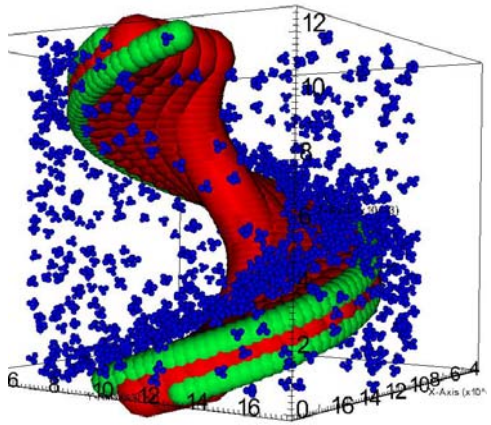
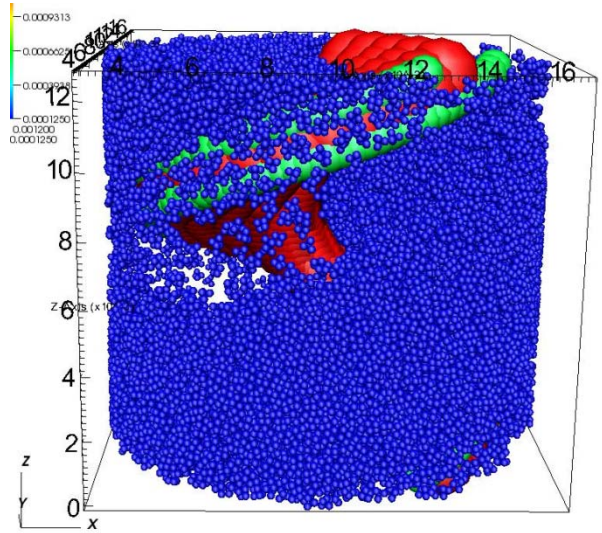
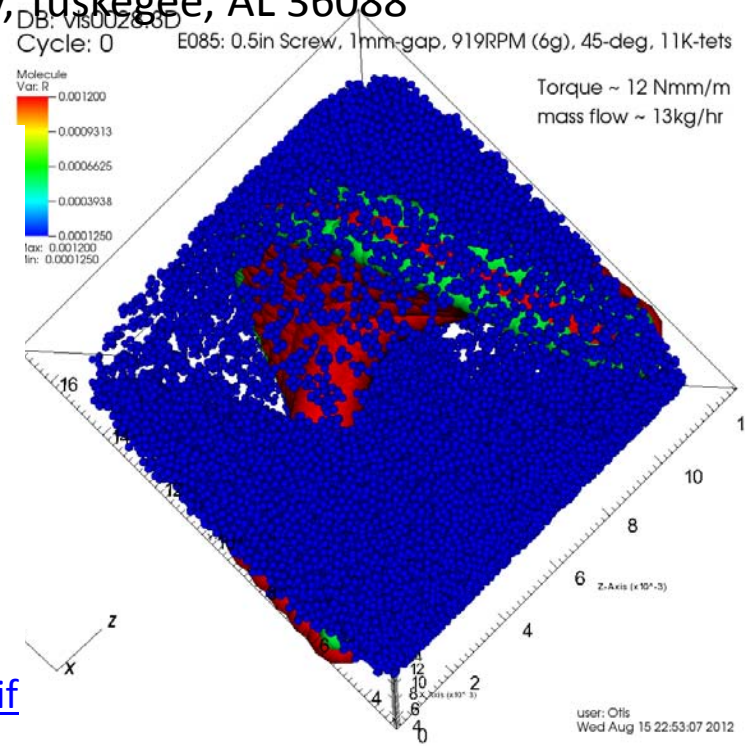
Micro-Gravity Screw Conveying: Robust and Efficient. Is This Possible?

Otis Walton[1], Hubert Vollmer[1], Brandon Vollmer[1], Logan Figueroa[1], Ali Abdel-Hadi[2]
[1] Grainflow Dynamics, Inc. 1141 Catalina Drive, PMB-270, Livermore, CA 94550
[2] Aerospace Science Engineering Dept., Tuskegee University, Tuskegee, AL 36088







Videos at: http://www.grainflow.com/index_files/750RPMconvey.gif
and: http://www.grainflow.com/index_files/750RPMslice.gif

Overview:

Examples – screw conveying in ½" and ¾" conveying lines
Compare Simulations with Lab Tests – Vertical & Inclined orientations
Background – Details of models/particles in the DEM code & prior results
Simulation Parameter Study Results – Terrestrial-G, Lunar-G, Micro-G conveying

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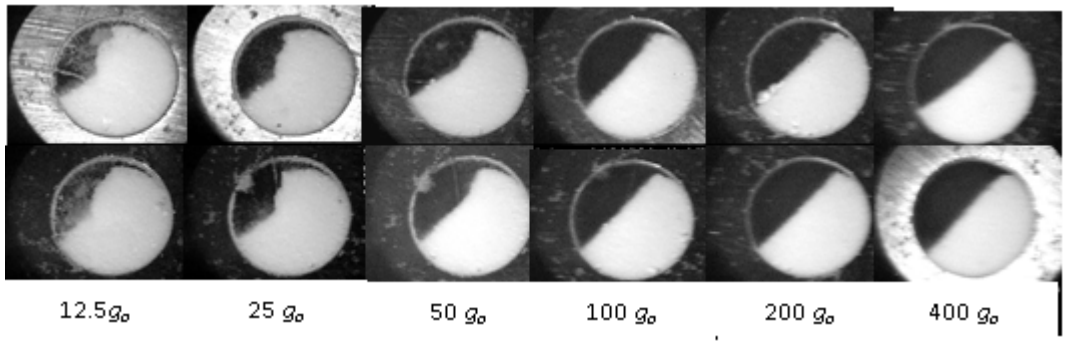
Background:

- **Lunar Soil (Regolith) has wide size distribution and large quantity of very fine particles**
- **In-situ material is highly 'overconsolidated'**

This project is concerned about <u>transport & handling of regolith after it has been excavated</u>

(Prior work has demonstrated that a factor of 4 change in g-level can change apparent 'cohesiveness' from very-cohesive to free-flowing)



Rotating drum 'angle of repose' tests at the end of a centrifuge arm with a very cohesive powder. As the g-level increases the cliffs and avalanches appear to disappear and the powder appears to be 'less cohesive'. **The inverse is also true, if gravity decreases by a factor of 4 a powder that appears free flowing may change so that it appear to be quite cohesive (in the same size apparatus).** [Walton, 2008, Granular Matter]

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The feasibility of utilizing light-weight screw-conveyors to transport regolith simulant in enclosed ducts, at any inclination was demonstrated as part of a Phase-1 NASA-SBIR project focused on ISRU technology development. Such systems can provide dust free conveyance for regolith which can facilitate extraction and transport with minimal loss of volatiles. Small, light-weight flexible systems conveyed material against terrestrial gravity, and transferred material from one conveying line to another ('up' against terrestrial gravity). The laboratory tests also demonstrated that utilization of compliant components increases robustness (i.e., especially with respect to occasional oversize particles) and improves conveying efficiency. The flow rates delivered from the 1.27cm diameter (0.5") conveyors exceeded the requested 5gk/hr of the SBIR solicitation for which the work was performed. The 2cm diameter systems were capable of conveying over 50kg/hr.

JSC-1A conveyed w/horizontal to horizontal transfer 'up' against terrestrial gravity.

JSC-1A conveyed with horizontal to vertical transfer 'up' against terrestrial gravity. Vertical conveying line run at higher RPM than horizontal

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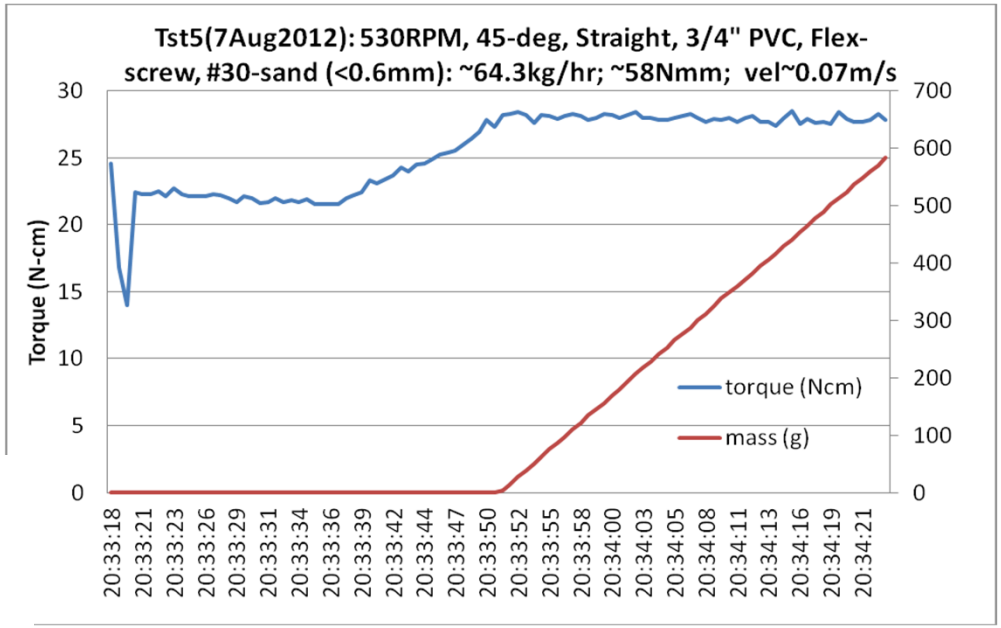

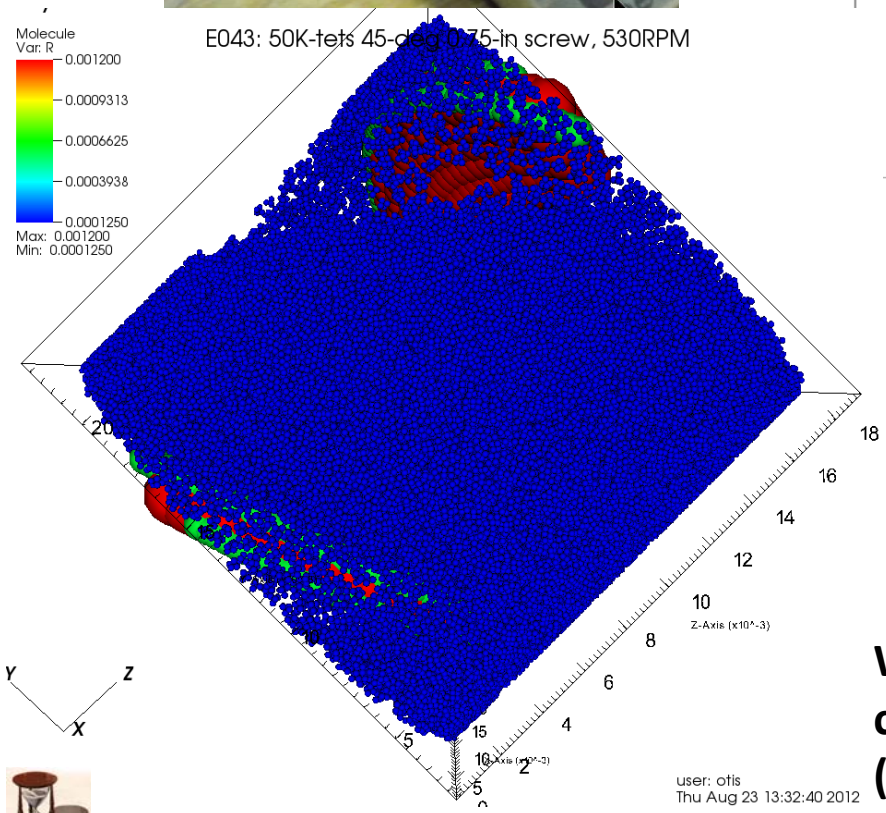

Left Top: Snapshot during 530RPM 45° inclined conveying test .

Right: Torque & mass curves .The Torque value in the title is the torque for just the 32-inch (0.81m) conveying length, which corresponds to 71.3Nmm/m of 'conveying torque'.

Bottom Left: Snapshot of corresponding simulation. The simulated mass flow rate is approximately 62 kg/hr, and the simulated conveying torque is approximately 92Nmm/m (during the last half of the simulation time). The average axial velocity of the material in the simulations was 0.070m/s.

When mass-loading & rotation rates were comparable, simulations & measurements agree (e.g., conveying torques within 20% to 30%)

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Some features/behavior we knew from previous work

DEM Behavior controlled by:

- **Interparticle interactions (e.g. force-displacement relations)**
- **Size and shape distributions of particles**

Particle-assembly behavior (from DEM & Expts):

- **Frictional Spheres:**

  20° < Angle of Repose < 30°

  for 0.1 < Friction coefficient < 1

- **Changing Shape: can increase Angle of Repose to > 40°**
  (but does not produce large clumps , cliffs, arches, etc.)
- **Cohesion produces arches, clumps, cliffs, no-flow conditions**
- **Cohesion + contact moments produce low-density floc-like structures**
- **Scaled 'calculational particles' capture general flow modes, but lose details**

  (size-scaling relations verified in previous simulation studies)

- **Reducing gravity makes material appear more 'cohesive'**

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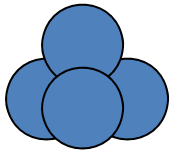
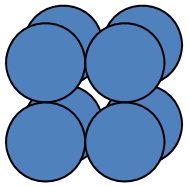
Simple aspect-ratio-one particle shapes were used in simulations to represent regolith

Spheres



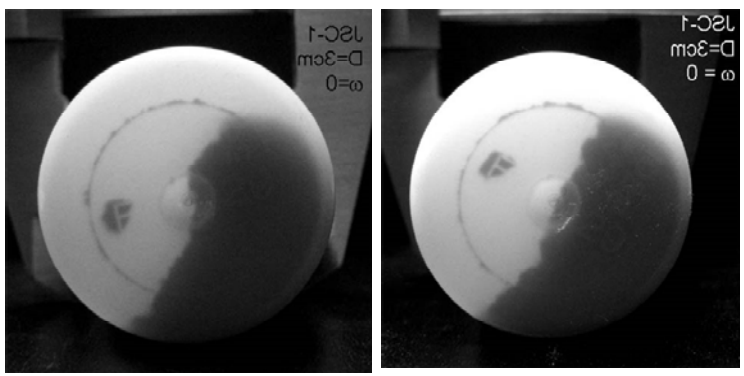
4-Spheres arranged in a tetrahedral cluster



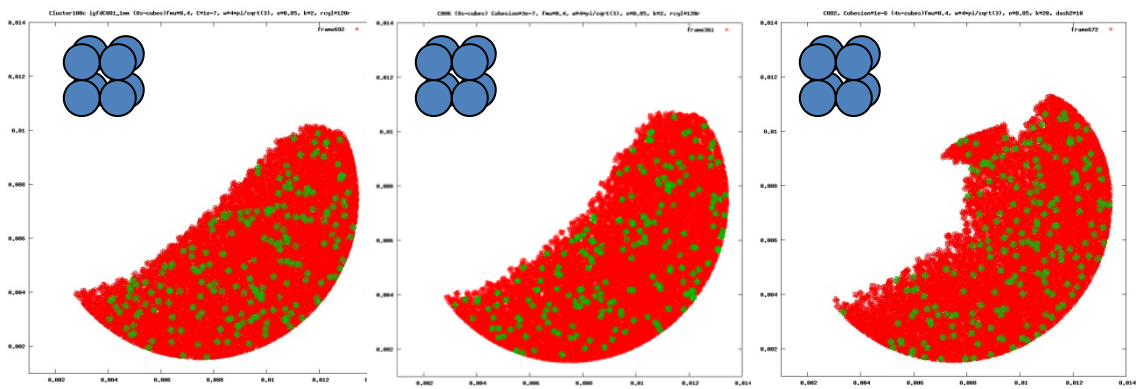
8- Spheres arranged in a cubical cluster

Scaled 'calculational particle' properties:

Stiffness $K \propto R^3$ Cohesive Force $F_C \propto R^2$



JSC-1 sumulant in a 3cm diameter cylindrical container



$C_0 = 0.1\mu N$ $C_0 = 0.3\mu N$ $C_0 = 1\mu N$

100-micron spheres in a 12mm diameter rotating horizontal drum

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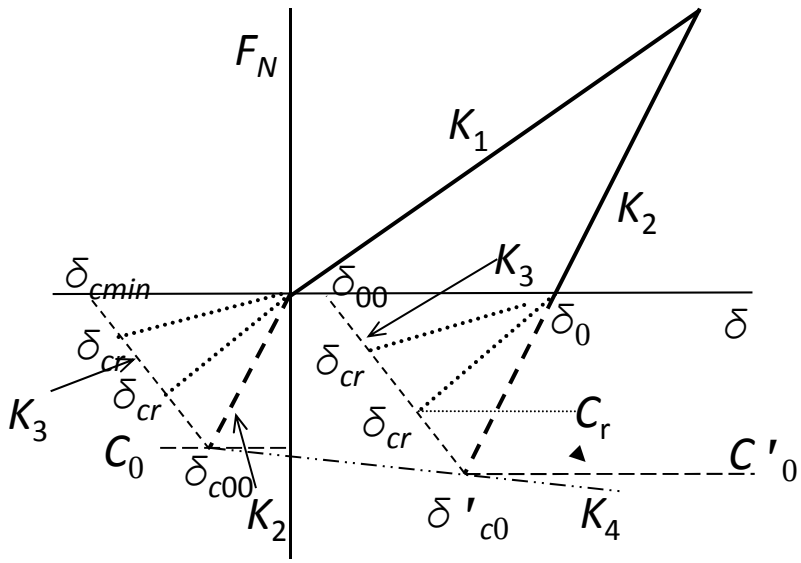
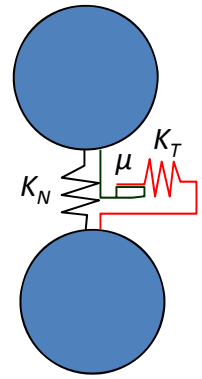
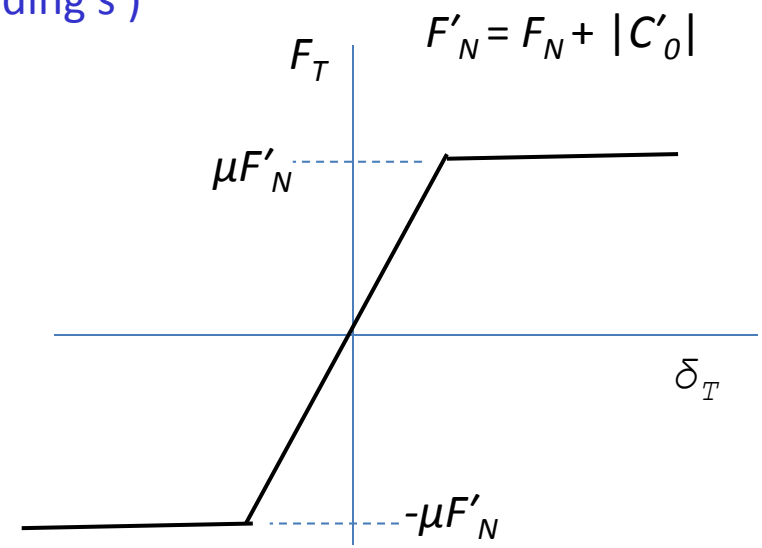
Piece-wise linear cohesion model (similar to S. Luding's)



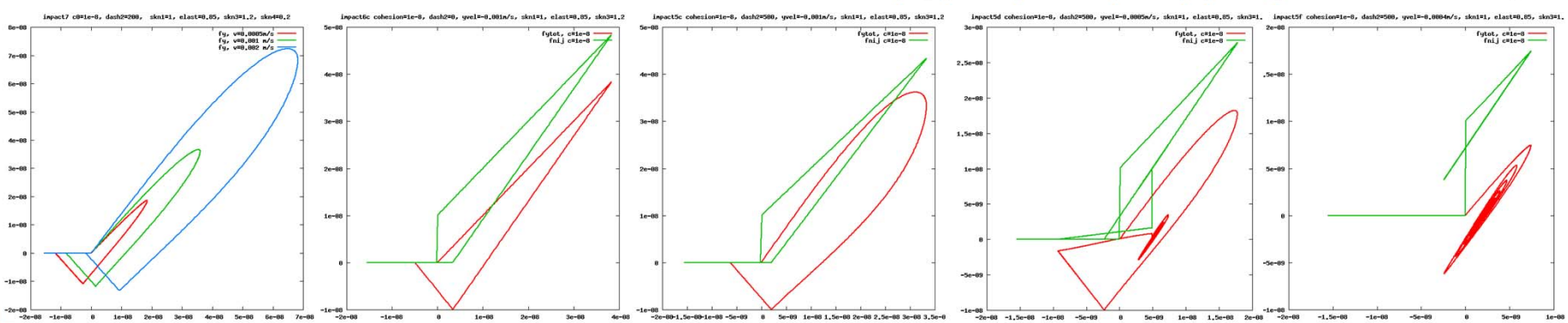




"Sticking" requires energy loss, not just cohesion (*i.e.*, need hysteresis or viscous terms)

Optional viscous damping also allowed, *D*, *D'* coeff

$$F_N = \begin{cases} K_1\delta + D\delta\dot{\delta} & -\,loading \\ K_2(\delta - \delta_0) + D'(\delta - \delta_0)(\dot{\delta} - \delta_0) & -\,unloading \end{cases}$$



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Technical Objectives for Phase-1:

- **Demonstrate the feasibility of small, light-weight flexible screws conveyors for regolith materials under reduced-gravity and micro-gravity environments.**
- **Predict the effects of reducing gravity (from terrestrial levels to zero) on the conveying efficiency and power requirements for small-scale screw conveyors.**

Results:

Extensive simulations demonstrated the effects of a number of parameters on conveying efficiency, under terrestrial, lunar and micro-gravity conditions. The simulations confirmed scaling relations previously obtained for granular flows in other rotating configurations, including horizontal drum-flows, and rotating pipe conveyors. The simulations also showed that these scaling relations begin to fail at low gravity when interparticle cohesion becomes a significant factor in granular material flow behavior.

The simulated torques and mass flow rates agreed with the laboratory measurements of those same quantities, when the mass-loadings and rotation-rates in the conveying simulations were set to the values used in the laboratory tests with sand and lunar regolith simulant JSC-1A. The good correlation between the terrestrial-gravity lab tests and the simulations provided a reasonable degree of confidence in the simulation-predictions of reduced gravity behavior. One unanticipated finding, obvious in hindsight, was that for micro-gravity conditions increasing the gap spacing between the screw and duct wall increases robustness, but unlike under terrestrial conditions, a large gap size does not significantly affect the conveying power, torque or overall conveying efficiency. Under micro-gravity large wall gaps just become filled with a stationary layer of regolith, which then acts as a compliant inner lining on the duct wall surrounding the conveying auger.

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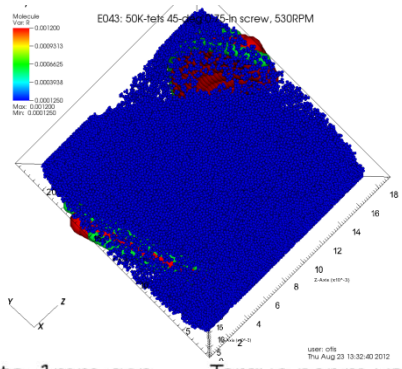

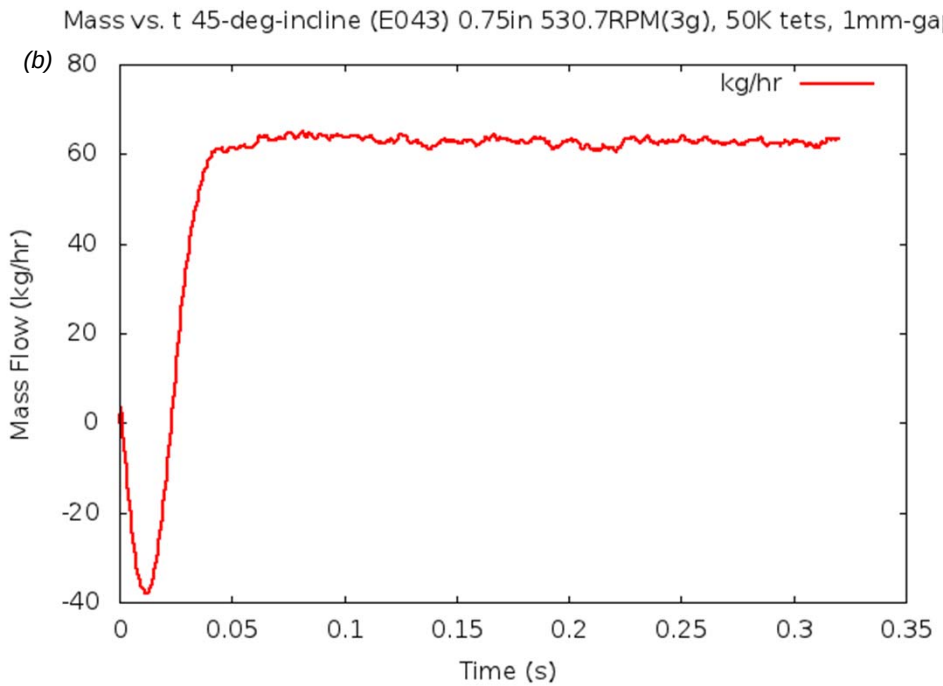

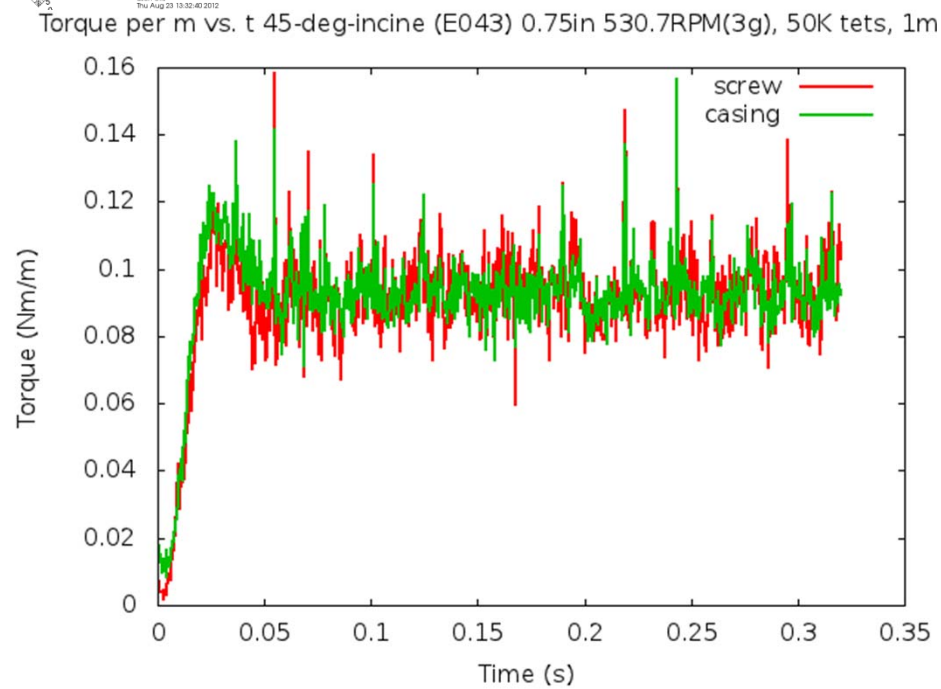

Simulation results for a Discrete Element Method (DEM) simulation of 50000 0.4mm tetrahedral sphere-cluster particles in one flight of a ¾" diameter screw conveyor (~245g/m mass-loading in the simulated conveyor) inclined at 45°, with a 1-mm gap between the screw and the wall and a screw rotation rate of 530RPM (coefficient of friction ~0.4 with wall and 0.5 between particles).

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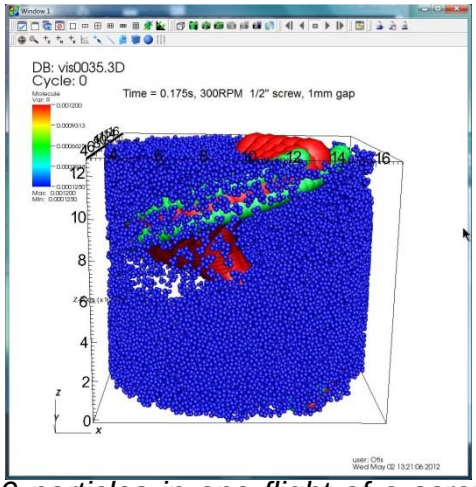
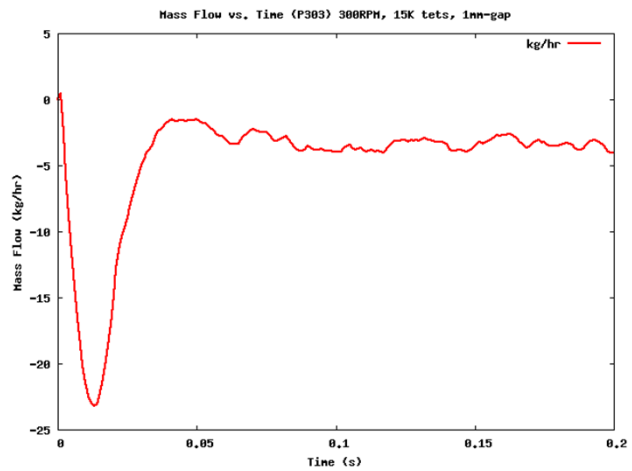
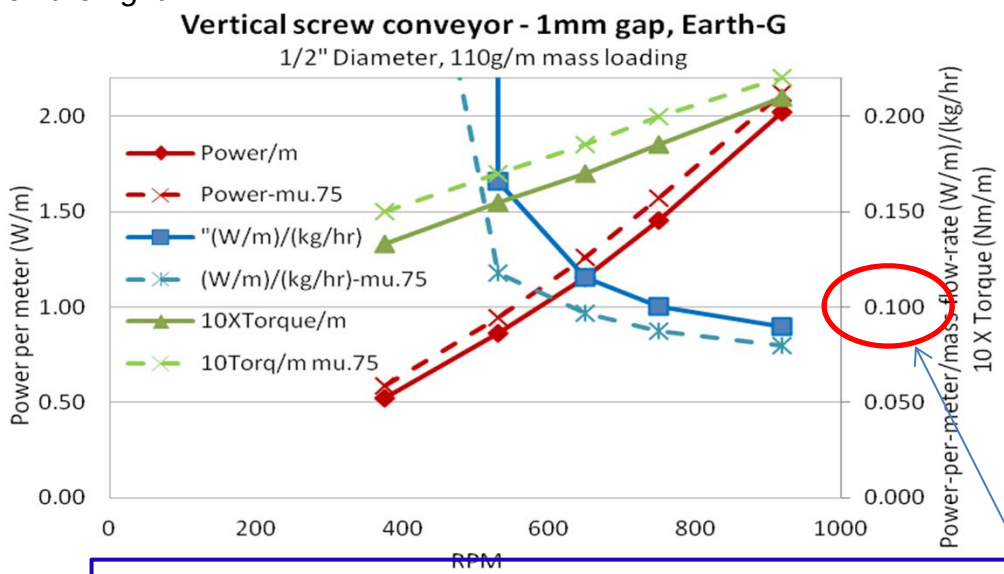




Simulation of 15000 particles in one flight of a screw rotating at 300RPM (with a 1mm gap between the screw and the pipe-wall). Particles are 'raining' down through the gap between the screw and the pipe wall faster than the screw is conveying them up, resulting in a negative mass flow rate, as indicated in the time history (over the 1st two revolutions of the screw) shown in the image on the right.



Power per meter, Power-per-meter-per-kg/hr, and Torque per meter for ½" diameter simulated vertical screw conveyor with 1-mm gap to pipe-wall under Earth conditions. The solid lines are for coefficient of friction of 0.5 between particles and 0.4 with walls. The dashed lines have increased friction of 0.75 for all contacts. Even though the higher friction case has higher Torque and higher Power, the overall conveying efficiency (blue squares and asterisks) is better for the high-friction case (lower Power per kg conveyed) because the mass flow rate is higher for the simulated high-friction material.

The circled value is an indication of the predicted conveying efficiency, @ terrestrial-G

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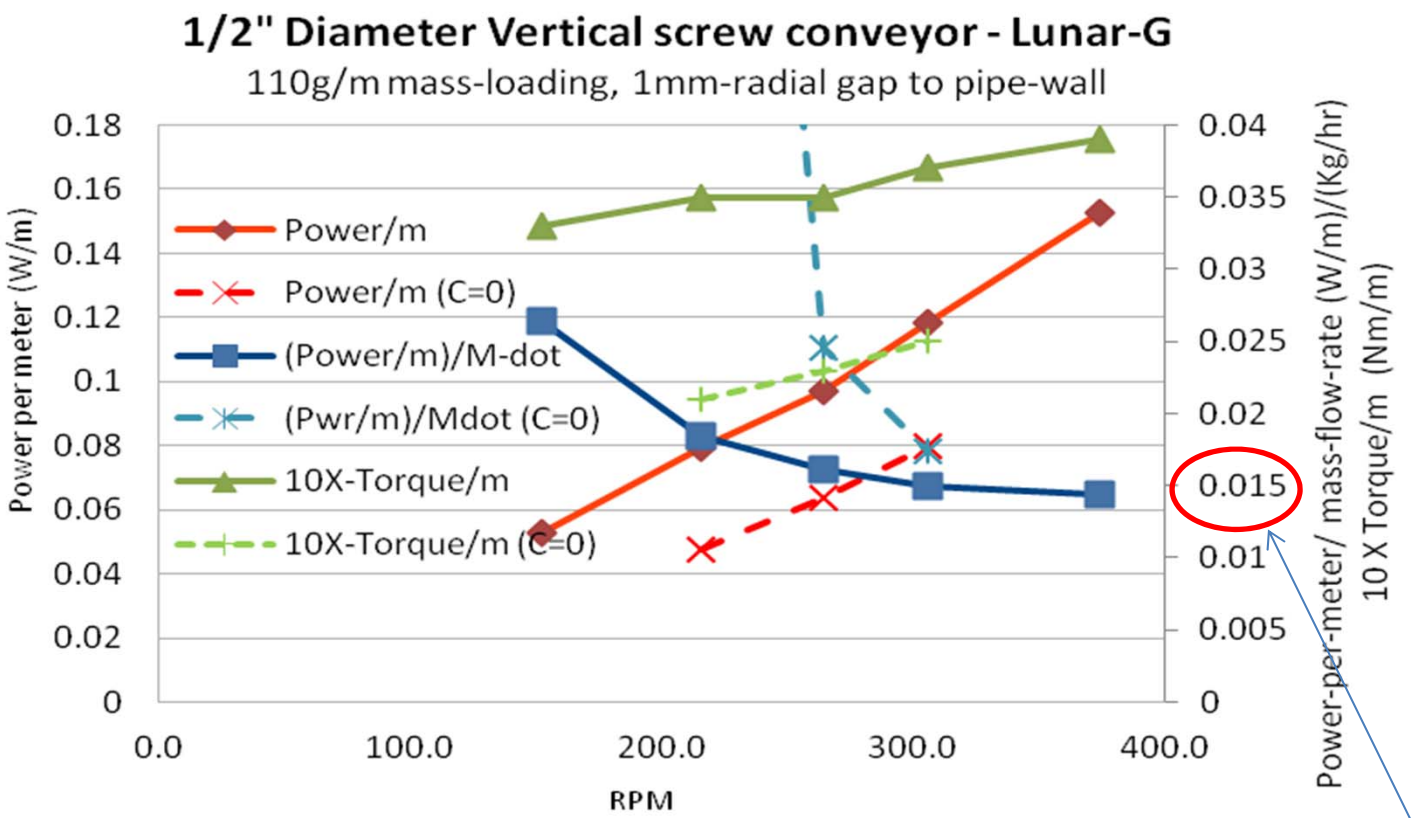

Power per meter, Power-per-meter-per-kg/hr, and Torque per meter for ½" diameter simulated vertical screw conveyor with 1-mm gap to pipe-wall under Lunar conditions (Problems L01- L05 of Table-2).

The circled value is an indication of the predicted conveying efficiency @ lunar G (a smaller value indicates less power per kg of material conveyed per hour)

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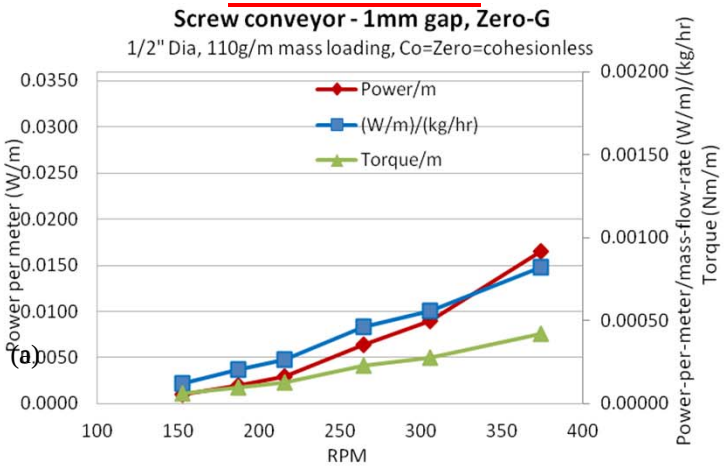
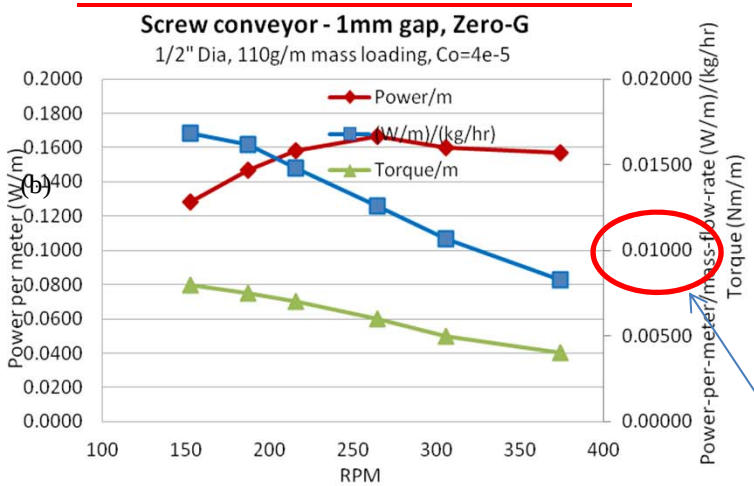
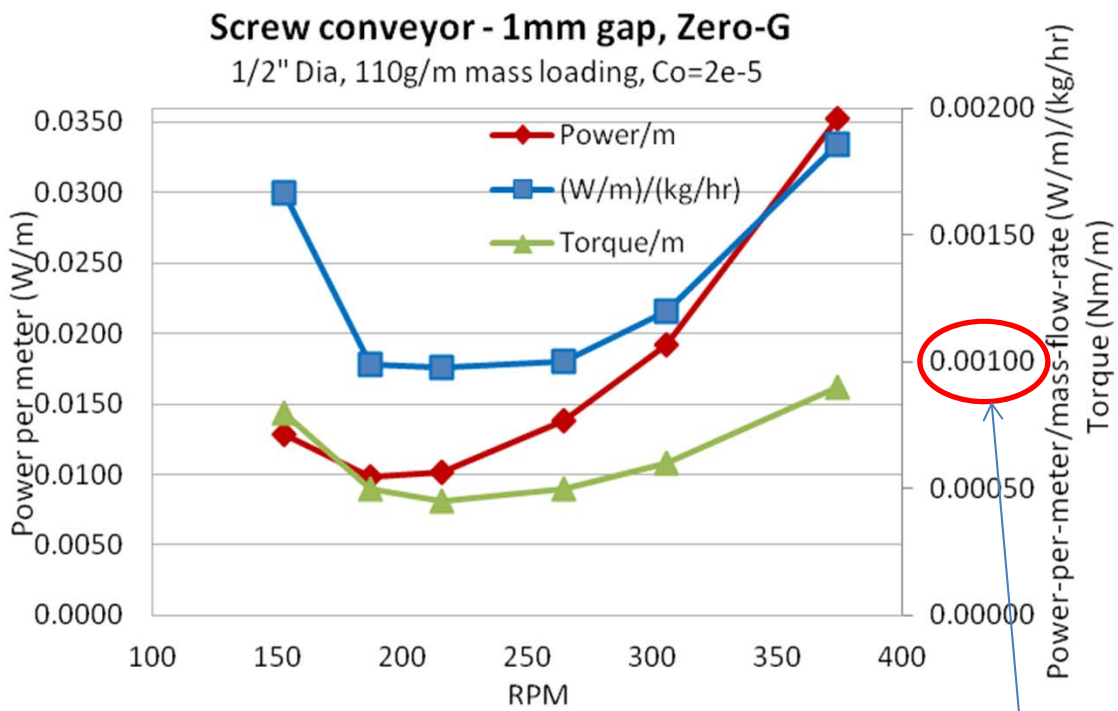
Cohesionless



Twice the Nominal Cohesion



Nominal Cohesion value



Simulation results for materials with various assumed interparticle cohesion under Zero-G conditions. (a) cohesionless, (b) Interparticle pull-off force limit Co=2e-5N, (c) Co=4e-5N

The circled value is an indication of the predicted conveying efficiency @ Zero - G

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Observations and Concluding Remarks:

- The simulations predict that the power and torque requirements are dramatically reduced under low-gravity (by up to an order of magnitude under lunar-gravity conditions and as much as two-orders of magnitude for micro-gravity conditions).
- **The results are very sensitive to the value of the interparticle cohesion used in those simulations. Such a high sensitivity to material cohesion indicates that equipment will need to be designed to handle the entire range of anticipated regolith cohesive strengths, or the cohesive properties of regolith will require careful characterization.**
- Future confirmation of the predictions, under reduced-gravity conditions, might allow the focus of future ISRU conveying technology development to shift its emphasis from efficiency to robustness (with efficiency as a secondary priority).

The simulations for this project were performed before the lab tests:

- Simulations allowed tests to focus on parameter settings that would 'work'
- **Entire sub-studies were dropped because the simulations showed no benefit** (e.g. rotating pipe conveyors were originally planned as part of the study – they were only examined in simulations, saving countless hours of fabrication and testing).
- As physics-based simulation models improve, we should be able to do more studies with simulations, and focus much of the lab effort on verification, validation, and confirmation of the model predictions of material behavior and performance of proposed equipment designs.

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