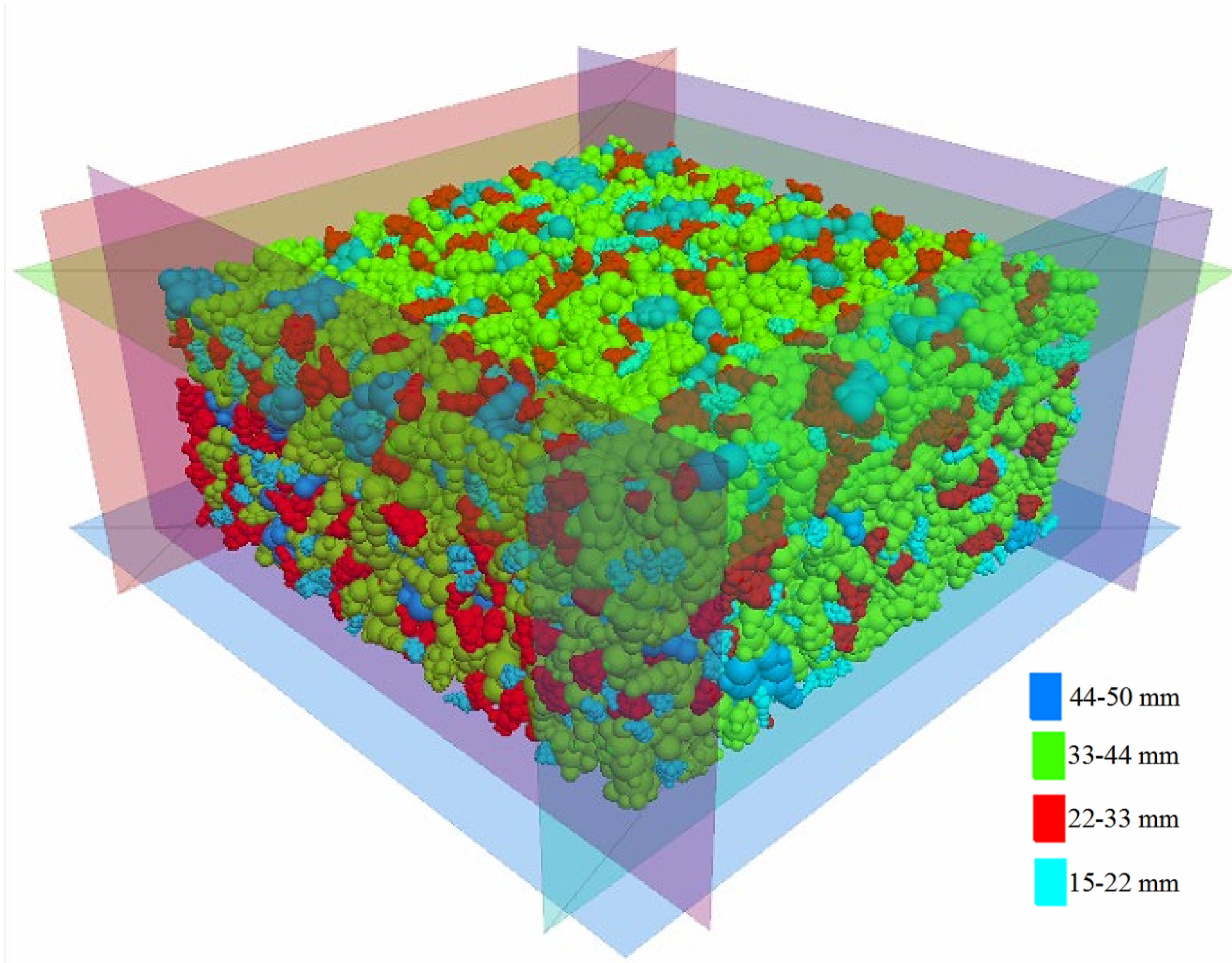
- Used material modeling support package in PFC to perform the Discrete Element simulation of SPCT

Initial Ballast Layer

Specimen Box

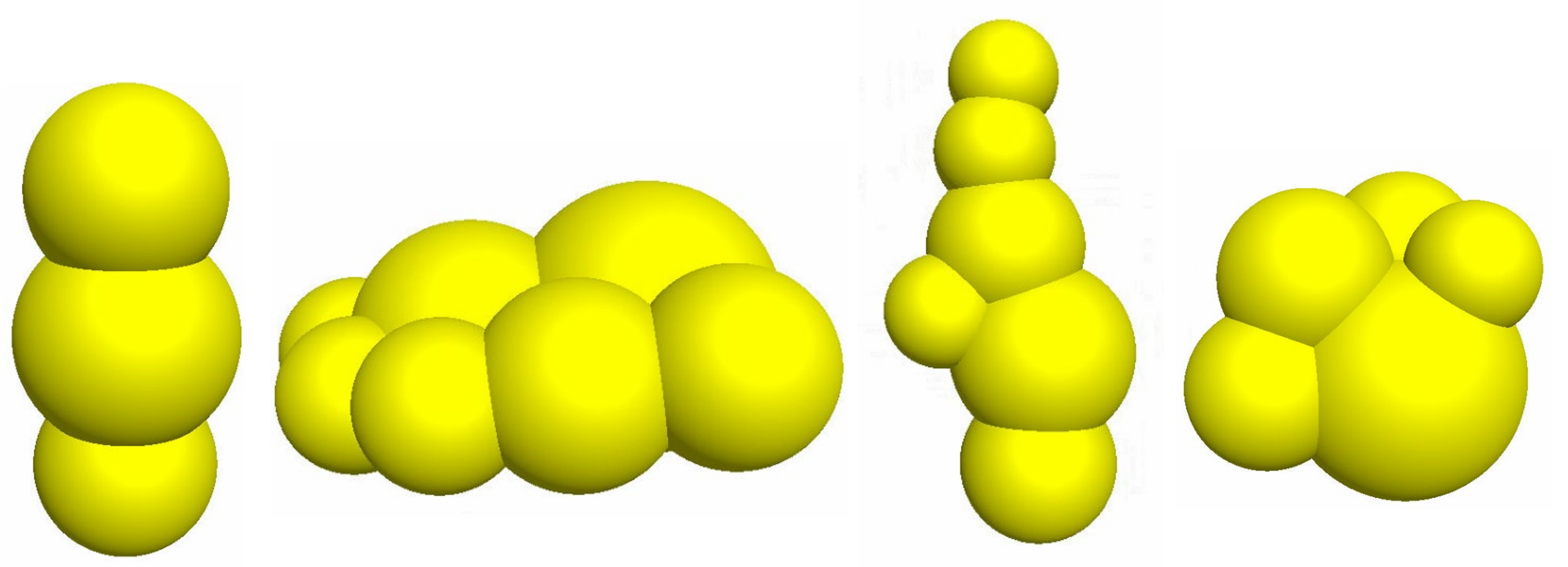
Length: 600 mm
Width: 600 mm
Height: 300 mm

Equal proportion of each polyhedral ballast shape



All ballast particles are initially unbreakable

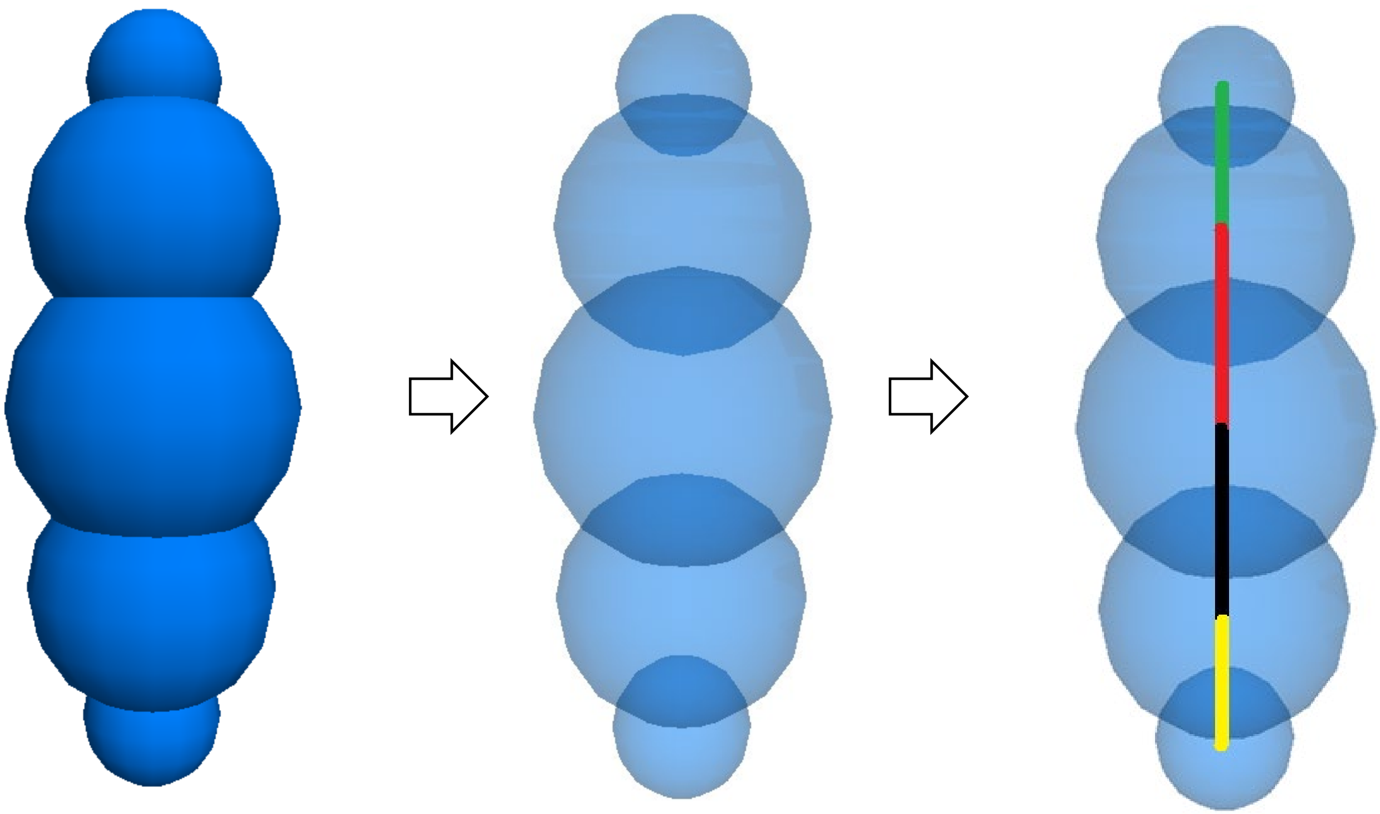
Ballast Particles



Ellipsoid *Ballast 1* *Ballast 2* *Ballast 3*

The number of spheres used in creating individual ballast particles was much lower than that used during the SPCT (to reduce computational time)

Modeling Particle Breakage

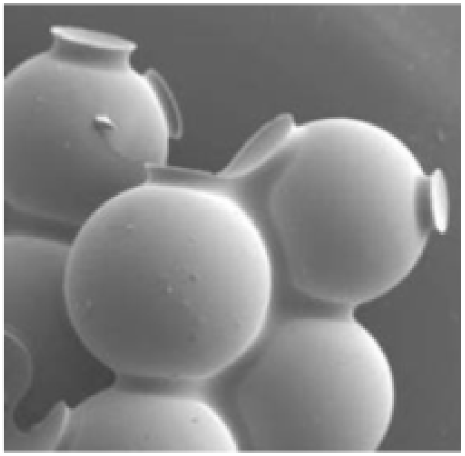


Clump
(Non-breakable ballast)

Cluster of Balls

Cluster of Balls bonded with Linear Parallel bond

Particle Breakage Criterion



Glass beads cemented with epoxy

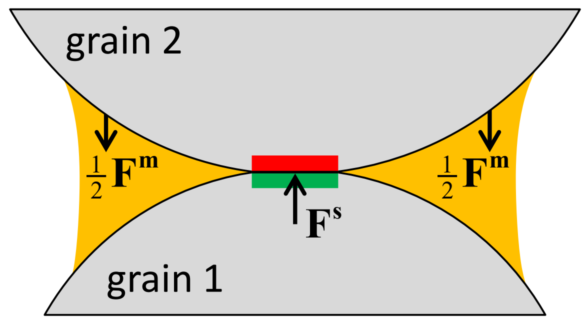
$$\bar{\sigma}^{max} = \frac{-\bar{F}^n}{A} + \frac{|\bar{M}^s|\bar{R}}{I} < \bar{\sigma}_c$$

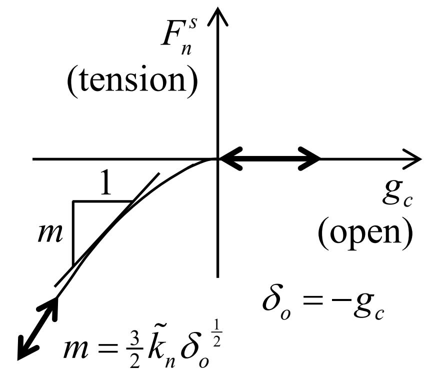
$$\bar{\tau}^{max} = \frac{|\bar{F}^s|}{A} + \frac{|\bar{M}^n|\bar{R}}{J} < \bar{\tau}_c$$

Bond breaks when stresses in the bond exceed strength values

Parallel Bond contact model
Behaves like finite-size, linear elastic and bonded interface that carries a force and moment.

Hertzian Contact between Ballast Particles

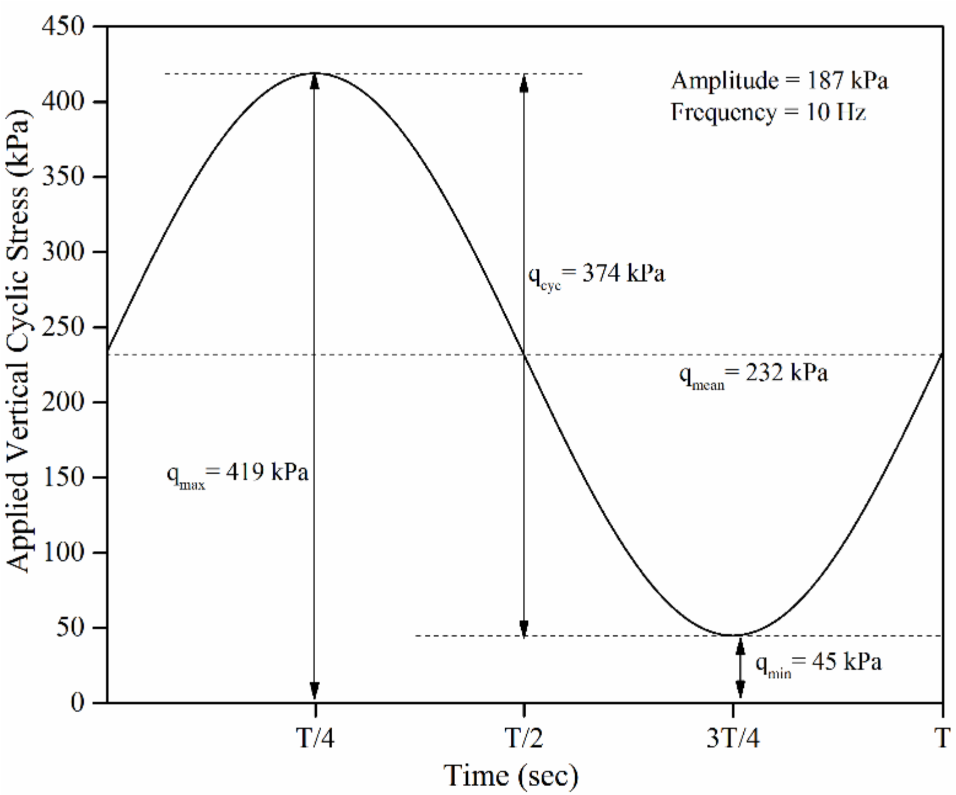




Hill contact model
Behaves like two elastic spheres with liquid bridge

- Surface-interaction force $\left(\mathbf{F}^{\mathrm{s}}\right)$: Hertzian (elastic bodies in contact)
  parameters: Young's modulus, Poisson's ratio, grain radius
- Moisture force $\left(\mathbf{F}^{\mathrm{m}}\right)$: similar to liquid bridge
  parameter: Suction

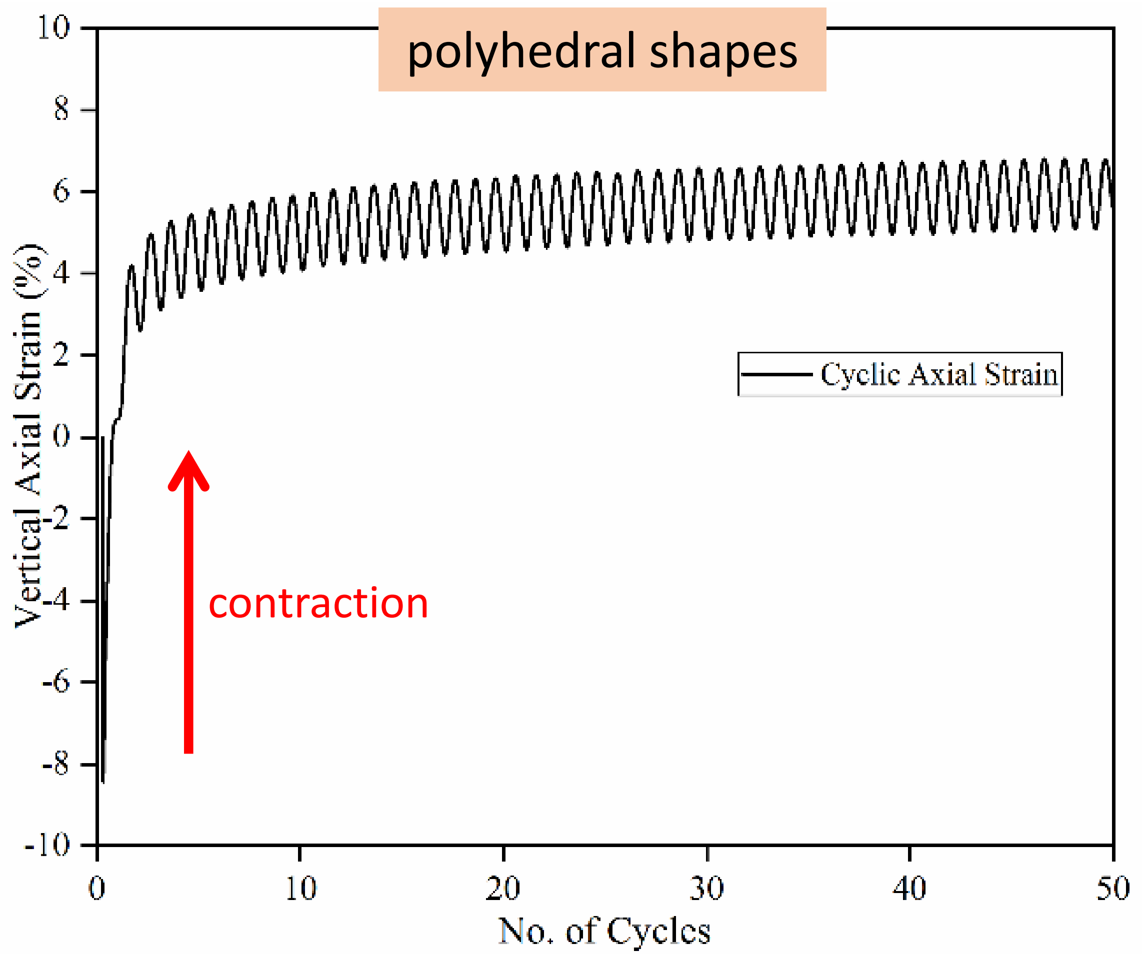
Application of Cyclic Loading



- The sinusoidal load was cycled between two compressive stress states of q_{min} and q_{max}
  - q_{min}: ballast layer pressure under unloaded state of track
  - q_{max}: maximum rail seat load
- 50 load cycles
- Stress-strain response of the ballast sample was plotted

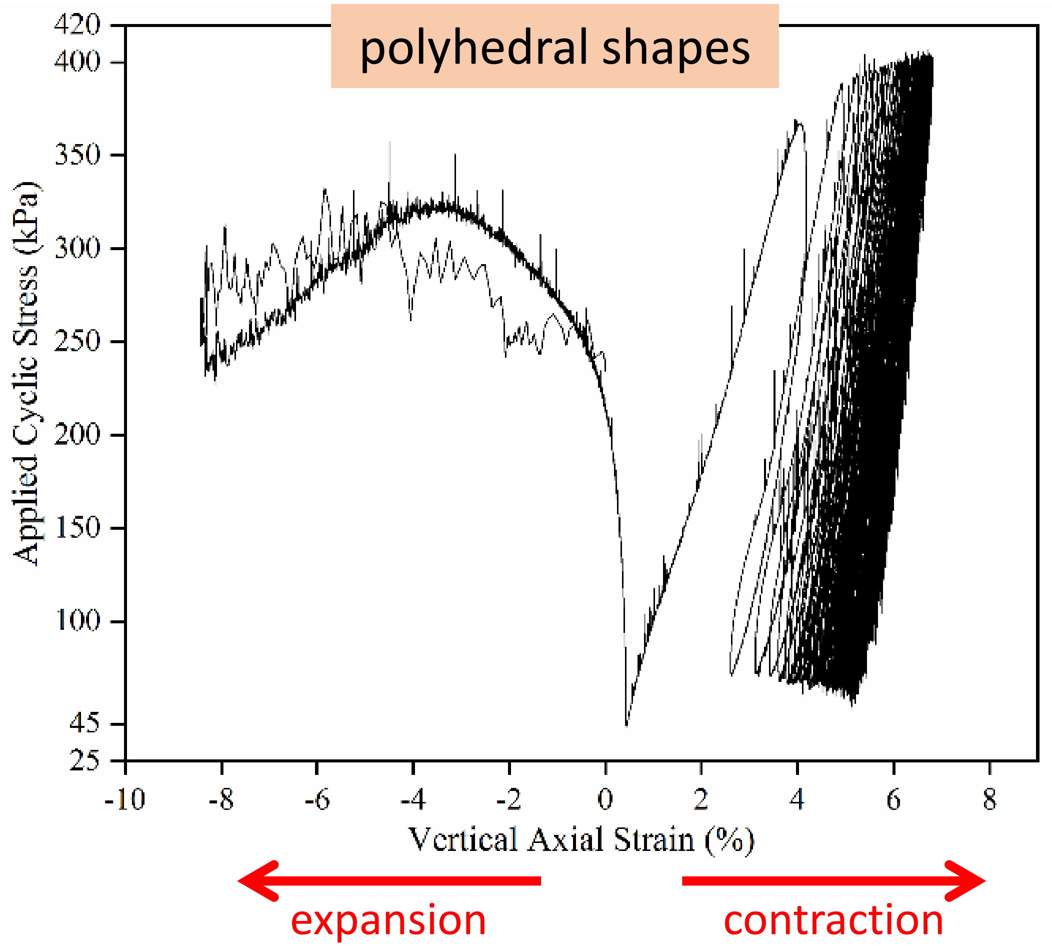
Axial Strain vs Loading Cycles

- Initial bulging due to overlap between cluster of bonded spheres *(locked-in stresses)*
- Rapid accumulation of permanent deformation under the initial load cycles
- Axial strain increases steadily with ↑ load cycles, then stabilizes.



Cyclic Stress vs Axial Strain

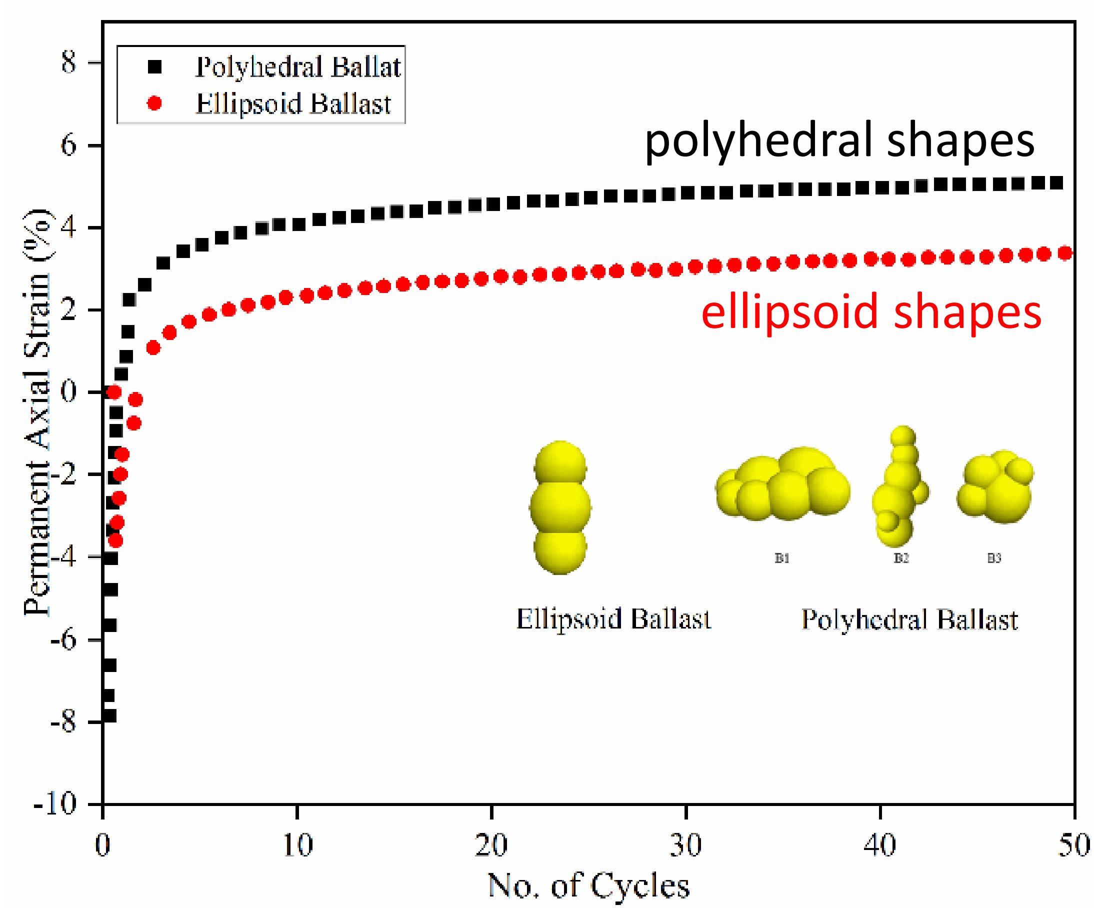
- Initial expansion (bulging) from locked-in stresses
- Spikes represent bond breakages in the ballast
- Significant vertical strain accumulation during initial load cycles
- Hysteretic/elastic behavior after 50 load cycles



Comparing Different Ballast Shapes

Permanent Deformation (PD)

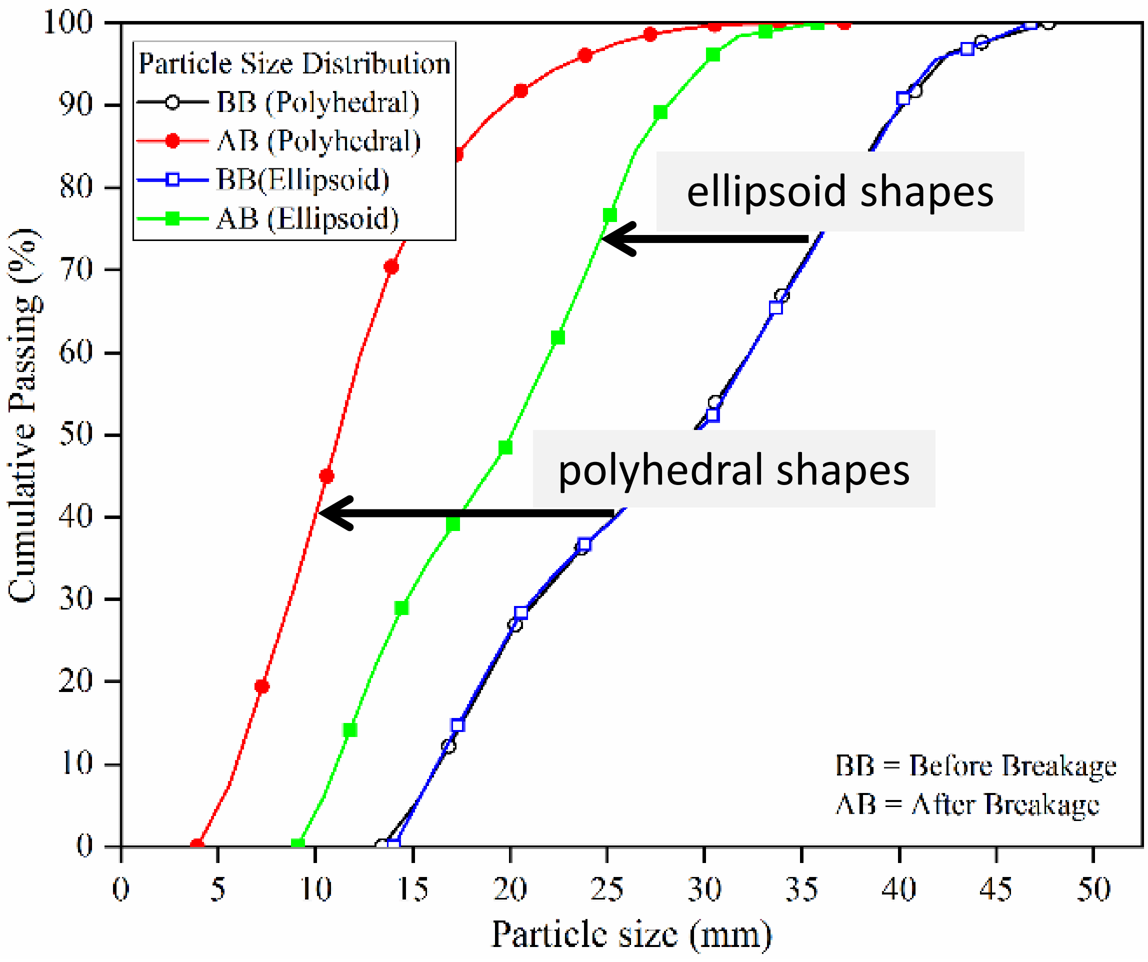
- The PD after 50 load cycles for the ballast layer with polyhedral particles is approx. 1.5 times that of the ellipsoid particles.



Comparing Different Ballast Shapes

Shift in Particle Size Distribution

Polyhedral particles experienced more breakage than ellipsoid particles.



Summary and Conclusions

- Particle breakage is the primary factor causing permanent deformation in railroad ballast.
- A novel approach was adopted to capture the shape of ballast particles using a modern smartphone camera; the images were then imported to the discrete element model.
- Comparing the results for ellipsoid and polyhedral ballast particles, significant differences in the extent of particle breakage and associated permanent deformation were observed.
- A prior research study reported no significant differences in permanent deformation for ballast particles of different shapes when non-breakable particles were considered (Dahal et al., 2018).

Thank You

Questions??

For detailed questions regarding this research contact:

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Oklahoma State University
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Detailed Information can be found in…

- Dahal, B., Mahmud, S.M., and Mishra, D. (2018). Simulating ballast breakage under repeated loading using the discrete element method. Proceedings of the 2018 Joint Rail Conference, April 18-20, Pittsburgh PA, USA.

- Dahal, B., and Mishra, D. (2020). Discrete Element Modeling of Permanent Deformation Accumulation in Railroad Ballast Considering Particle Breakage. Frontiers in Built Environment. https://doi.org/10.3389/fbuil.2019.00145

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