Computational Modeling of IPEx Drum-Lunar Regolith Interaction — Discrete Element Methods and Control Mechanisms

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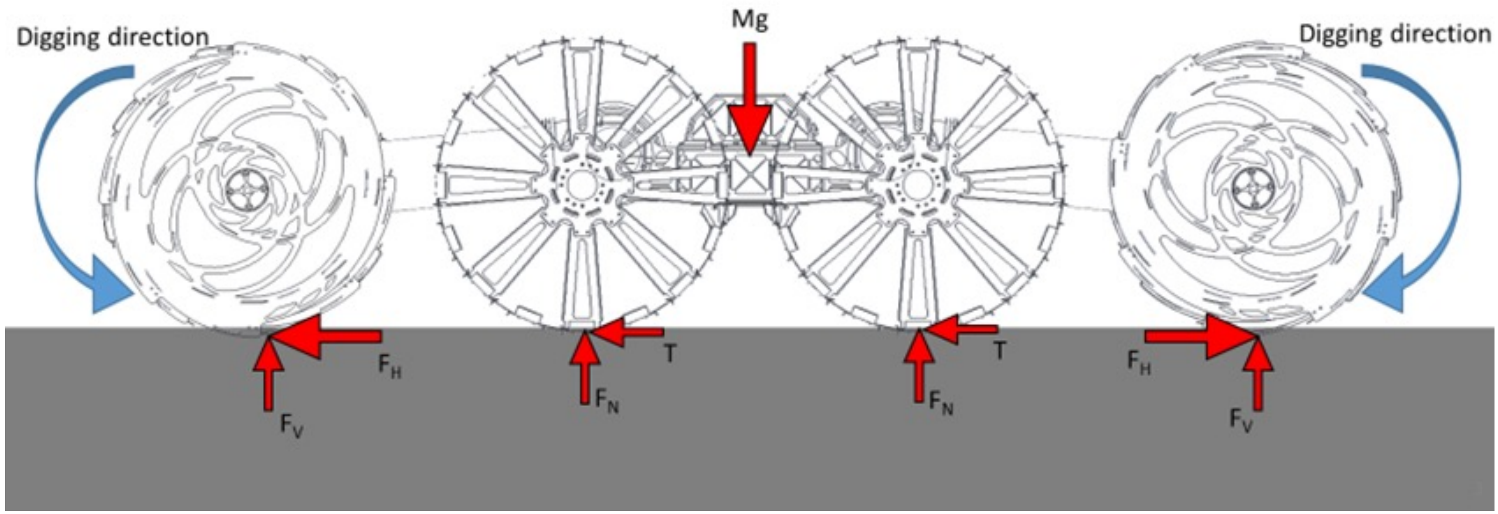
2024 Space Resources Roundtable
Golden, CO | June 4 – 7, 2024

ISRU Pilote Excavator (IPEx)

- A 30 kg-class robotic excavator developed at Kennedy Space Center to transport 10 metric tons of lunar regolith on the surface of the Moon (Schuler et al. 2022).
- An evolution of RASSOR, based on innovative design and use of counter-rotating bucket drums (Mueller et al. 2013, 2016).

RASSOR 2.0 (Credit: NASA KSC)

Counter-rotating bucket drums



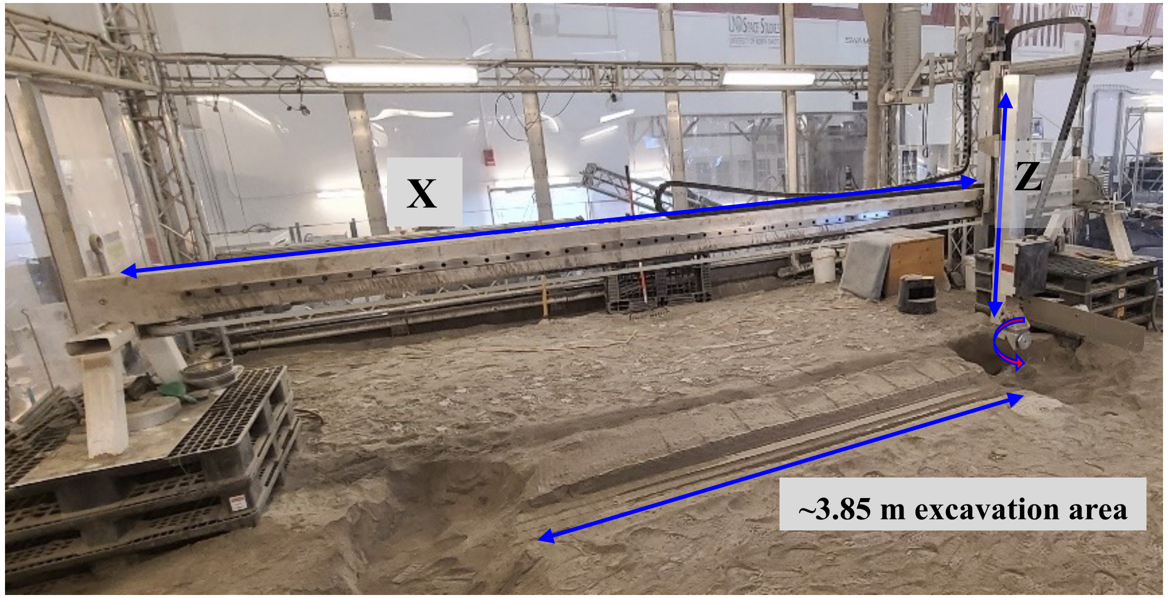
Schuler et al. (2022)

IPEx Experiments at KSC

- The IPEx drum was tested at KSC to reduce the size of the overall system from 65 kg to 30 kg while maintaining the goal of excavating large amounts of lunar regolith.

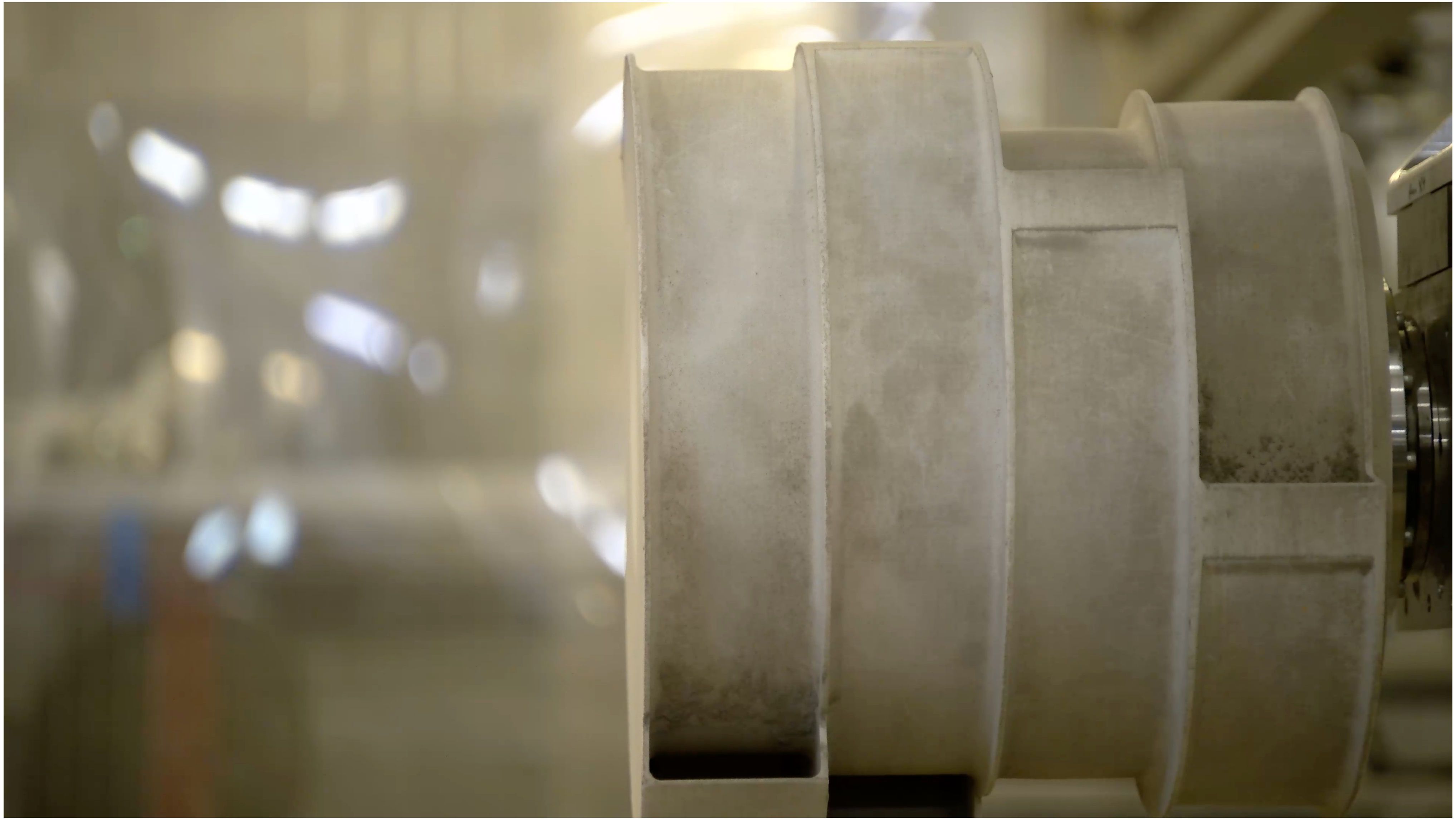
- Three drums were tested at varying cut speeds (10 mm/s and 30 mm/s)
  - Large (Original) 17.21” Diameter
  - Medium 11.62” Diameter
  - Small 9.35” Diameter

- Each drum was tested in a 3.85 m excavation area of BP-1 regolith simulant, and key performance parameters (KPPs), including force, torque, and mass accumulation, were recorded.



Schuler et al. (2022)

IPEx Experiments at KSC



Credit: NASA KSC

ISRU Pilote Excavator (IPEx)

- *No analytical models exist to predict KPPs given regolith properties and operation parameters.*
- *The scaling of KPPs with drum size and gravity field is yet to be understood.*

This work: develop computational models for IPEx bucket drum-lunar regolith system

- **Quantify KPPs for given regolith and operation parameters & predict KPPs beyond those tested and/or testable.**
- **Rapid investigation of different bucket drum operations and control algorithms to improve excavation efficiency.**
- **Enhance and accelerate the development of IPEx.**

Outline

1. Introduction

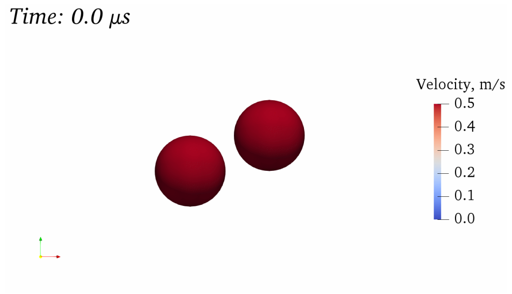
2. Methodology
   i. Discrete element method
   ii. IPEx-regolith model setup

3. Results and Analysis

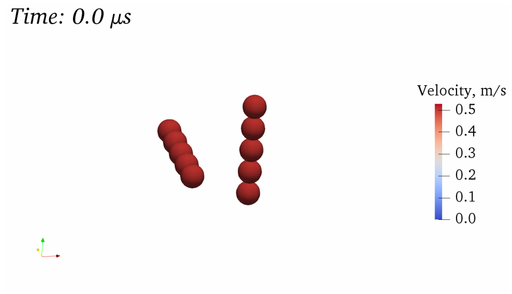
4. Ongoing Work & Summary

Discrete Element Method (DEM)

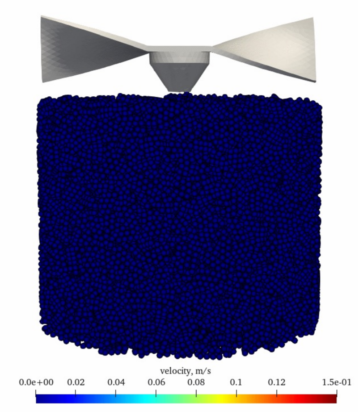
- DEM is a particle-based numerical method for modeling the mechanical behavior of particulate materials.
- DEM simulations track the motion and orientation of individual particles and resolve their collisions.
- The motions of and the interactions between the constituent particles at the microscopic scale result in the bulk mechanical behavior of the granular material and the system they form or interact with.



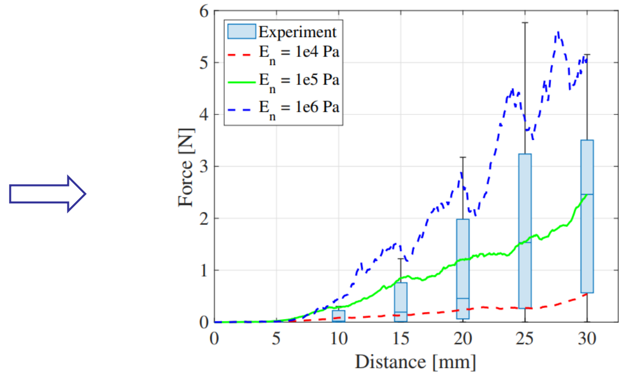
Particle collision (single sphere)



Particle collision (bonded-sphere)



FT4 rheometer



Force on impeller

Discrete Element Method (DEM)

Contact model:

- Hertz – Mindlin with JKR
  - The Hertz-Mindlin contact model will determine the:
    - Tangential elastic force
    - Normal dissipation force
    - Tangential dissipation force
  - JKR will model the cohesion of the system and follow the following formula for normal force:

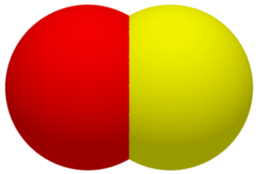
$$F_{JKR} = -4\sqrt{\pi\boldsymbol{\gamma}E^{*}a^{\frac{3}{2}}} + 4 * \frac{E^{*}}{(3R^{*})a^{3}}$$

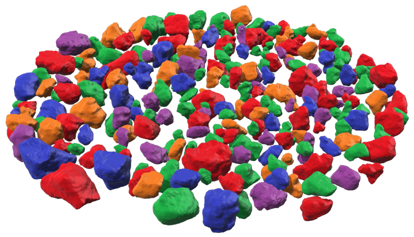
$$\delta = \frac{a^{2}}{R^{*}} - \frac{\sqrt{4\pi\boldsymbol{\gamma}\alpha}}{E^{*}}$$

- E* is equivalent Young's modulus, R* is the equivalent radius defined by Hertz-Mindlin
- γ =surface energy (J/m^2)

Particle shape template:

- Double sphere clumped particle
- More complex shape model is possible, but at the cost of increased computational time.



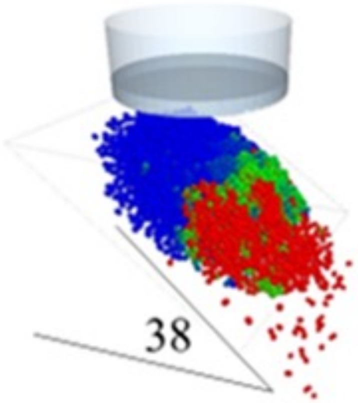


Discrete Element Method (DEM)

- DEM contact parameters were calibrated using test data of BP-1 lunar regolith simulant

Bulk Density

Angle of Repose



Inclined Plane

Table 1. Summary of DEM model parameters for BP-1 regolith simulant

Parameter	Value	Unit
Poisson’s ratio	0.25	-
Solids density	3200	kg/m^3
Shear modulus	1.00E+07	Pa
Restitution coefficient (P-P)	0.3	-
Static friction coefficient (P-P)	0.85	-
Rolling friction coefficient (P-P)	0.9	-
Restitution coefficient (P-G)	0.1	-
Static friction coefficient (P-G)	0.675	-
Rolling friction coefficient (P-G)	0.3	-
JKR surface energy	0.9	J/m^2

(Note: P-P stands for particle-particle; P-G stands for particle-geometry)

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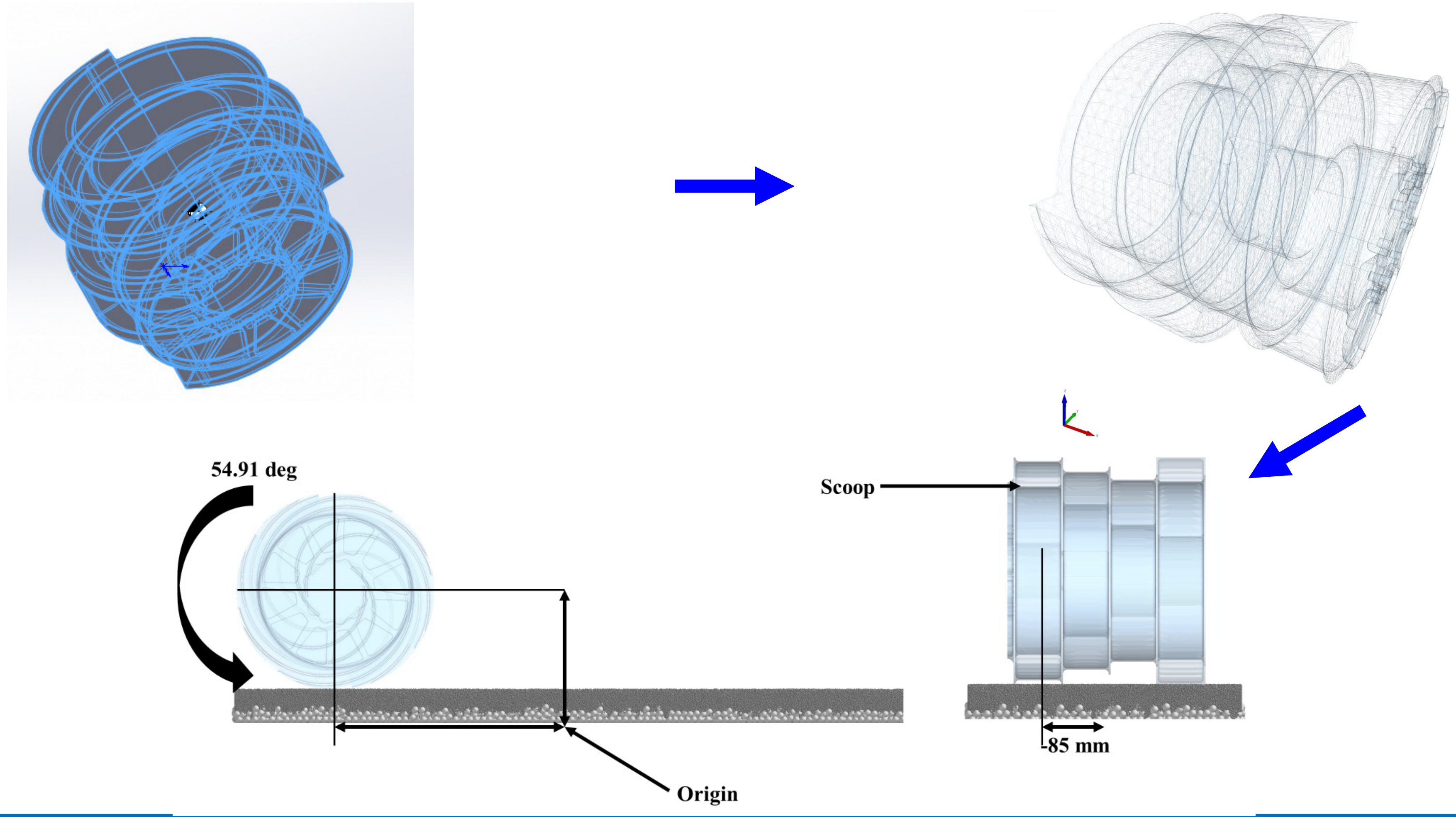
Model Setup – the IPEx Drum

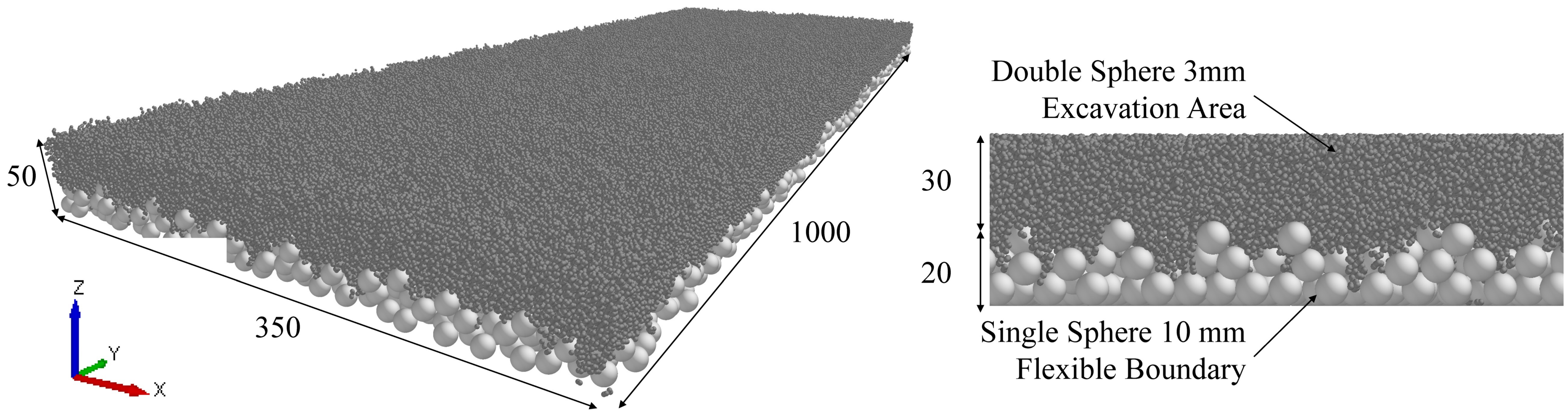
- The 3D printed Nylon medium sized drum was obtained from KSC as a SolidWorks part.
- The drum was then meshed with triangular elements and geometry adaptive meshing scheme.
- The meshed drum file was then imported to build the IPEx-regolith model in DEM.



Model Setup – Regolith Bed Generation

- BP-1 regolith bed was generated using the rainfall method (pouring regolith from a certain height).
- Two-layer regolith bed (finer on top and coarser at the bottom) to reduce computational time.
- Different initial packing densities can be achieved by applying a consolidation pressure.
- Regolith bed was equilibrated before excavation sequence started.

Rainfall

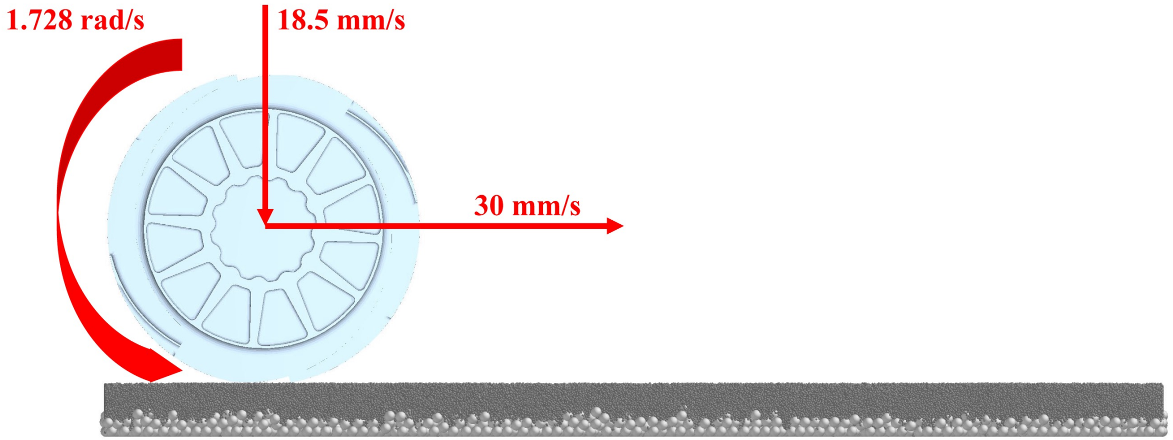


Model Setup – Control Mechanisms

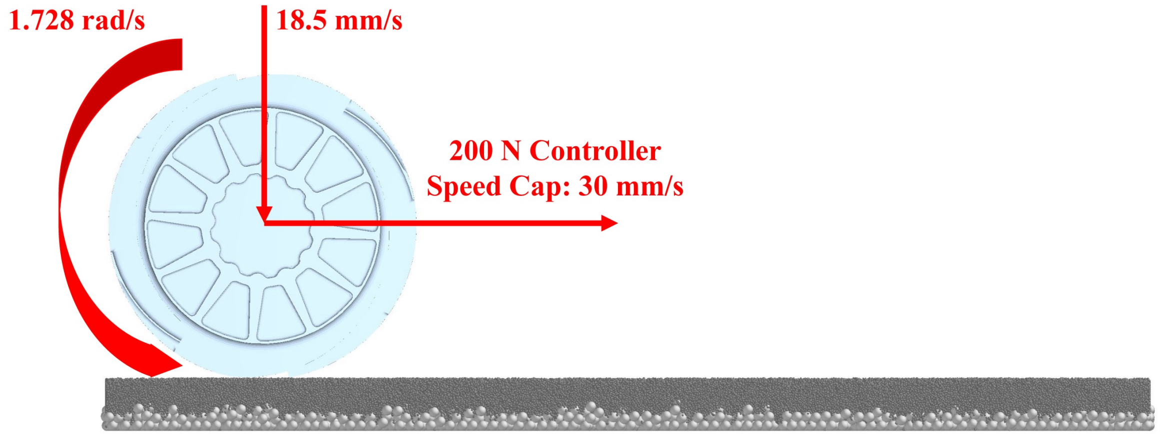
- The drum was then positioned to be above the regolith bed at the back of the bed.
- The drum was rotated so that the scoop would make impact on initial start of the rotation phase.

- **Motions Specified**

1. Imposed velocities

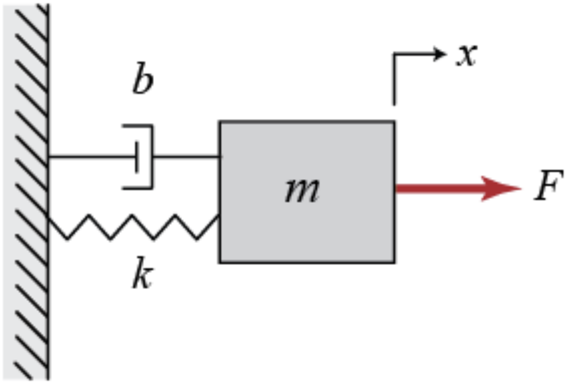


2. Imposed velocities + Excavation force controller



Model Setup – Control Mechanisms

- For this model, a simple Proportional-Integral-Derivative force controller was used:
  - Uses a governing equation for the system.
  - Then the Laplace transform is taken to obtain the transfer function for the system.
  - For the EDEM implementation, there is a force controller then a speed cap controller to keep the speed at 30 mm/s.



$$m\ddot{x} + \mathrm{b}\dot{x} + kx = F$$

$$\frac{X(s)}{F(s)} = \frac{1}{ms^2 + bs + k}$$

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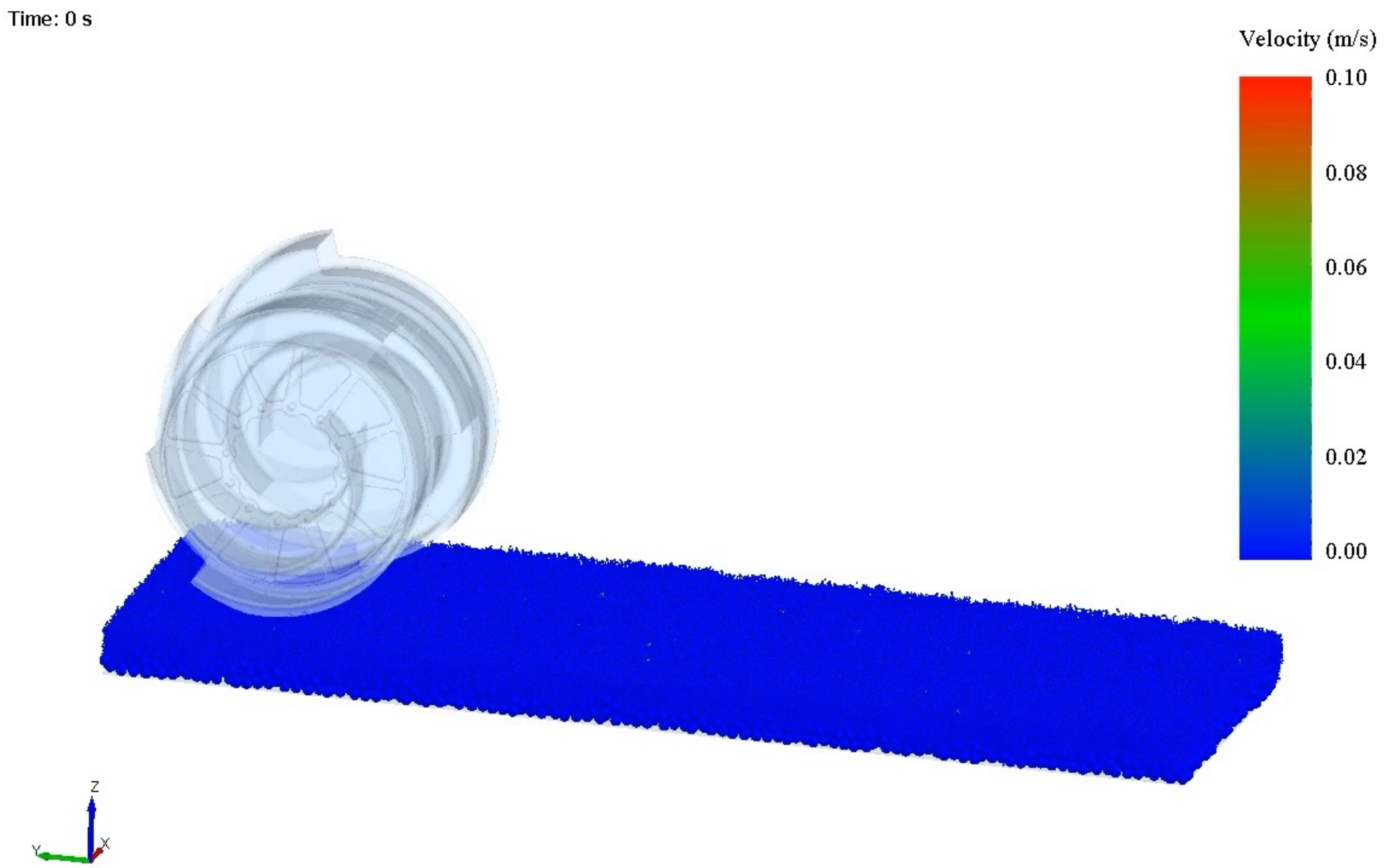
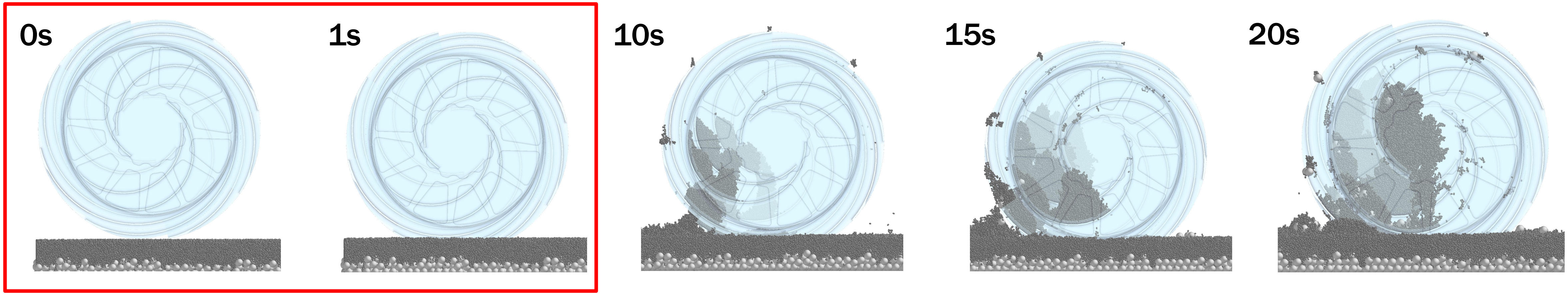
Results – One Excavation Simulation

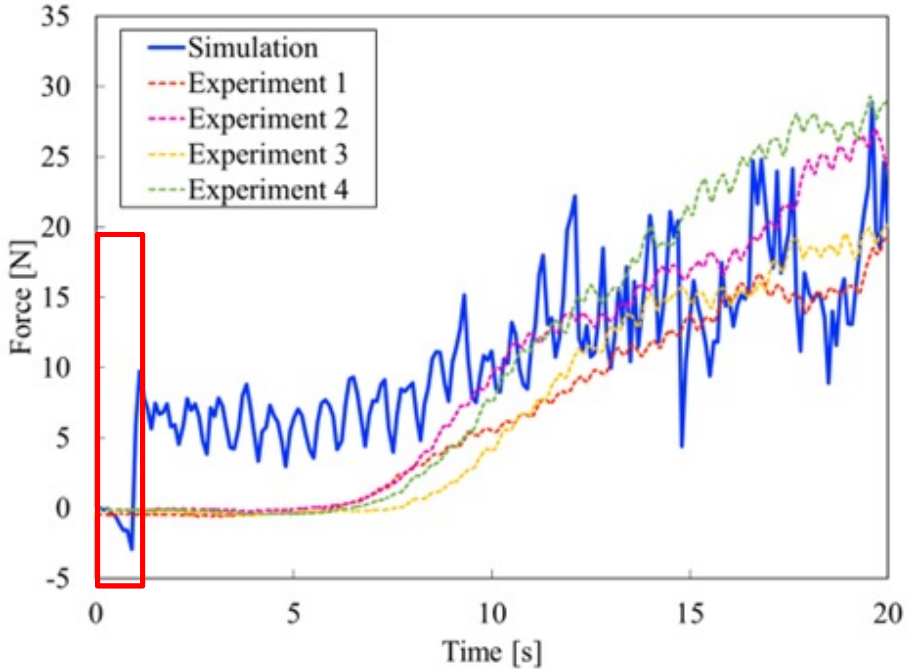
- 30 mm/s cut speed
- Imposed velocities
- No pre-cut

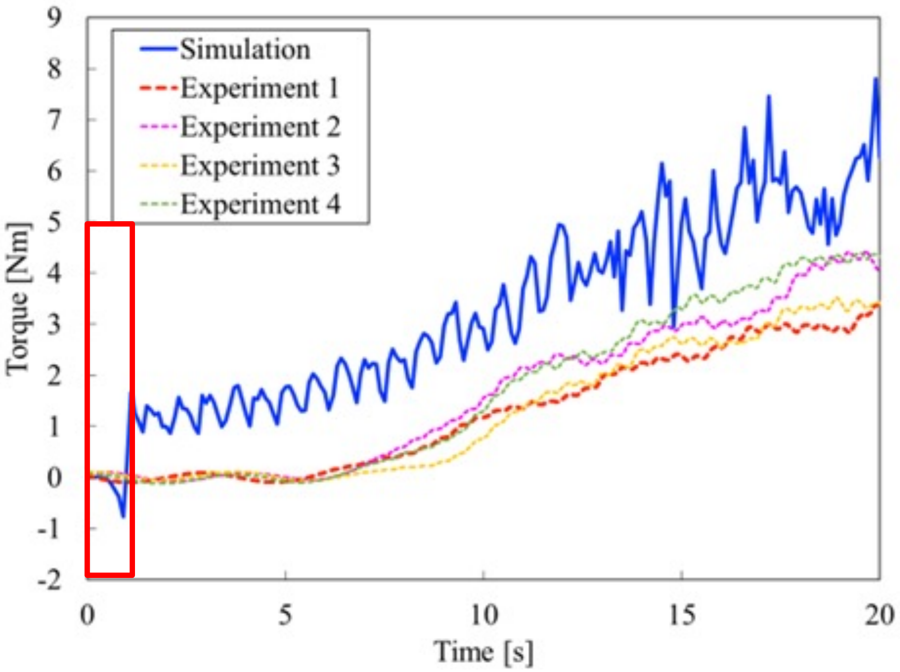


Altair EDEM™

Results – Simulation Versus Experiment



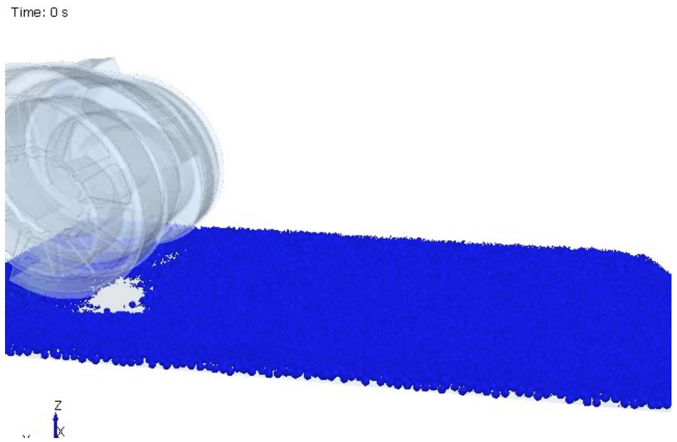


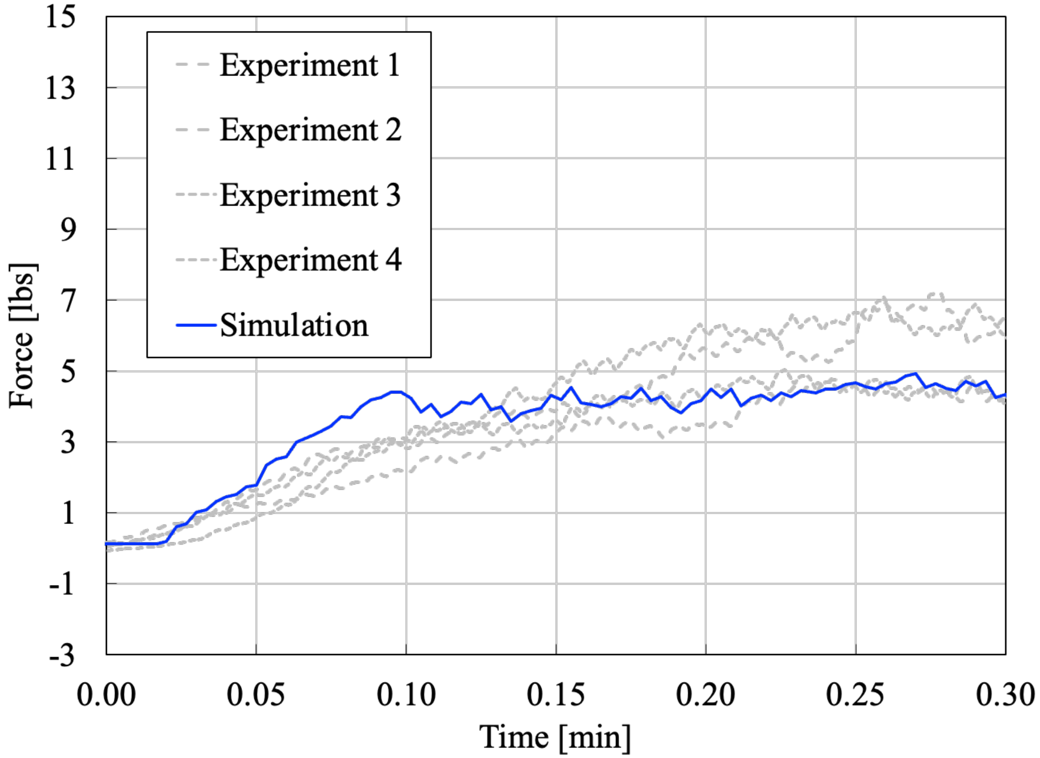


Results – Excavation Simulation

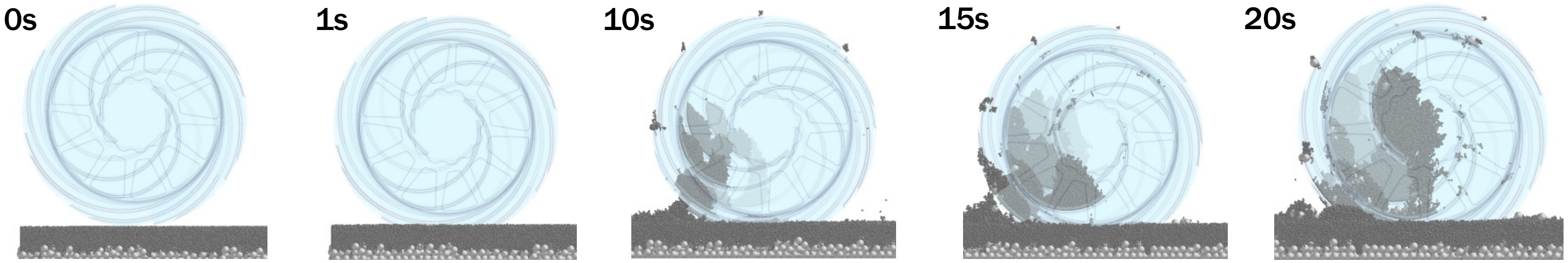
Modified simulation sequence (pre-cut; alignment of starting point)

- Drum used to excavate to a depth of a multiple of 40% of scoop height (16 mm approx.)
    - 2x – 2 s drop
- Drum then excavated forward for 1 s at 30 mm/s translational speed
- Drum then moved to original position and bed cut down to original 50 mm height using domain.
- Drum is lowered using velocity vector 0.018 mm/s
- Drum begins to rotate at 1.708 rad/s
- Drum then translates at 0.030 mm/s while rotating

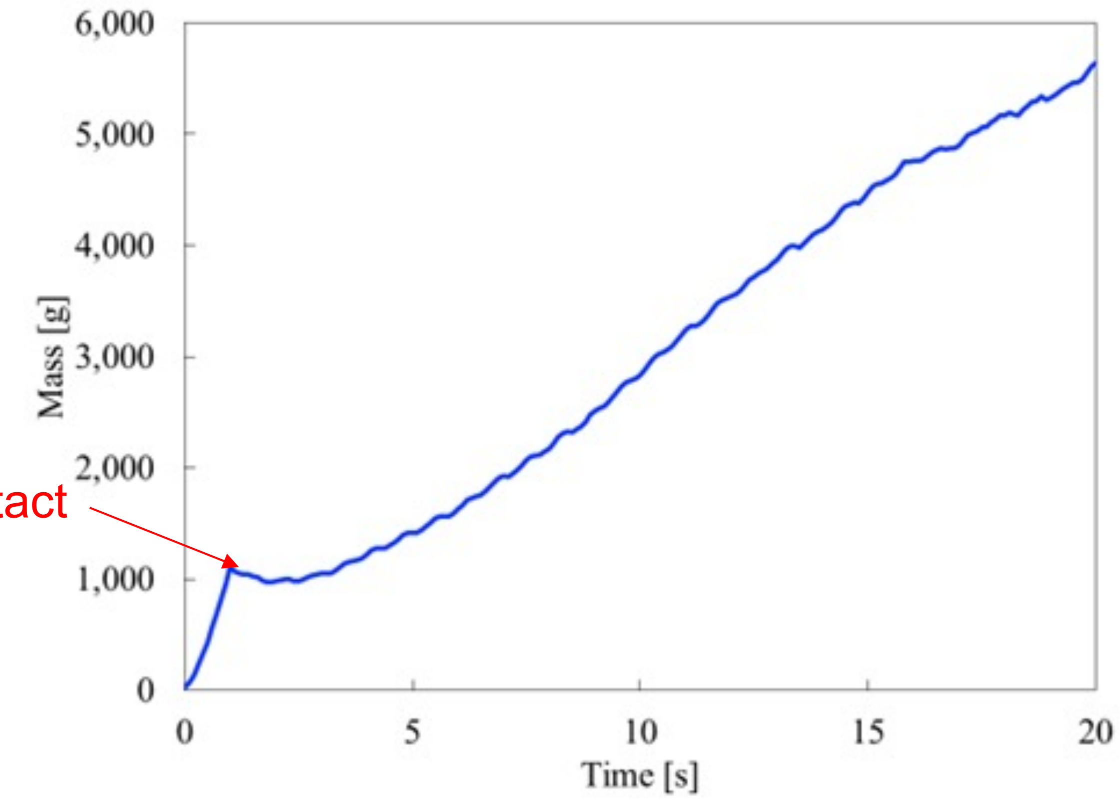


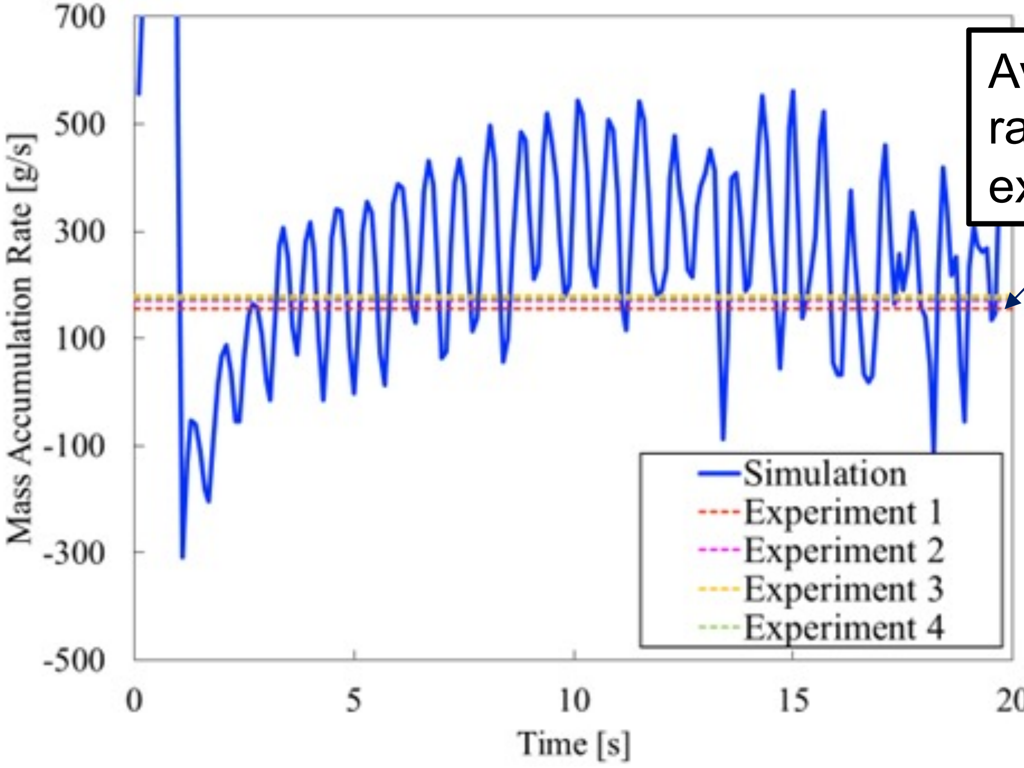


Results – Mass Accumulation



Contact

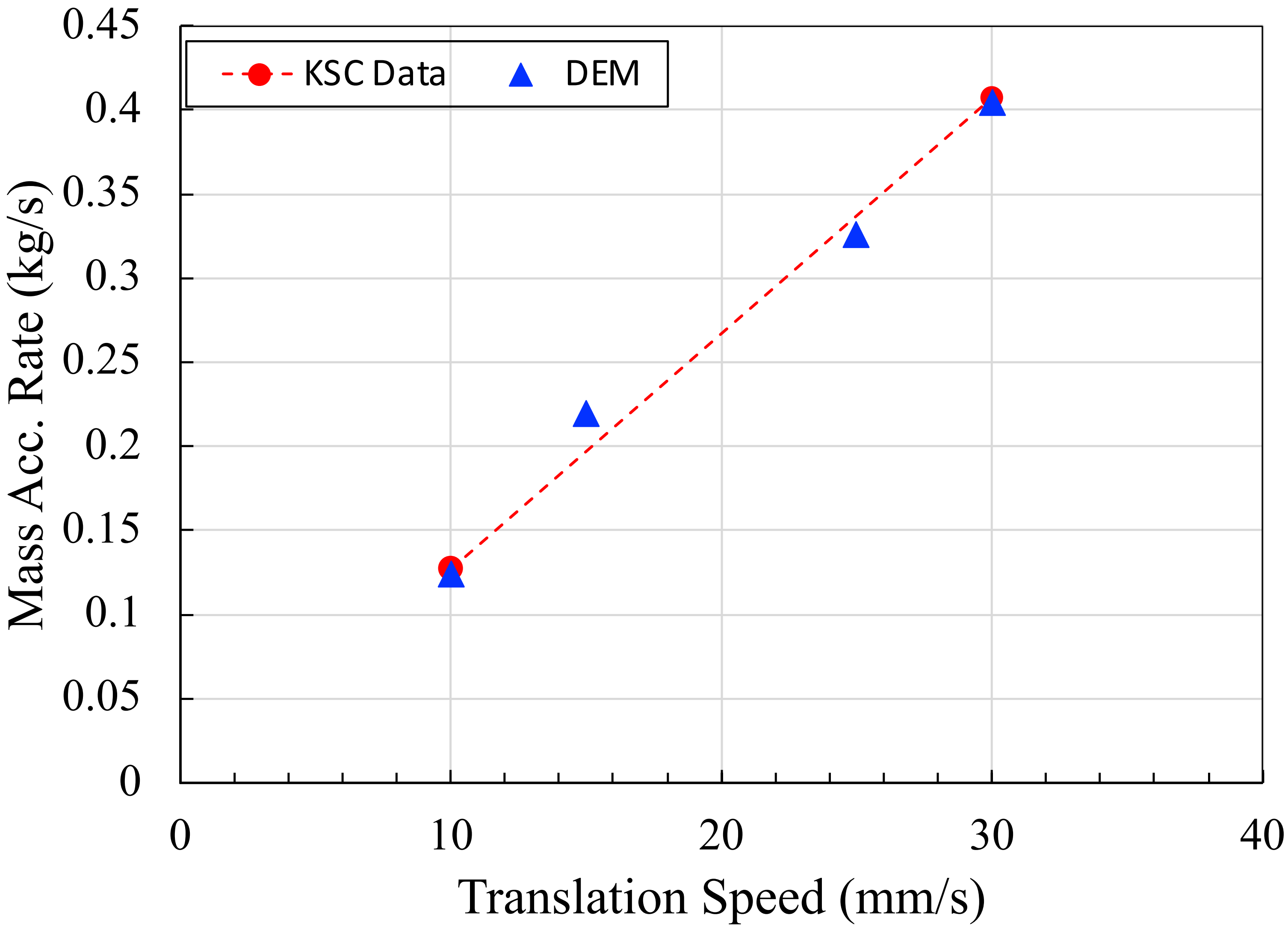




Averaged rate from experiment.

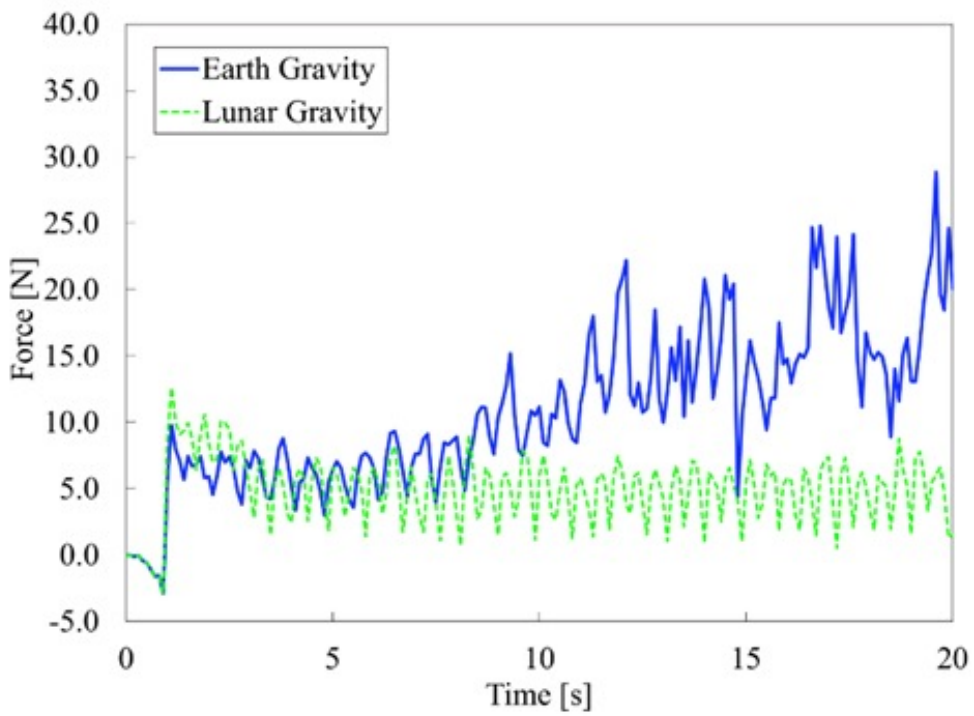
Results – Mass Accumulation

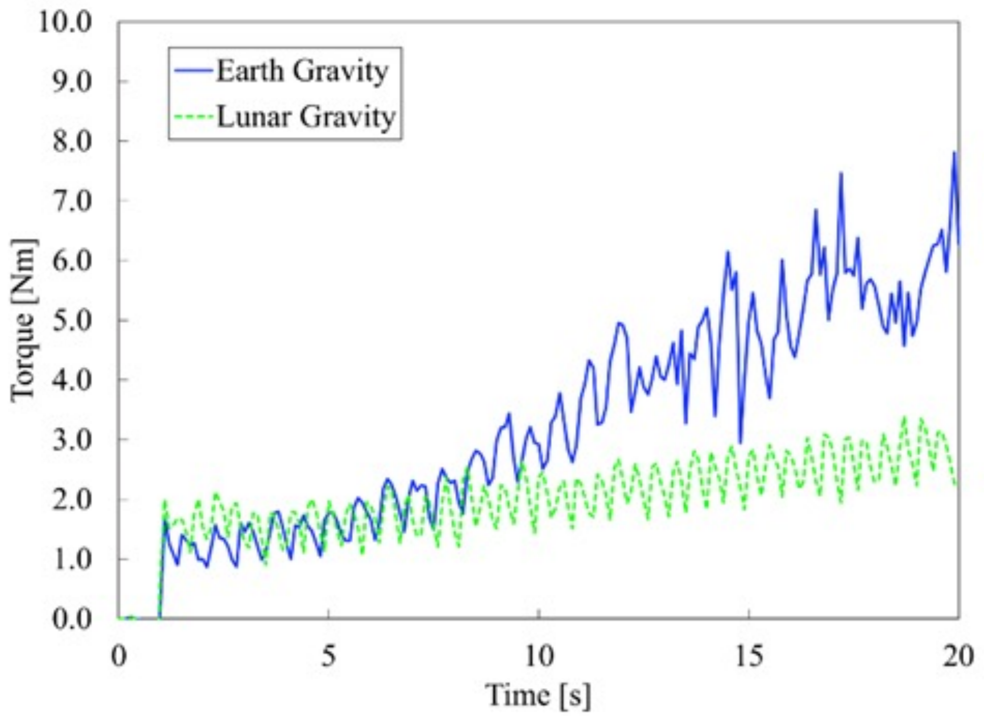
- Averaged Mass Accumulation Rate Data
  - KSC experiments:
    - 10 and 30 mm/s translational speeds
  - Simulation cases:
    - 10, 15, 25, 30 mm/s



Ongoing Work

- Couple DEM with multi-body dynamics to model more complicated motions in the regolith tool interaction.
- Parametric analysis on the impact of lunar regolith properties, operation parameters, and gravity field on IPEx performance.
- Generate data for developing analytical models to predict IPEx performance given regolith and operation parameters.





Summary

- Computational model developed for IPEx drum-regolith system using BP-1 simulant regolith model.
- The simulation of the 30 mm/s IPEx drum using a force controller in EDEM has shown that the excavation force and the torque behavior can be modeled with a reasonable amount of error and can be used to extrapolate future data for use in design and predict behavior.
- The mass accumulation rate for the 30 mm/s drum simulation matched well with that of the experiments, especially at the beginning and end of the simulated time period, but differed greatly from the experiments in the middle range of simulations.

Acknowledgment: This research is primarily supported by NASA EPSCoR under the federal award No. 80NSSC22M0064 and sub-award No. 521563-NE-RID-CM-005. We would like to express our gratitude to Dr. Jason Schuler and the Swamp Works team at KSC for generously providing the IPEx file and experiment data, as well as their feedback and guidance.

Thank you!

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