Large-scale DEM-LBM Modeling Towards Off-road Mobility

2019 DoD HCPMP User Group Meeting
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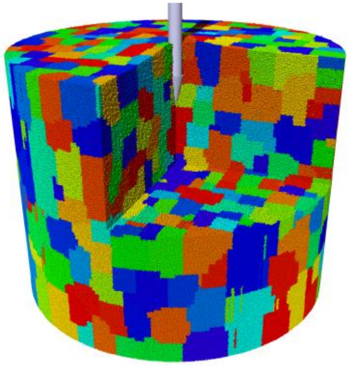

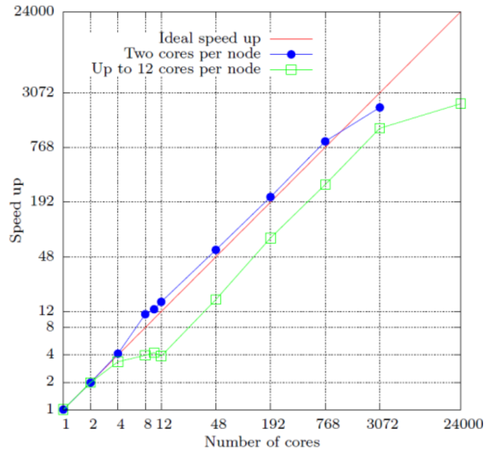

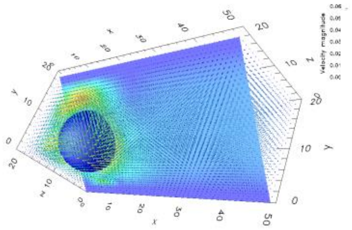

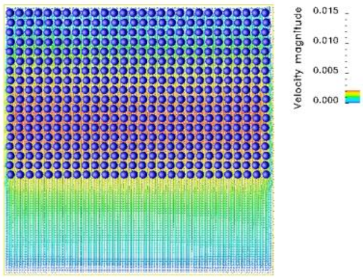

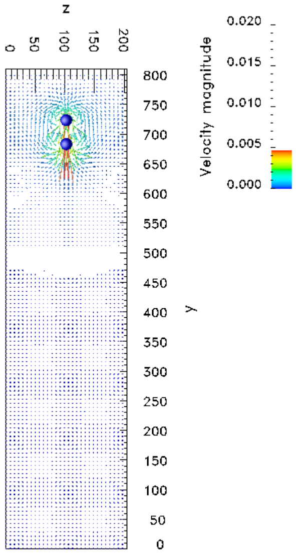

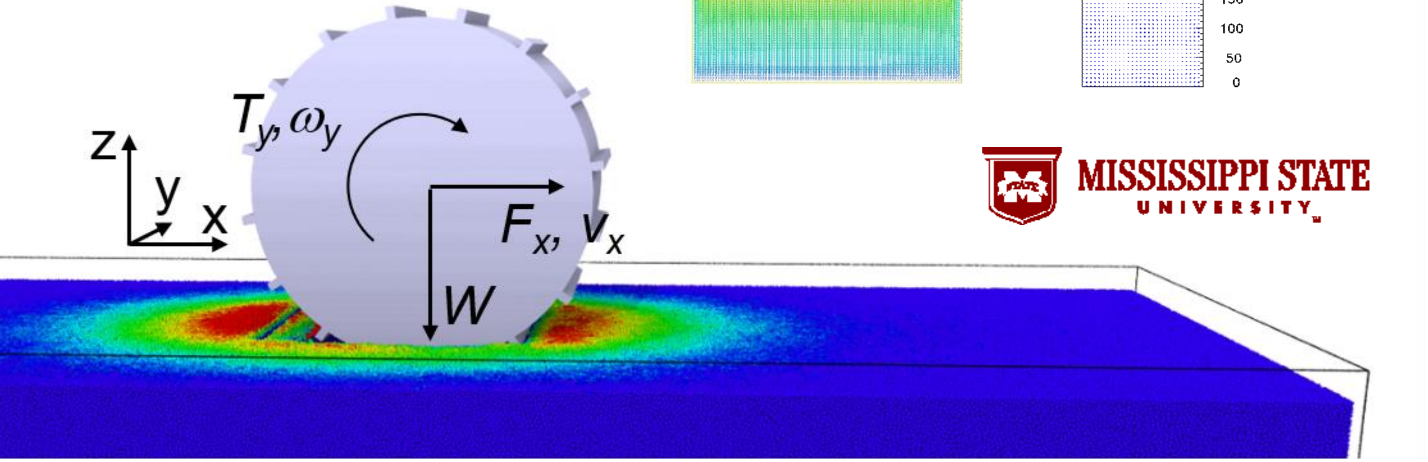

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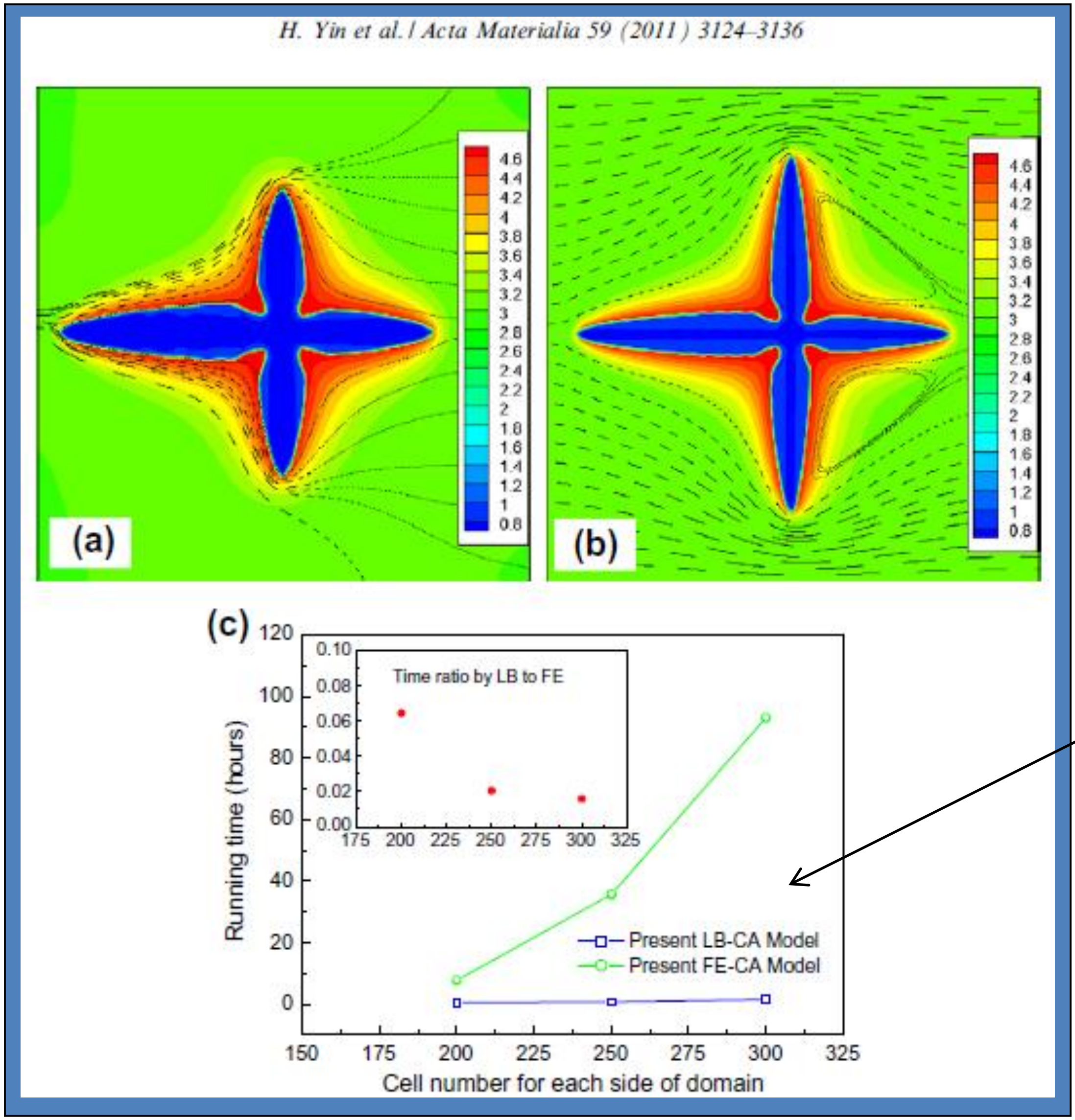
Summary

Lattice-Boltzmann method (LBM) for fluid flow
Discrete Element Method (DEM) for granular media

Coupled DEM-LBM system for shear thickening

DEM simulations of Cone Penetrometer Test,
particle size convergence study
DEM simulations of small driven wheel
DEM simulations to obtain pull/traction-slip curve
for smallest wheel in the DROVE database
DEM simulations of low-deflection wheel

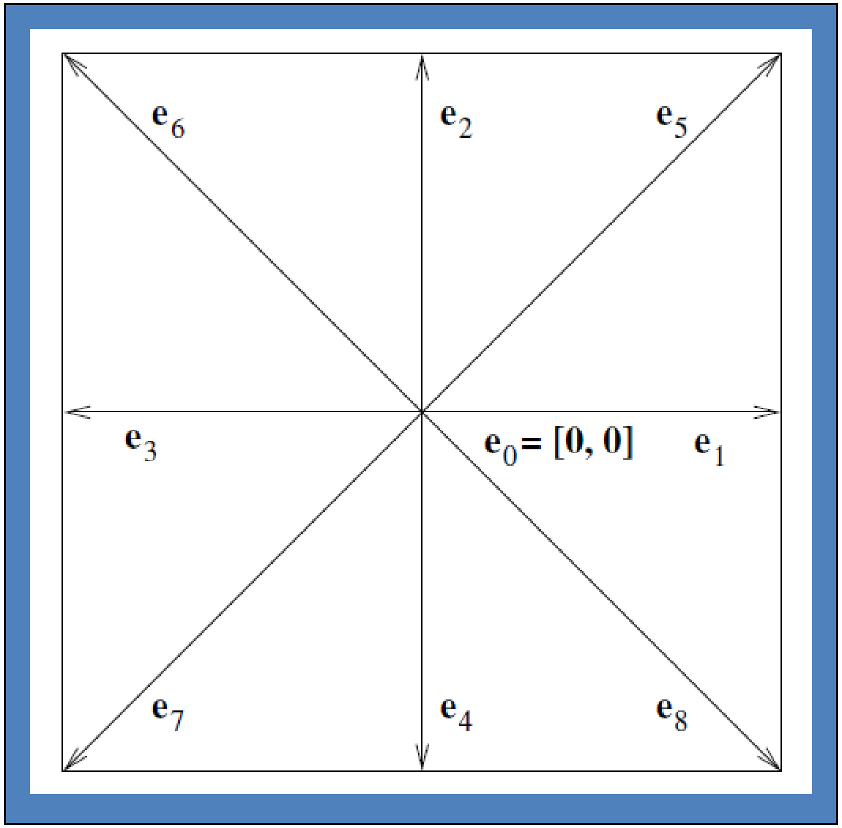
Why LBM/CA?



H. Yin et al. / Acta Materialia 59 (2011) 3124–3136

For the full resolution calculation of the fluid flow around solidifying dendrites, Lattice-Boltzmann / Cellular Automata method is faster than alternatives.

Lattice-Boltzmann method



D2Q9 lattice

Each node has 9 distribution functions f_i representing portion

of the mass density moving in the lattice direction $\boldsymbol{e}_i$

$$\rho = \sum_{i=0}^{8} f_i, \quad \rho \boldsymbol{u} = \sum_{i=0}^{8} f_i \boldsymbol{e}_i$$

$$f_i(\boldsymbol{r} + \boldsymbol{e}_i \Delta t, t + \Delta t) = f_i(\boldsymbol{r}, t) + \frac{1}{\tau_{\mathrm{u}}} \left(f_i^{\mathrm{eq}}(\boldsymbol{r}, t) - f_i(\boldsymbol{r}, t) \right)$$

Time evolution of the distribution functions

$$\nu = \frac{\tau_{\mathrm{u}} - 0.5}{3}\frac{\Delta x^2}{\Delta t}$$

For each lattice direction ***e**_i* , *i*=0..8

τ_{u} ~kin. viscosity

$$f_i(\boldsymbol{r} + \boldsymbol{e}_i\Delta t, t + \Delta t) = f_i(\boldsymbol{r}, t) + \frac{1}{\tau_{\mathrm{u}}}\left(f_i^{\mathrm{eq}}(\boldsymbol{r}, t) - f_i(\boldsymbol{r}, t)\right)$$

<u>Streaming</u>:

Shifts each distribution function to the neighboring node

<u>Collision</u>:

Adjusts the distribution function to approach equilibrium distribution

Equilibrium distribution function

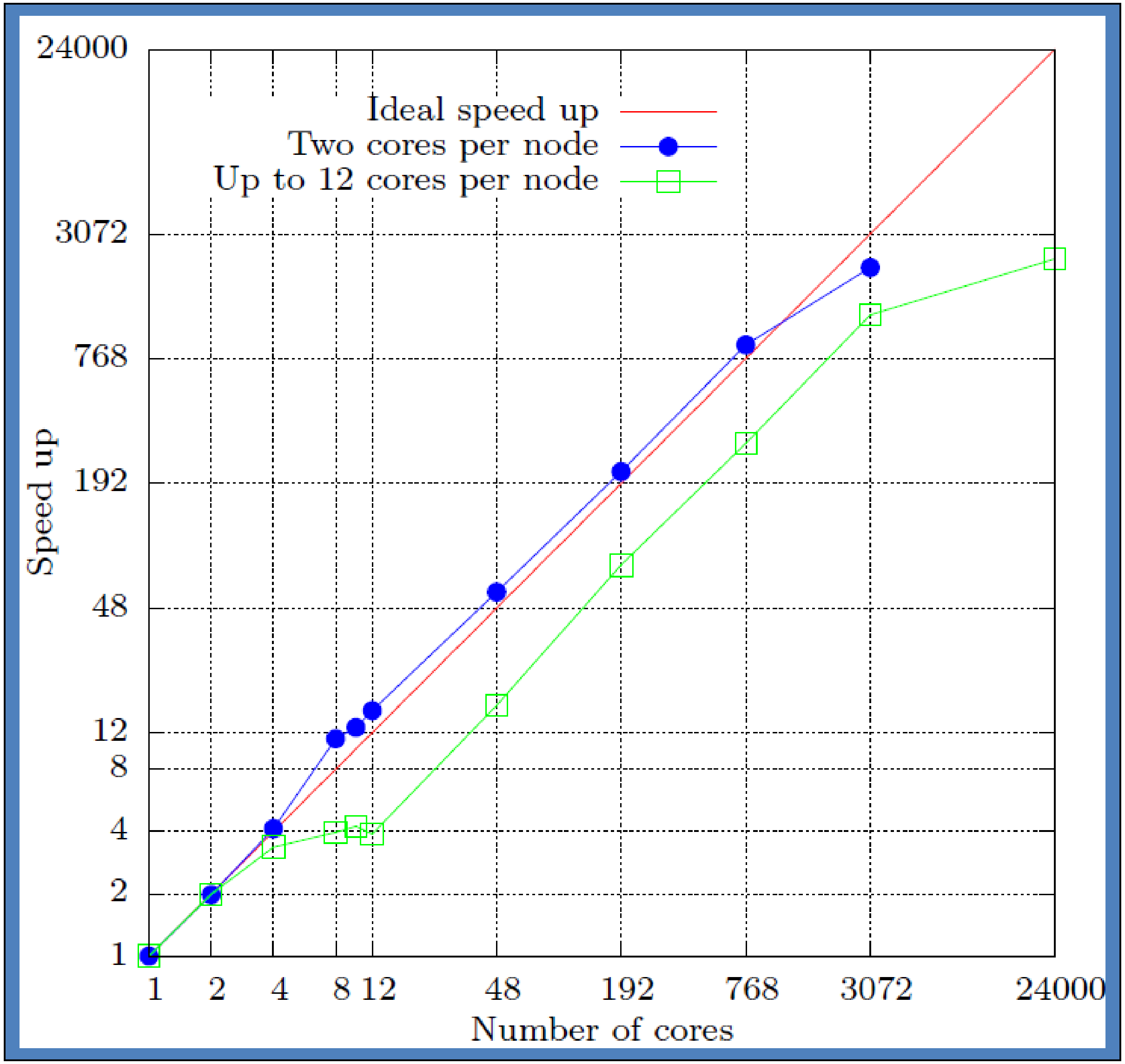
$$f_i^{\mathrm{eq}}(\boldsymbol{r}) = w_i \rho(\boldsymbol{r}) \left(1 + 3 \frac{\boldsymbol{e}_i \cdot \boldsymbol{u}(\boldsymbol{r})}{c^2} + \frac{9}{2} \frac{(\boldsymbol{e}_i \cdot \boldsymbol{u}(\boldsymbol{r}))^2}{c^4} - \frac{3}{2} \frac{\boldsymbol{u}(\boldsymbol{r}) \cdot \boldsymbol{u}(\boldsymbol{r})}{c^2} \right)$$

$$\downarrow \qquad\qquad \downarrow$$

$$w_i = \begin{cases} 4/9 & i = 0 \\ 1/9 & i = 1, 2, 3, 4 \\ 1/36 & i = 5, 6, 7, 8 \end{cases}$$

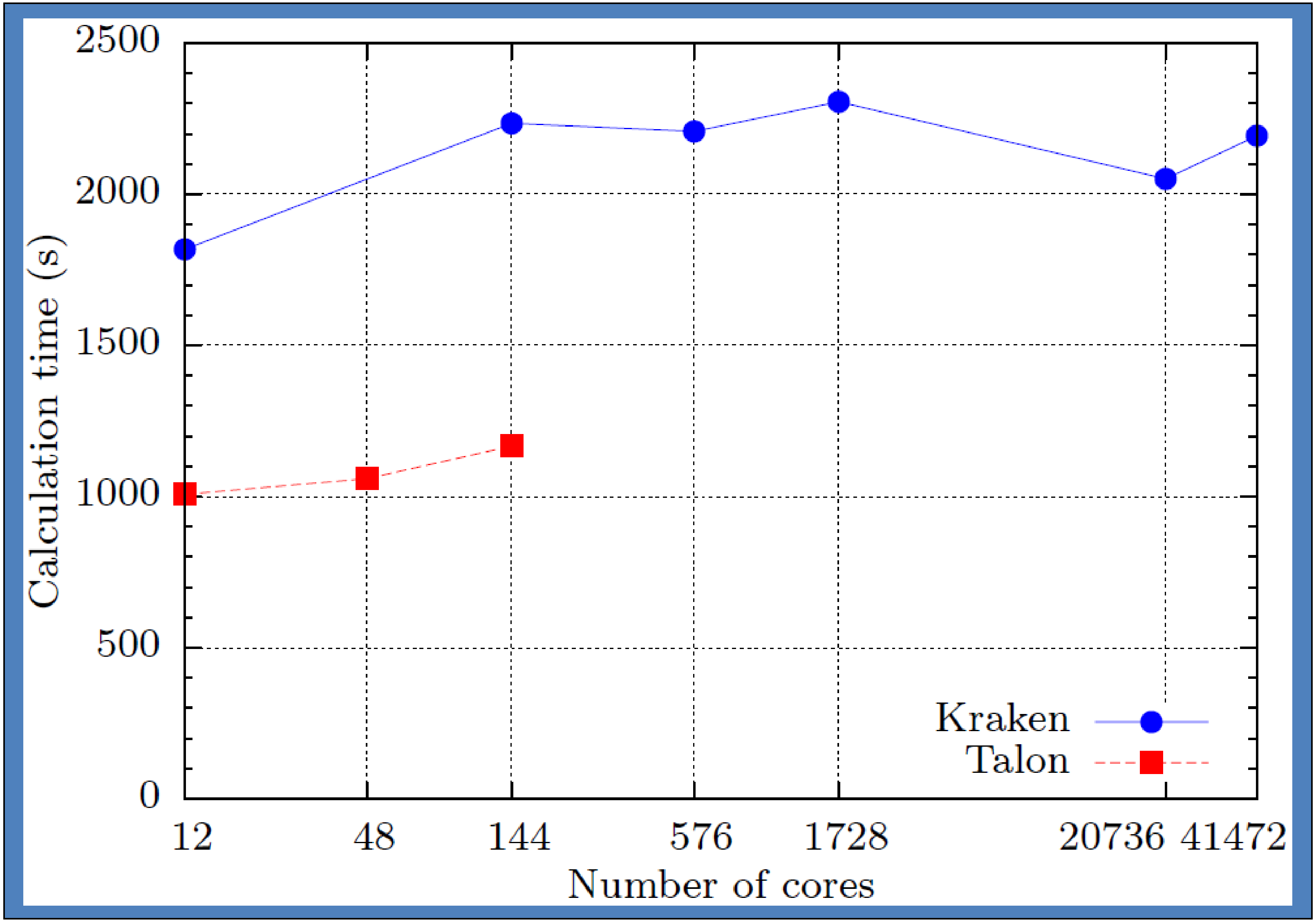
lattice velocity $c = \Delta x / \Delta t$

Speed up



- strong scaling (speed up) near perfect up to 3072 cores
- Algorithm is memory bandwidth limited on multi-core architecture (low FLOP/byte ratio)

Scale up



Goal:
constant
calculation
time

Discrete Element Method

- Tracks individual particles in granular media
- Interactions between particles given by contact laws, an example is linear spring contact:

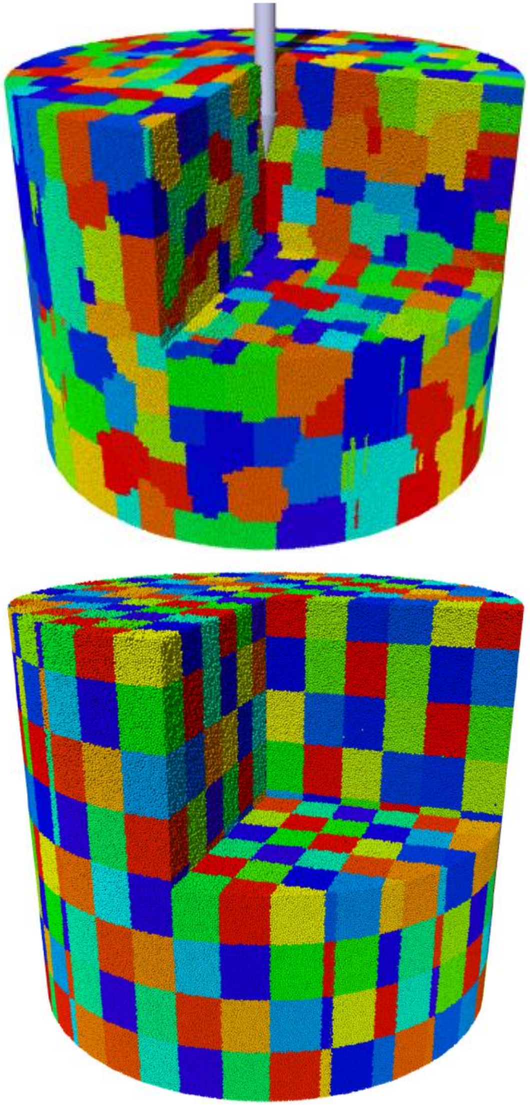
$$F_N = \alpha K_N \delta_n^m$$

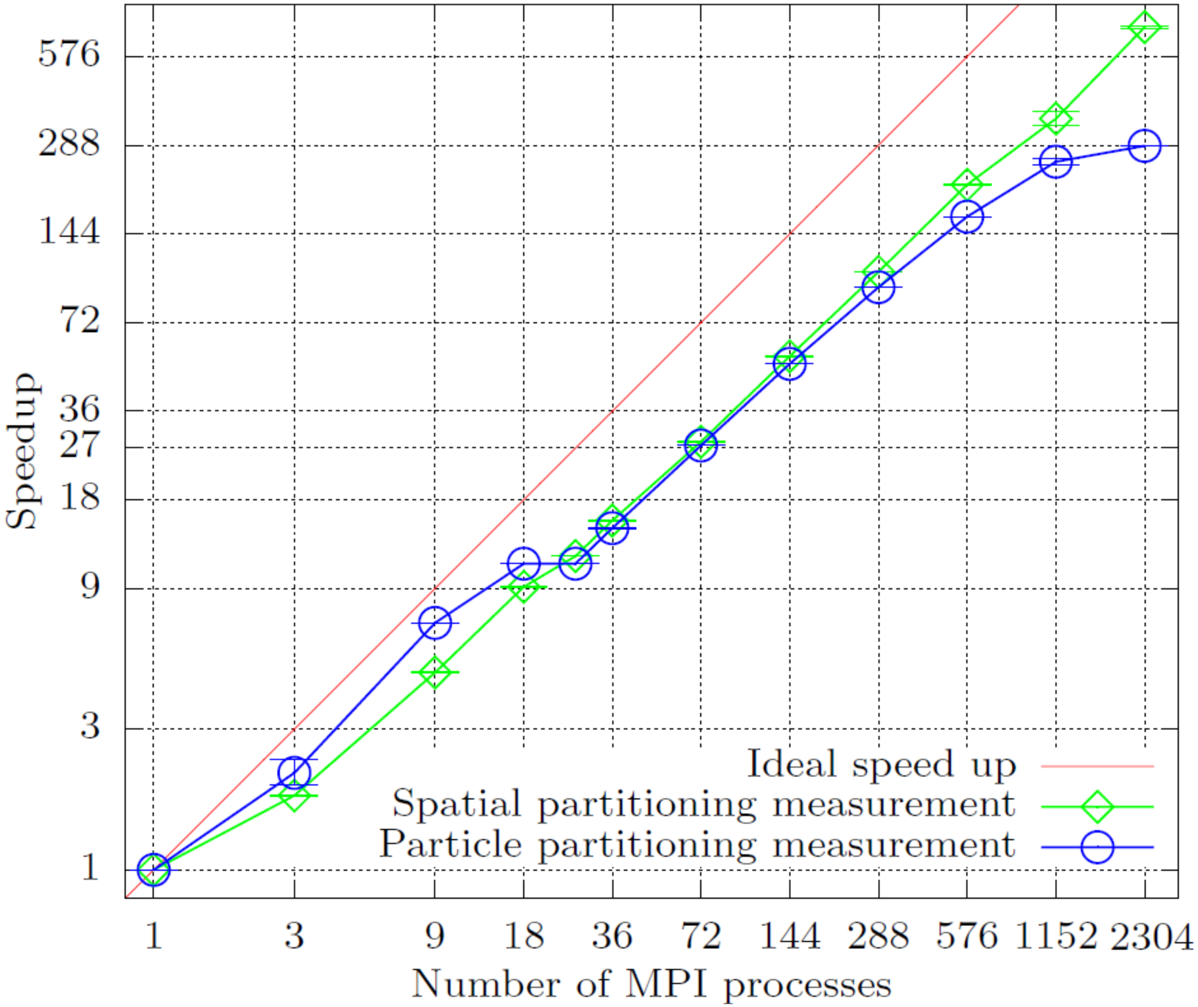
- Particle linear and angular velocity are determined by integrating Newton’s equations of motion:

$$m\frac{\partial v_i}{\partial t} = mg_i + \sum_{c=1}^{N_c} f_i^c \quad I_m\frac{\partial \omega_i}{\partial t} = \sum_{c=1}^{N_c} M_i^c$$

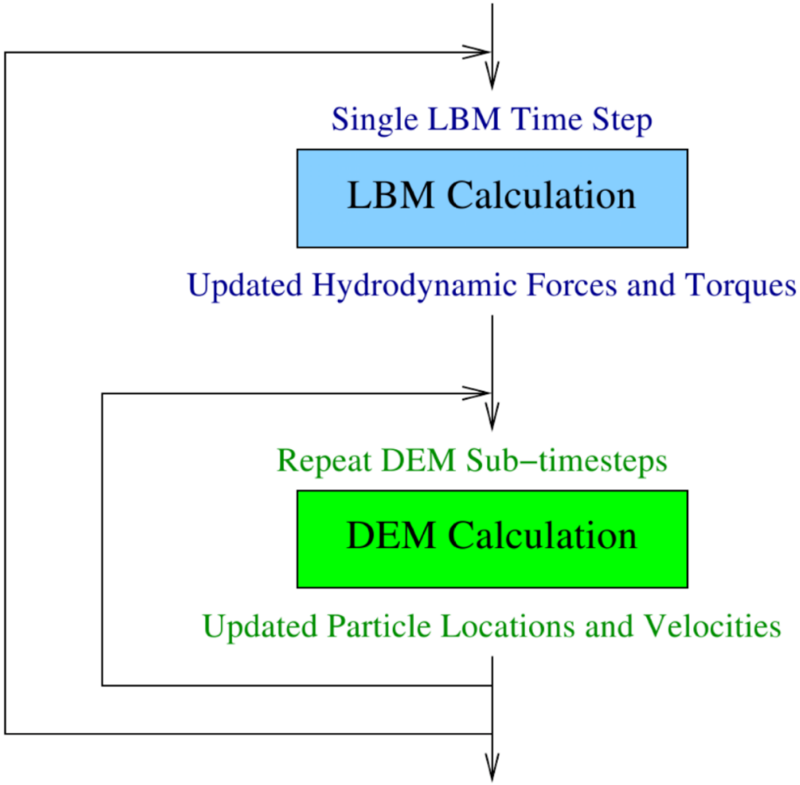
DEM parallelization

Particle (top) and spatial (bottom) domain decomposition





DEM-LBM coupling algorithm



Single LBM Time Step

LBM Calculation

Updated Hydrodynamic Forces and Torques

Repeat DEM Sub−timesteps

DEM Calculation

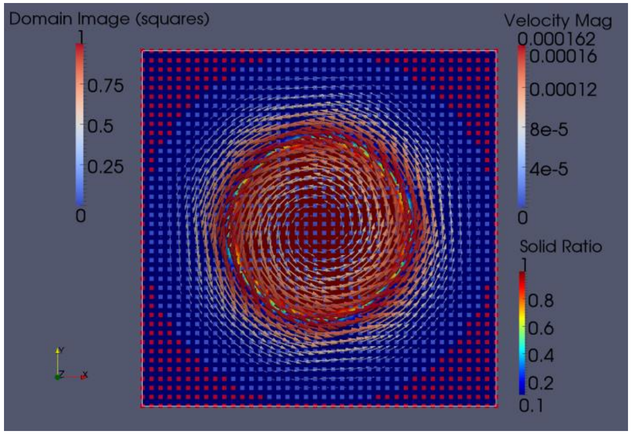
Updated Particle Locations and Velocities

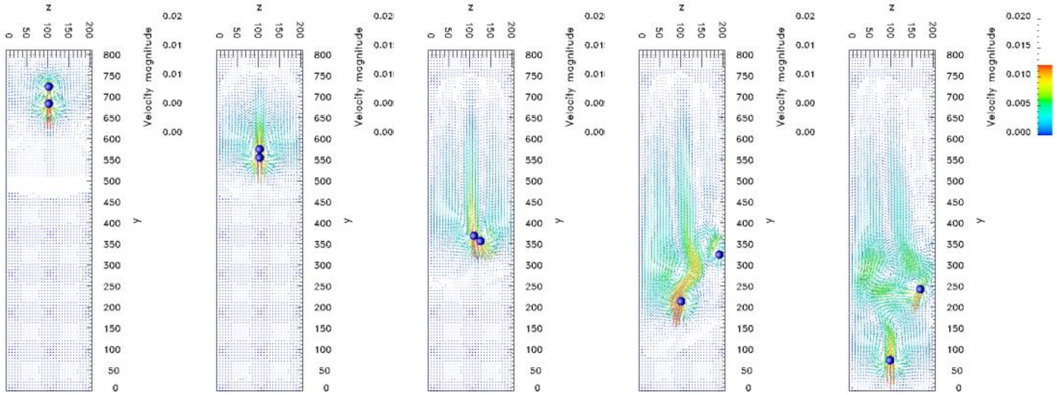
Force & torque by fluid on particles:

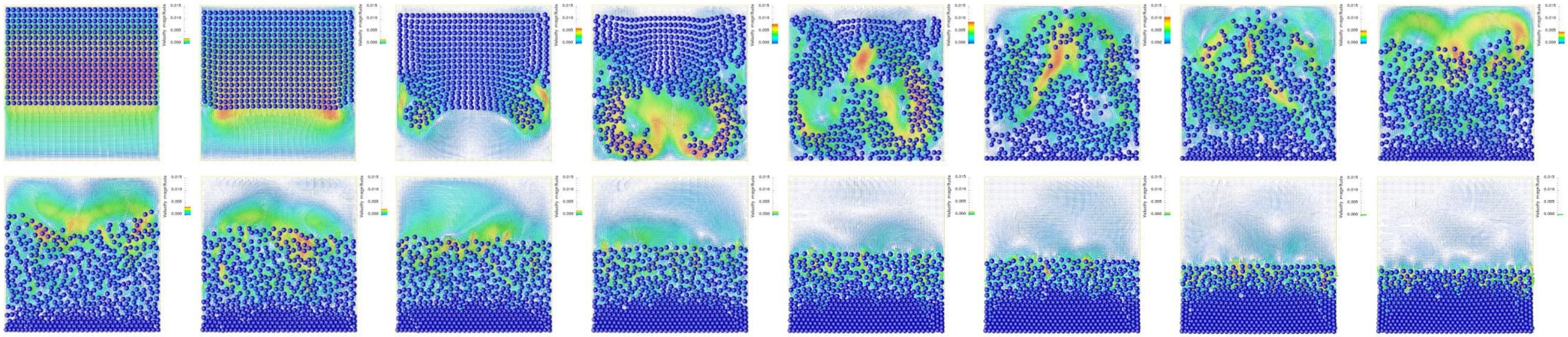
$$\boldsymbol{F}_F = \frac{\Delta x^3}{\Delta t} \sum_n \left(\beta_n \sum_{i=0}^{14} \boldsymbol{\Omega}_i^S \boldsymbol{e}_i \right)$$

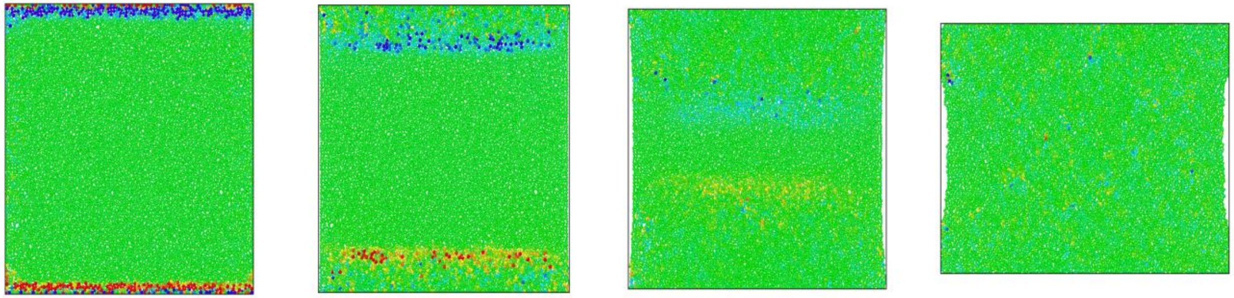
$$\boldsymbol{T}_F = \frac{\Delta x^3}{\Delta t} \sum_n (\boldsymbol{r}_n - \boldsymbol{r}_c) \times \left(\beta_n \sum_{i=0}^{14} \boldsymbol{\Omega}_i^S \boldsymbol{e}_i \right)$$

DEM+LBM Coupled Model of Densely Packed Particle assemblies in Fluid









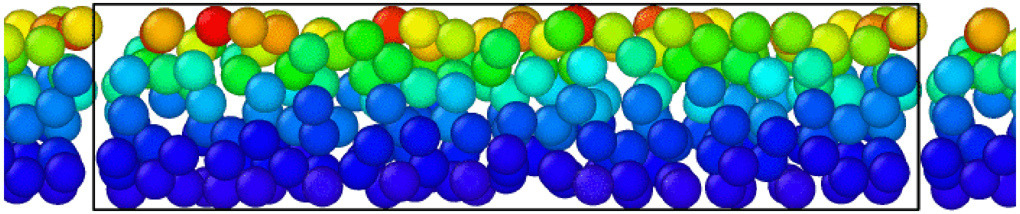
Coupled DEM (serial) / LBM (parallel) model for saturated granular media

Starting point:

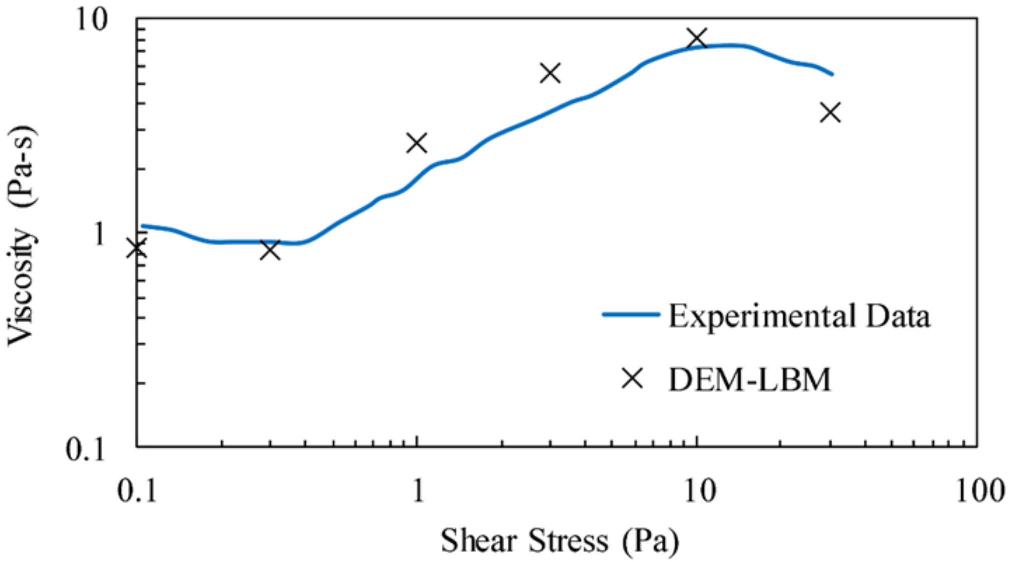
- Single-component single-phase lattice-Boltzmann model coupled with DEM for spherical particles submerged in fluid
- Coupling utilized immersed moving boundary with subgrid resolution (Owen et al., Int. J. Numer. Meth. Fluids 2007, 55)

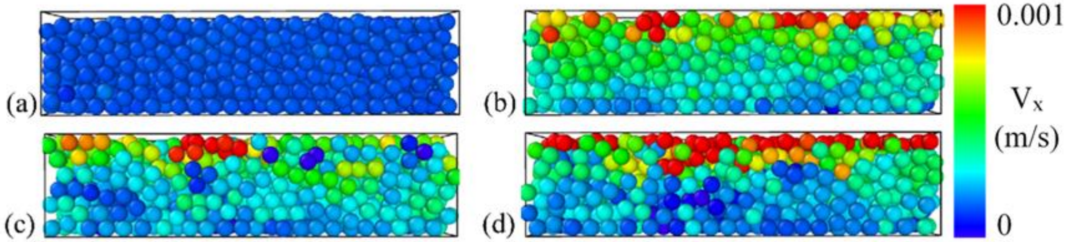
Present application:

- Coupled DEM+LBM system for numerical modeling of shear-thickening of granular suspensions



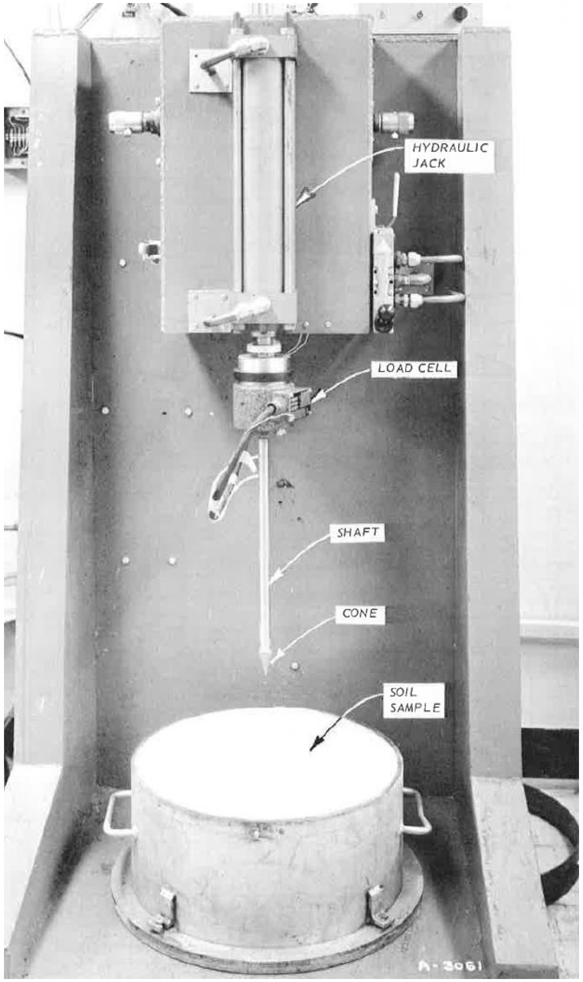
Deformation-Fluid Coupling

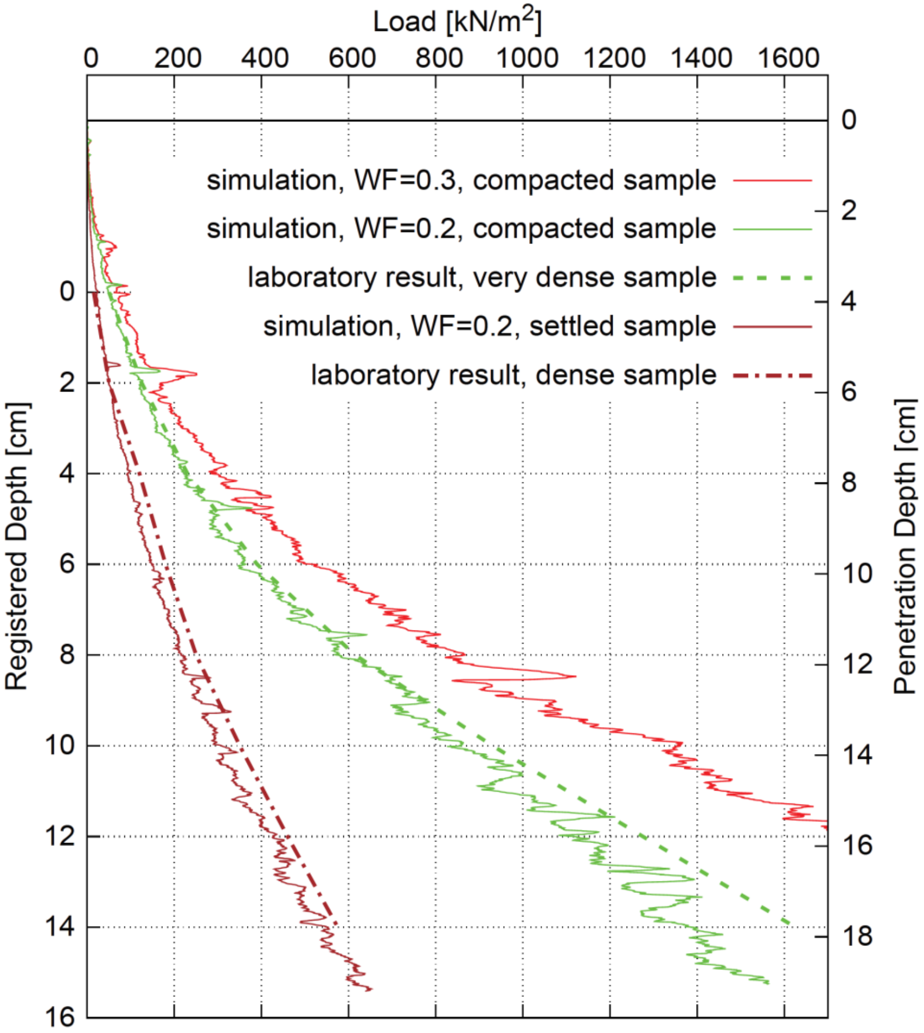




- Moisture state is an important component of subgrade reaction
- Most subgrades are partially saturated
- Successful simulation of undrained dilation is important for sand and silt subgrades
- Successful simulation of shear thickening fluids demonstrates capability to model fluid-soil interaction

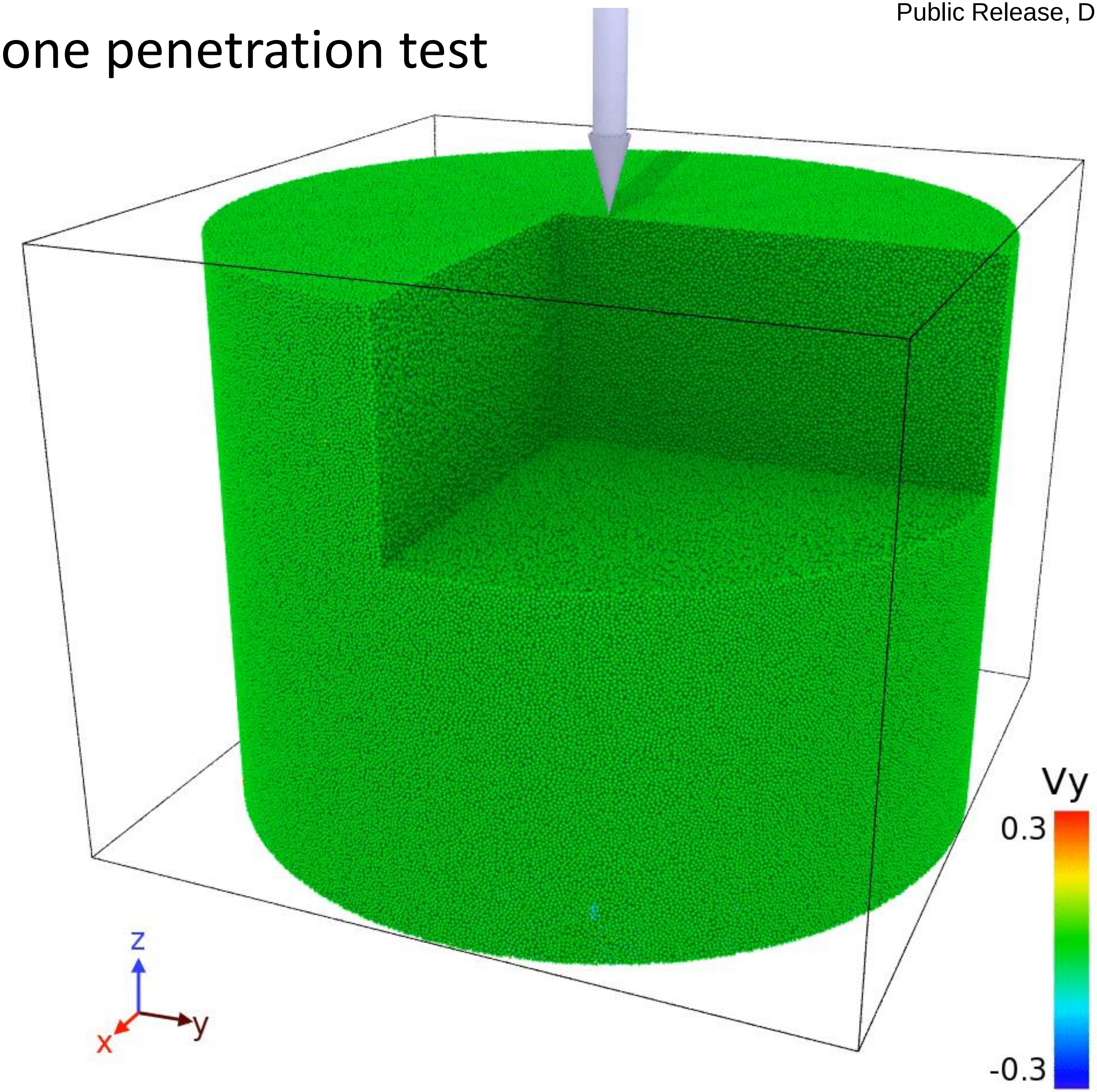
Simulation of cone penetrometer test (CPT) for calibration of DEM parameters





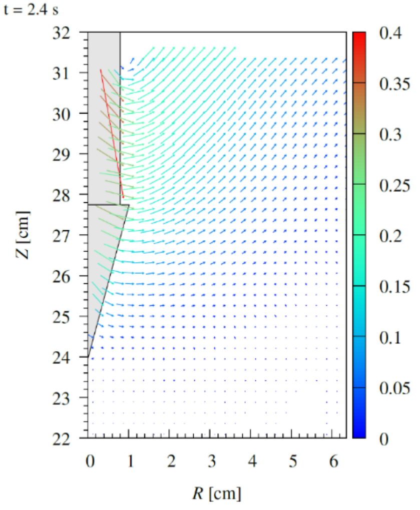
DEM: 9.5 mil. spherical particles in cylindrical mold, rigid cone-tip probe

Cone penetration test

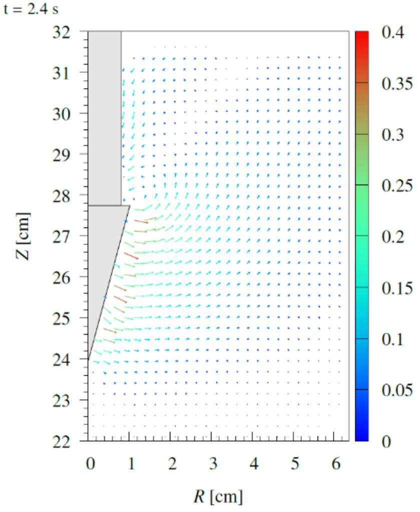


Macroscopic averages from DEM CPT simulations

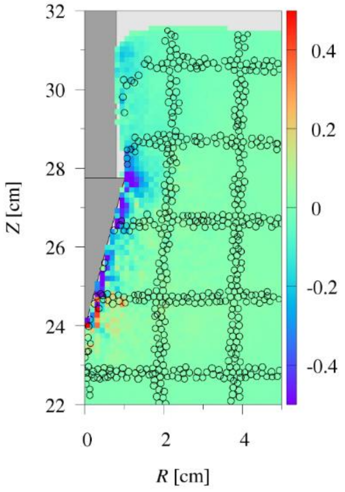
Displacement



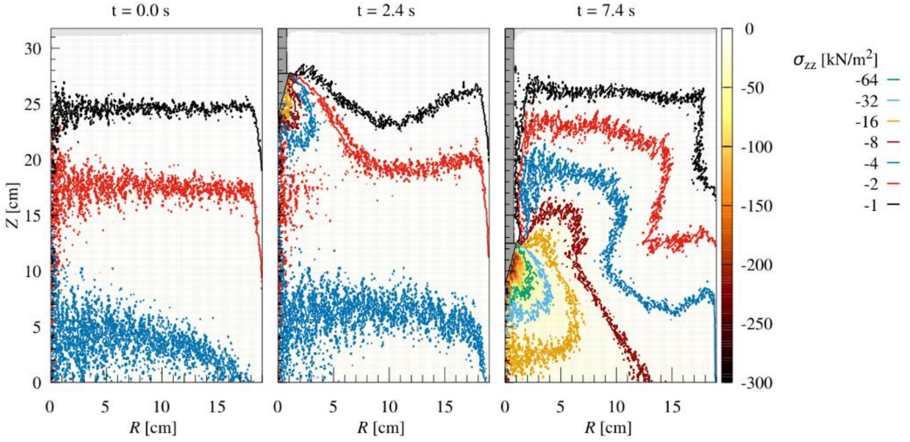
Velocity



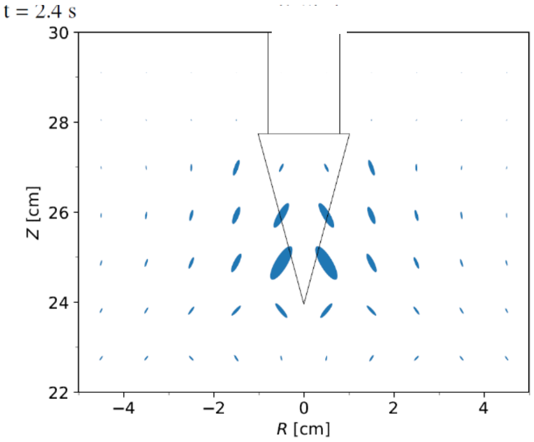
Angular velocity



Vertical stress

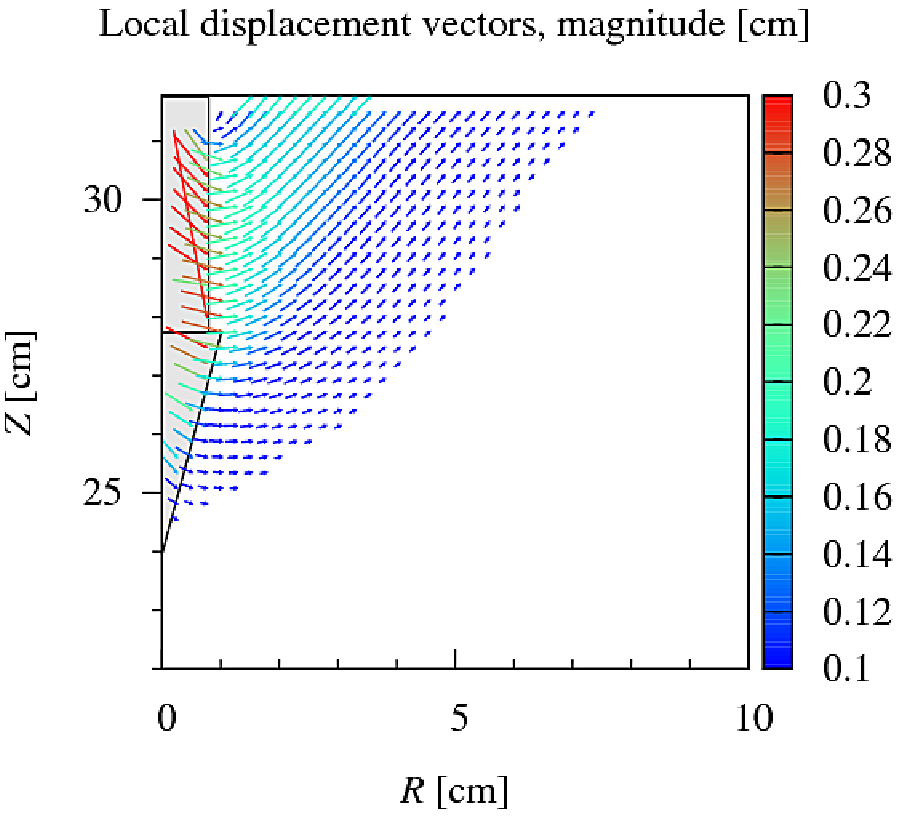


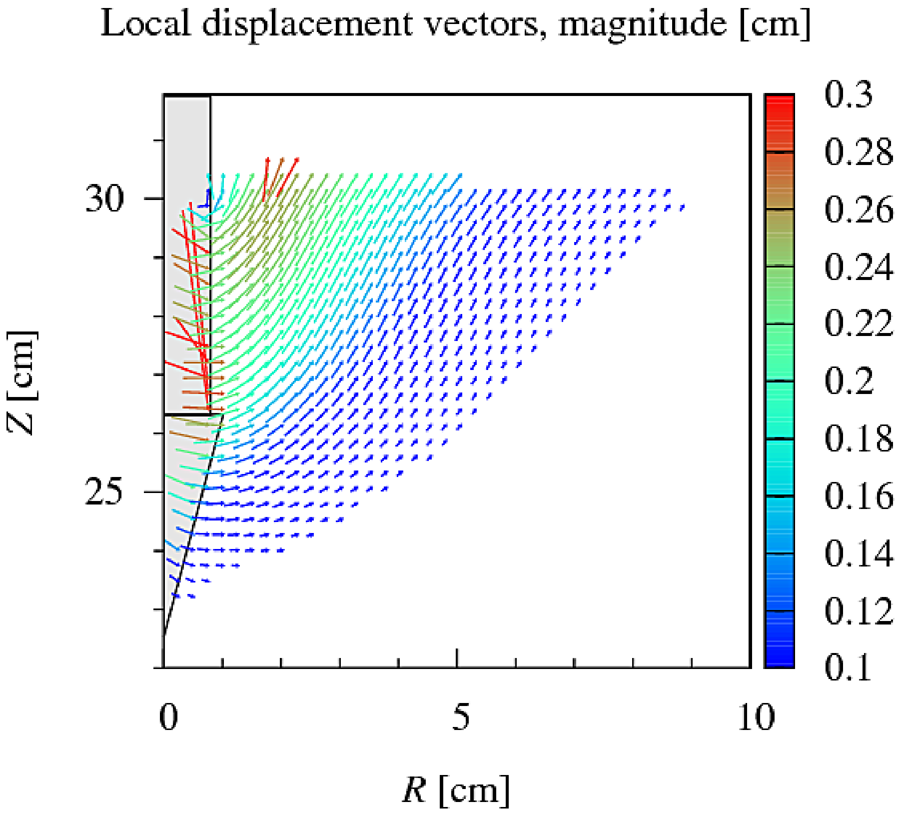
Principal stress ellipse



Average particle displacement

Dense sample t=2.4s Very dense sample


Local displacement vectors, magnitude [cm]

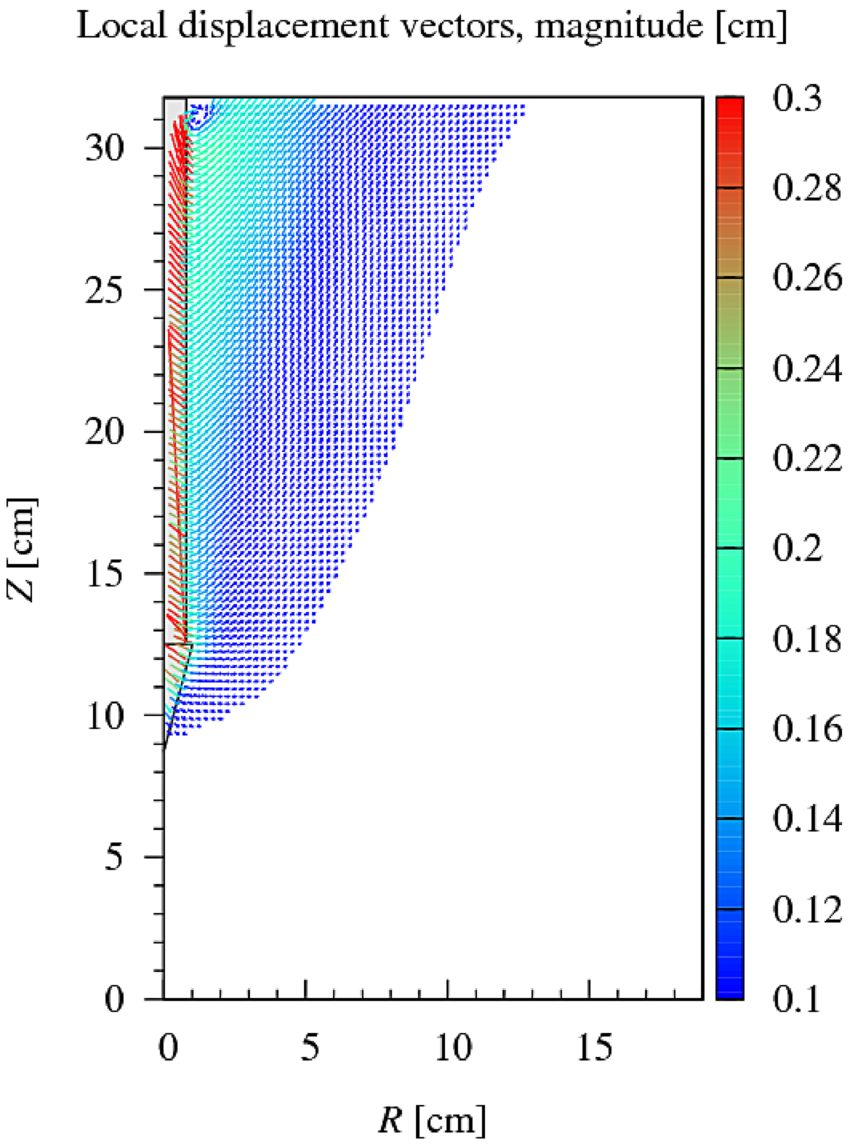

Local displacement vectors, magnitude [cm]

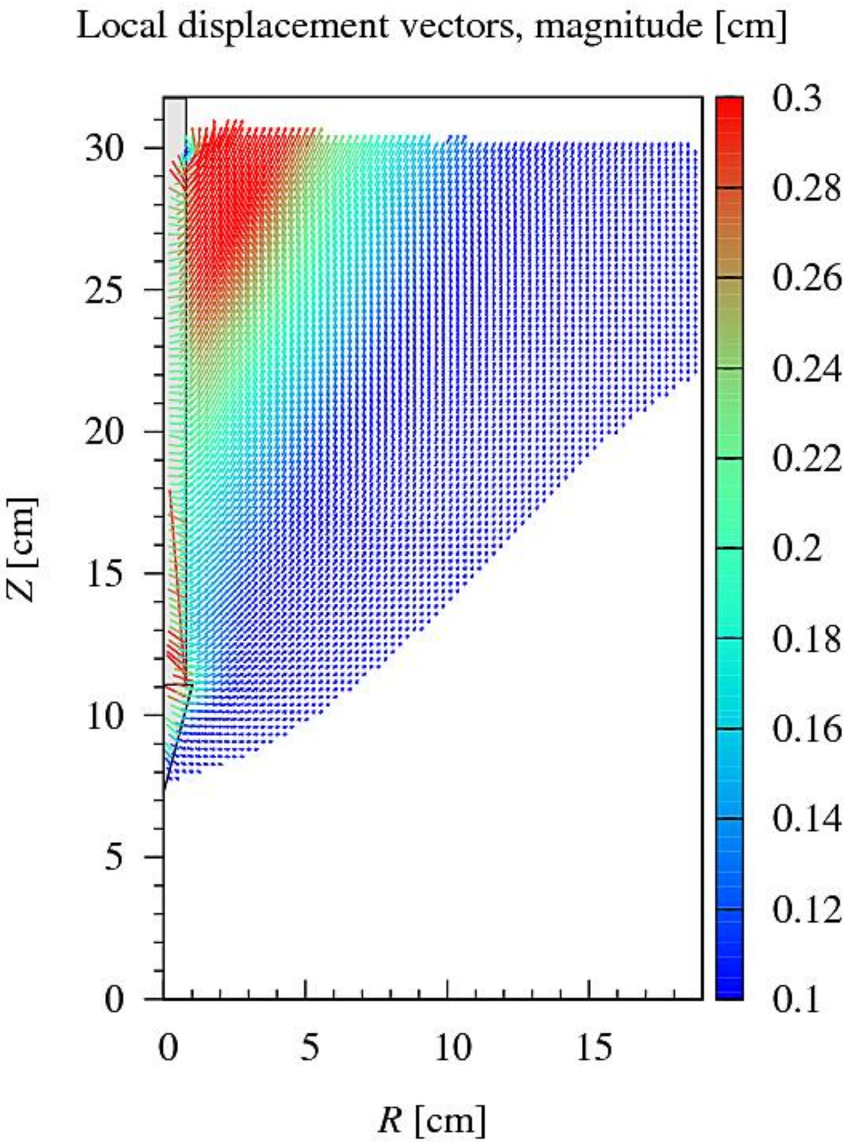
Average particle displacement

Dense sample

t=7.4s

Very dense sample



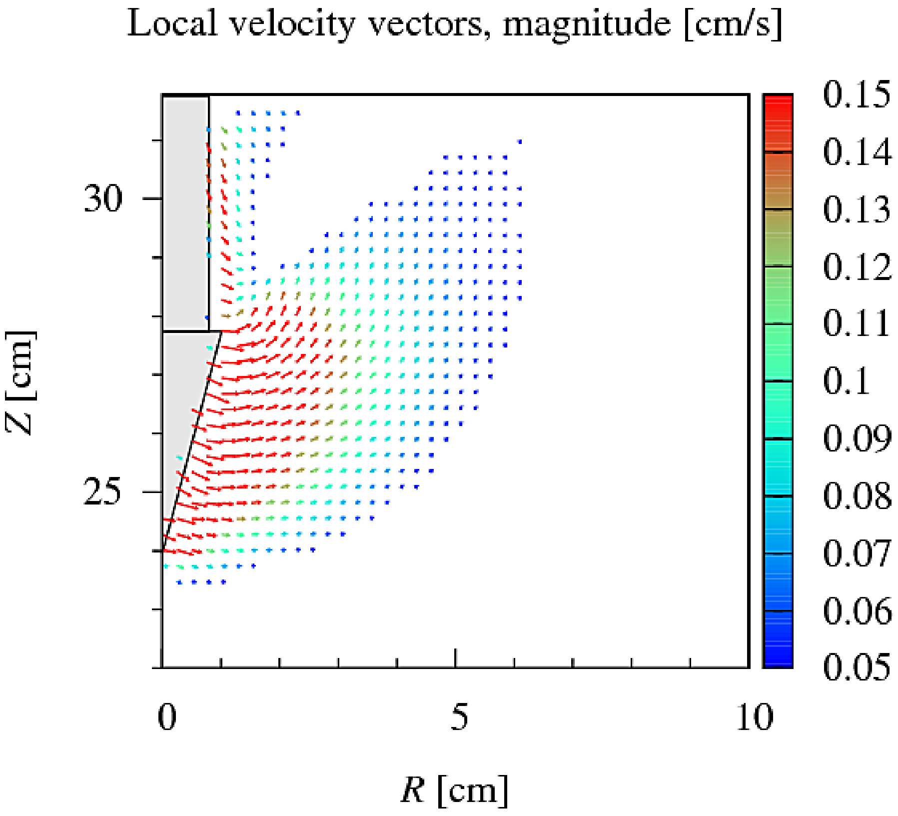


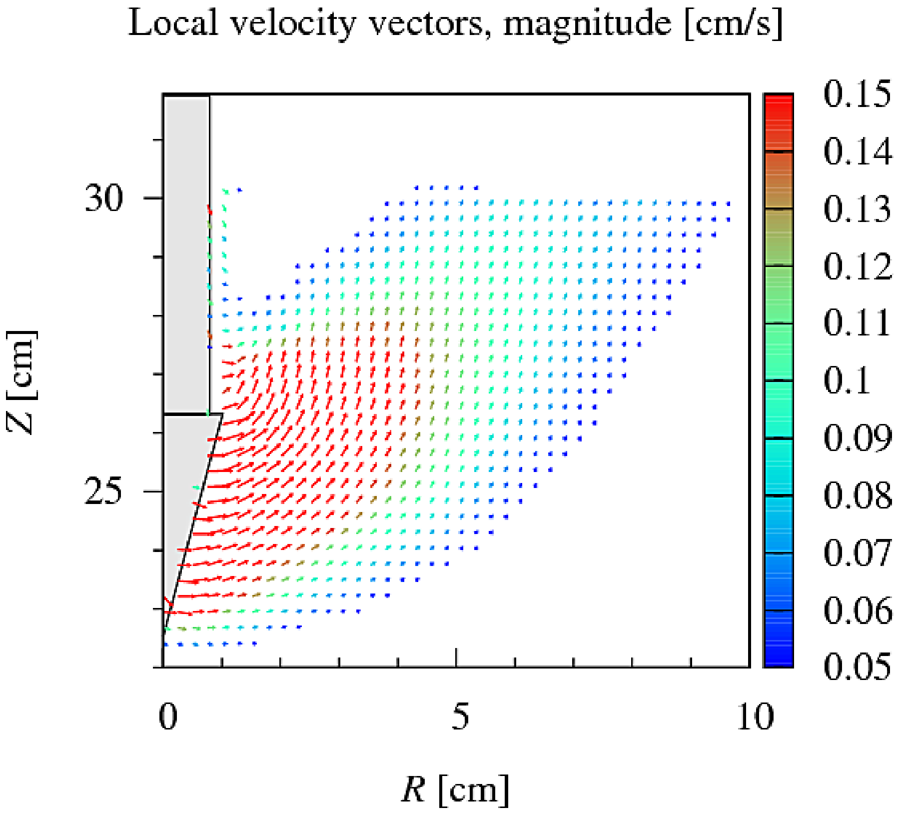
Average particle velocities

Dense sample

t=2.4s

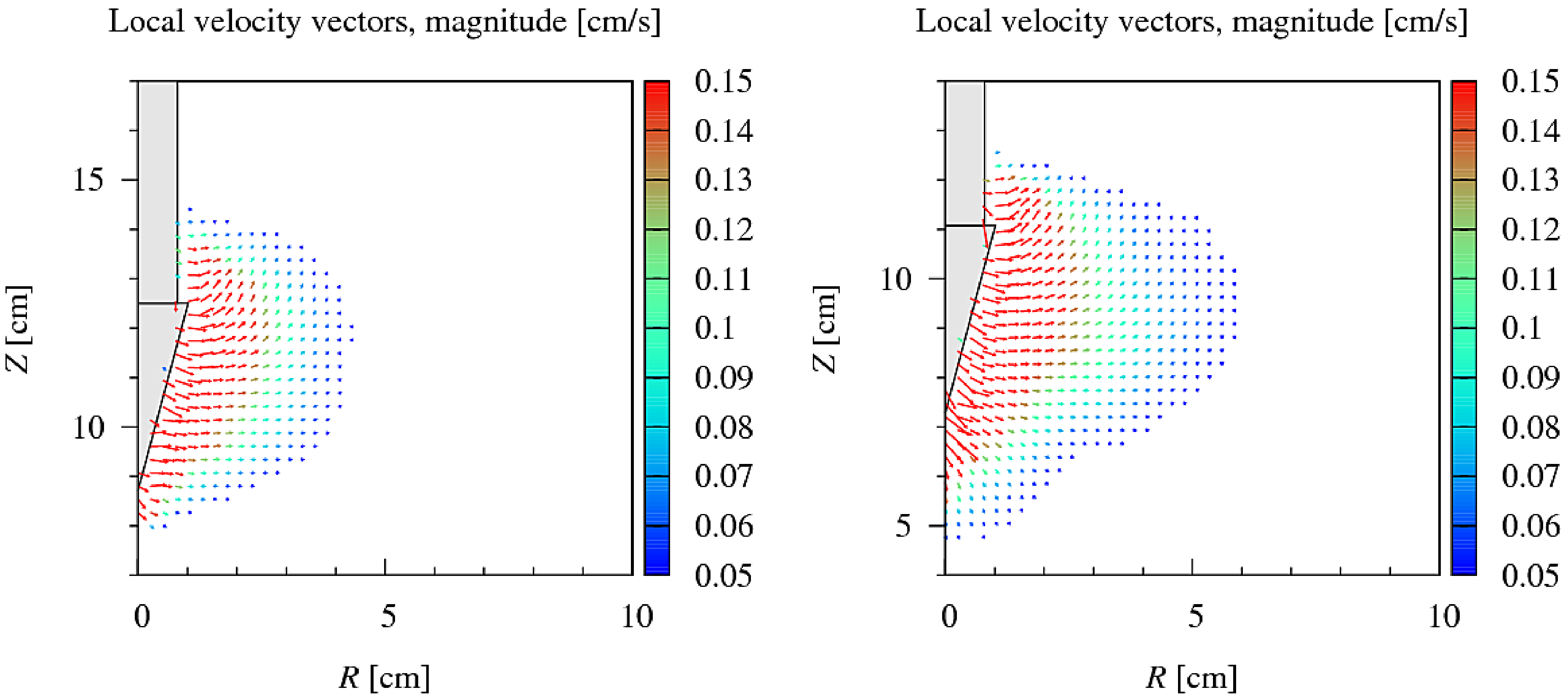
Very dense sample





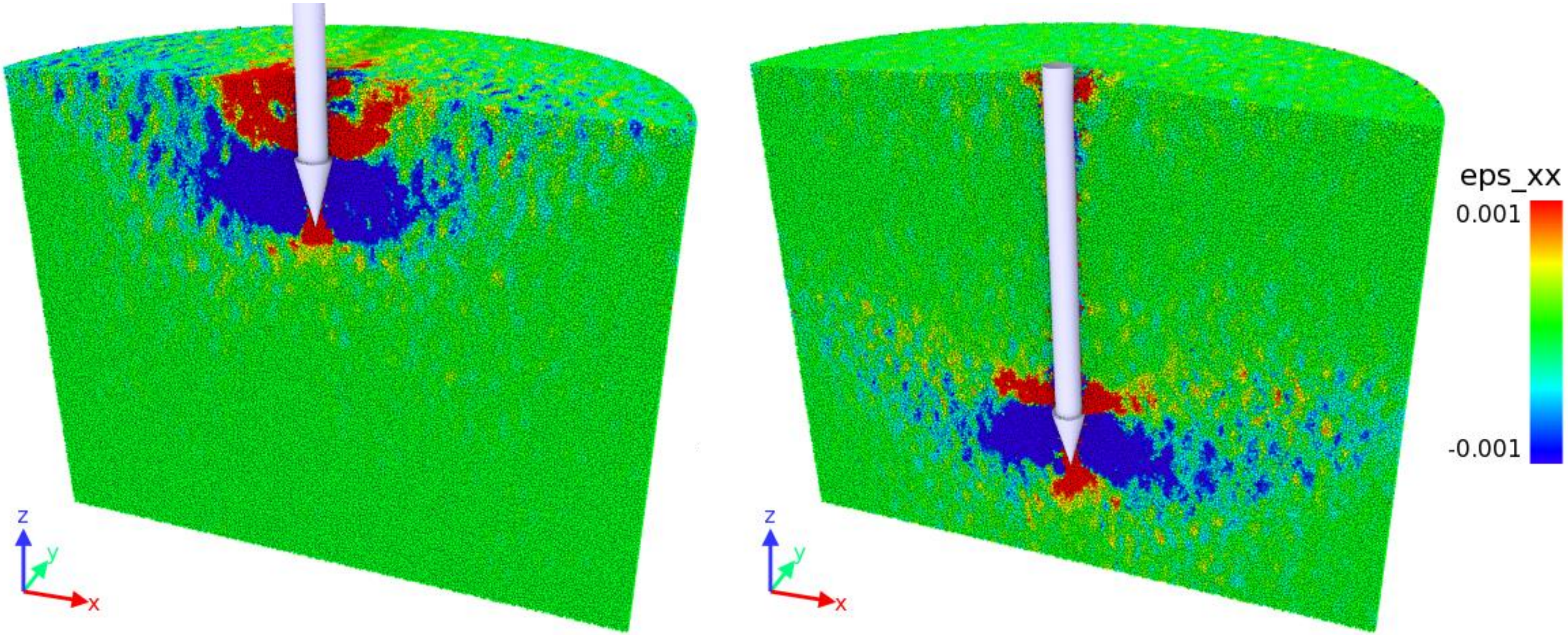
Average particle velocities

Dense sample t=7.4s Very dense sample



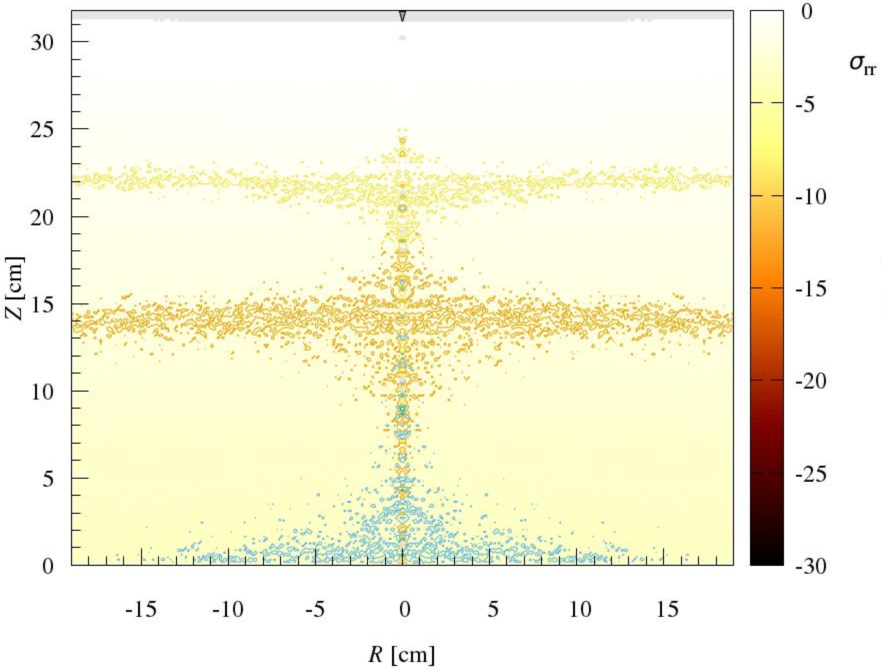
Local strain calculated from particle displacement

t=2.4s Very dense sample t=7.4s

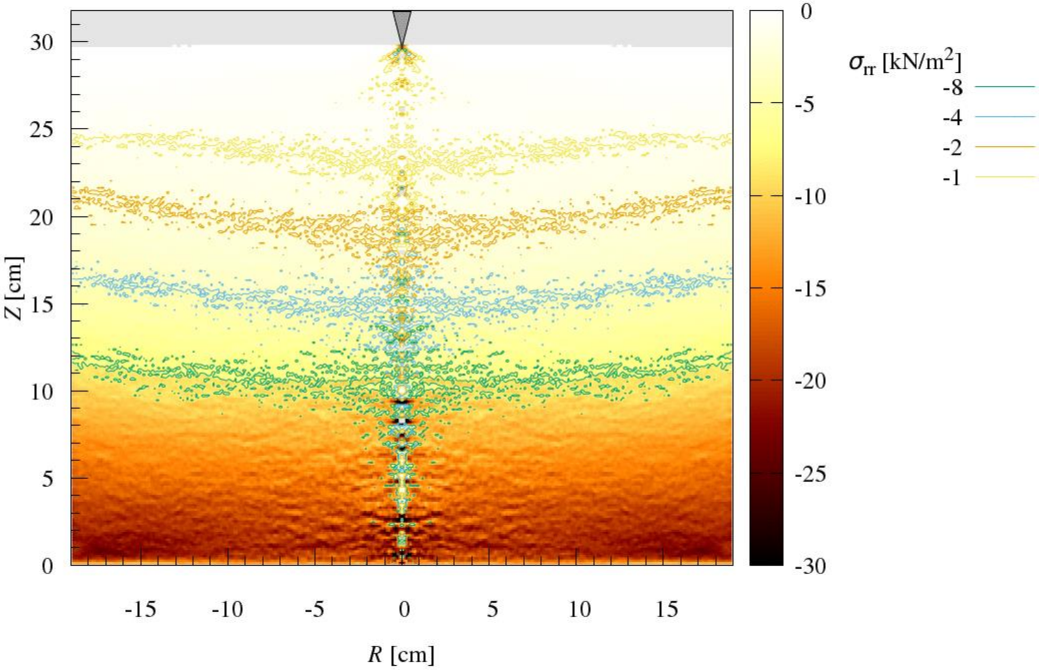


Evaluating stress from CPT simulations
Radial stress component σ_{rr}

Dense sample

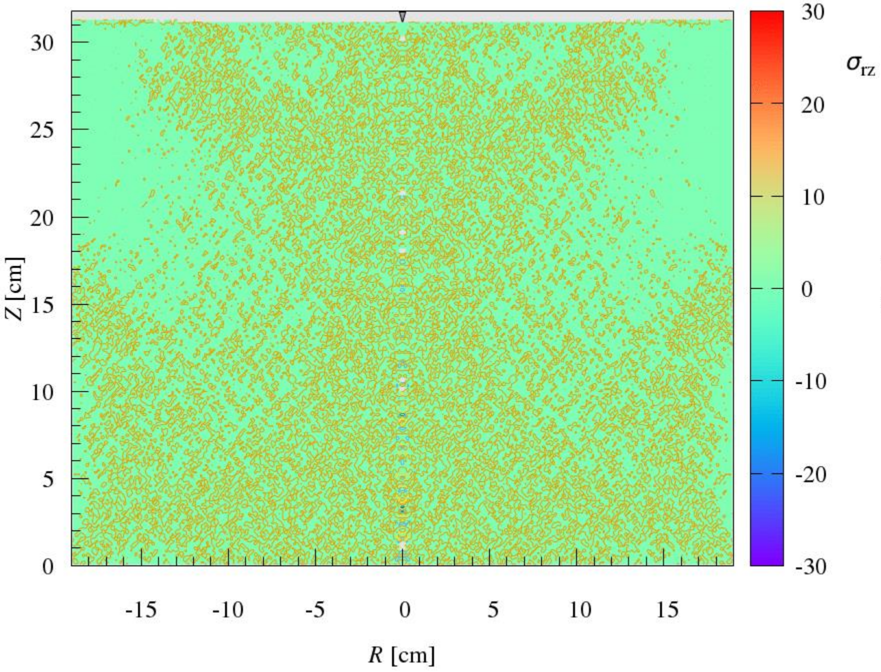


Very dense sample

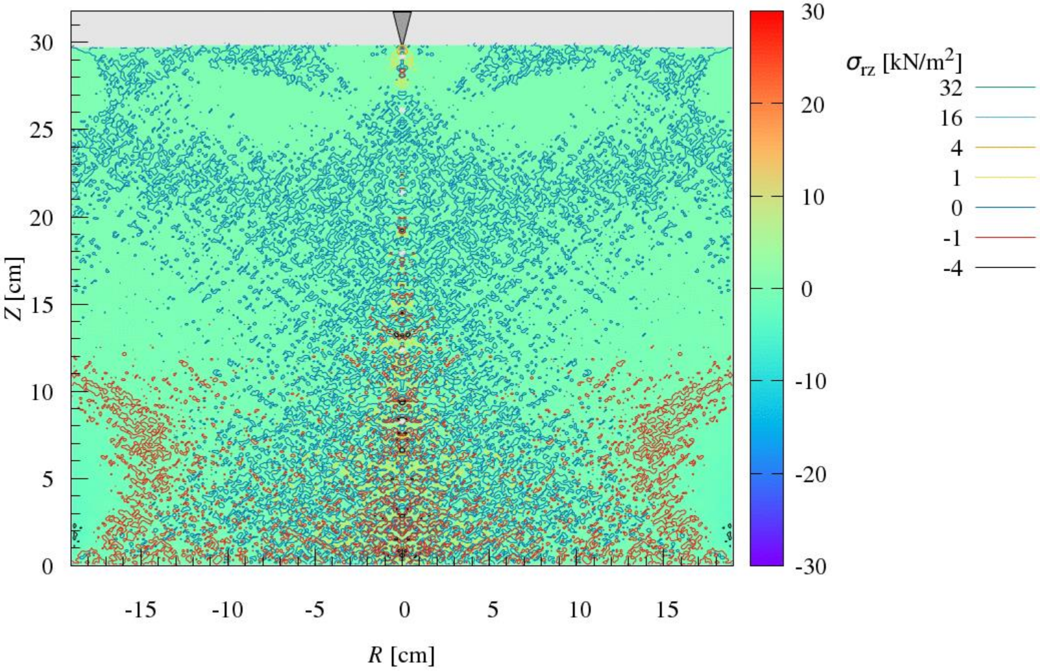


Evaluating stress from CPT simulations
Shear stress component σ_{rz}

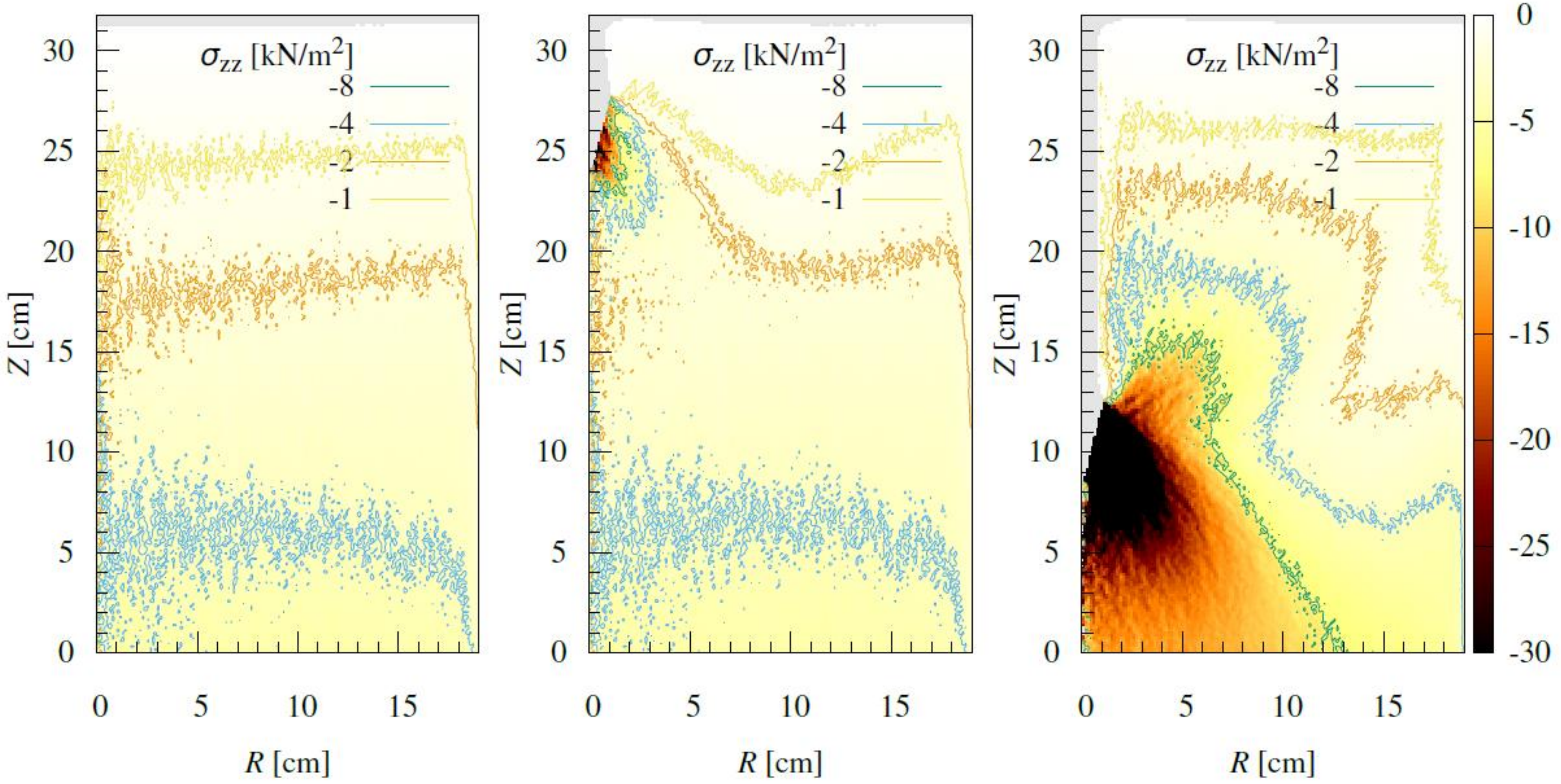
Dense sample



Very dense sample



Evaluating vertical stress during CPT
Dense sample
σ_{zz} component

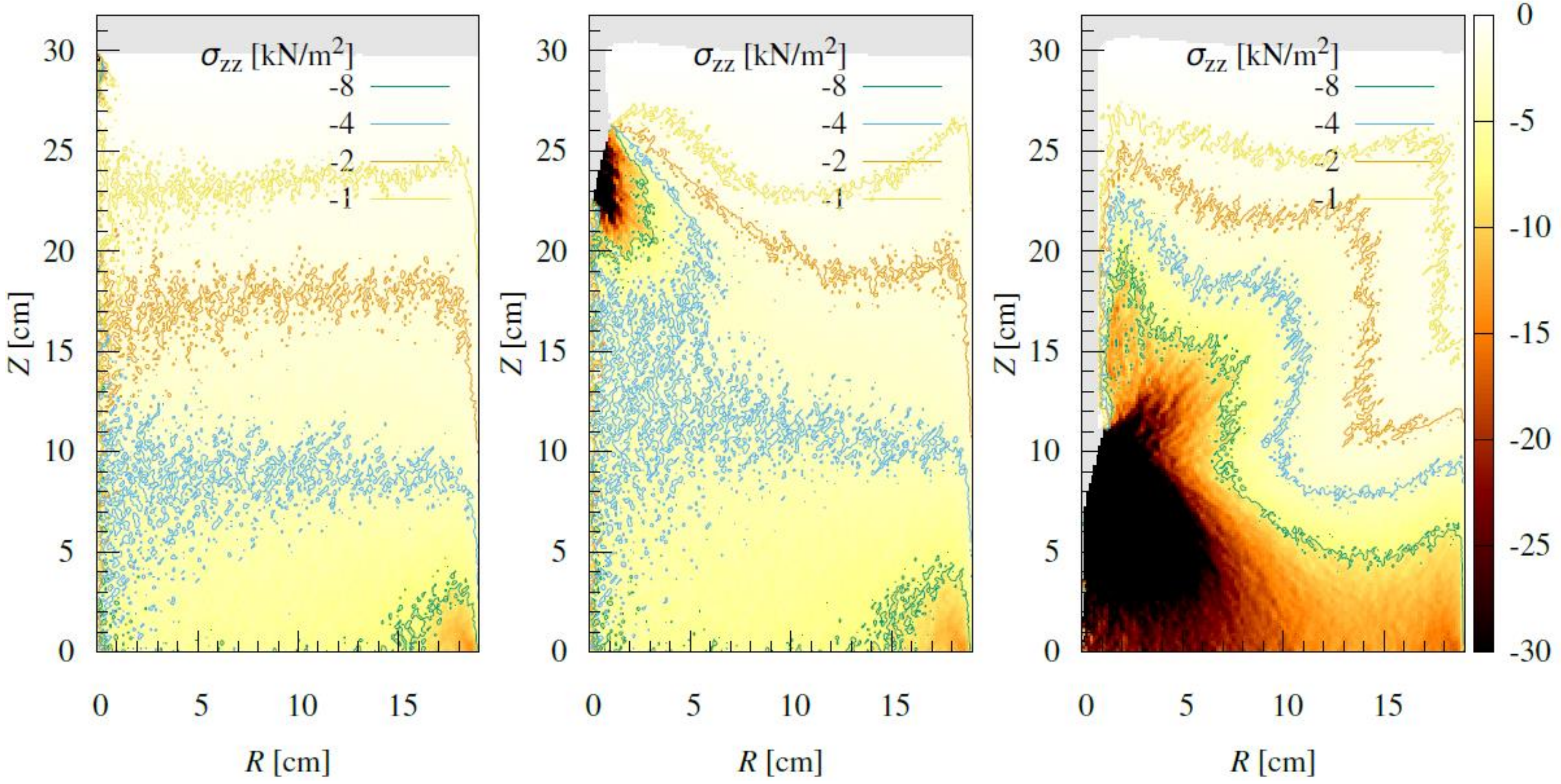


0.05 s

2.4 s

7.4 s

Evaluating vertical stress during CPT
Very dense sample
σ_{zz} component

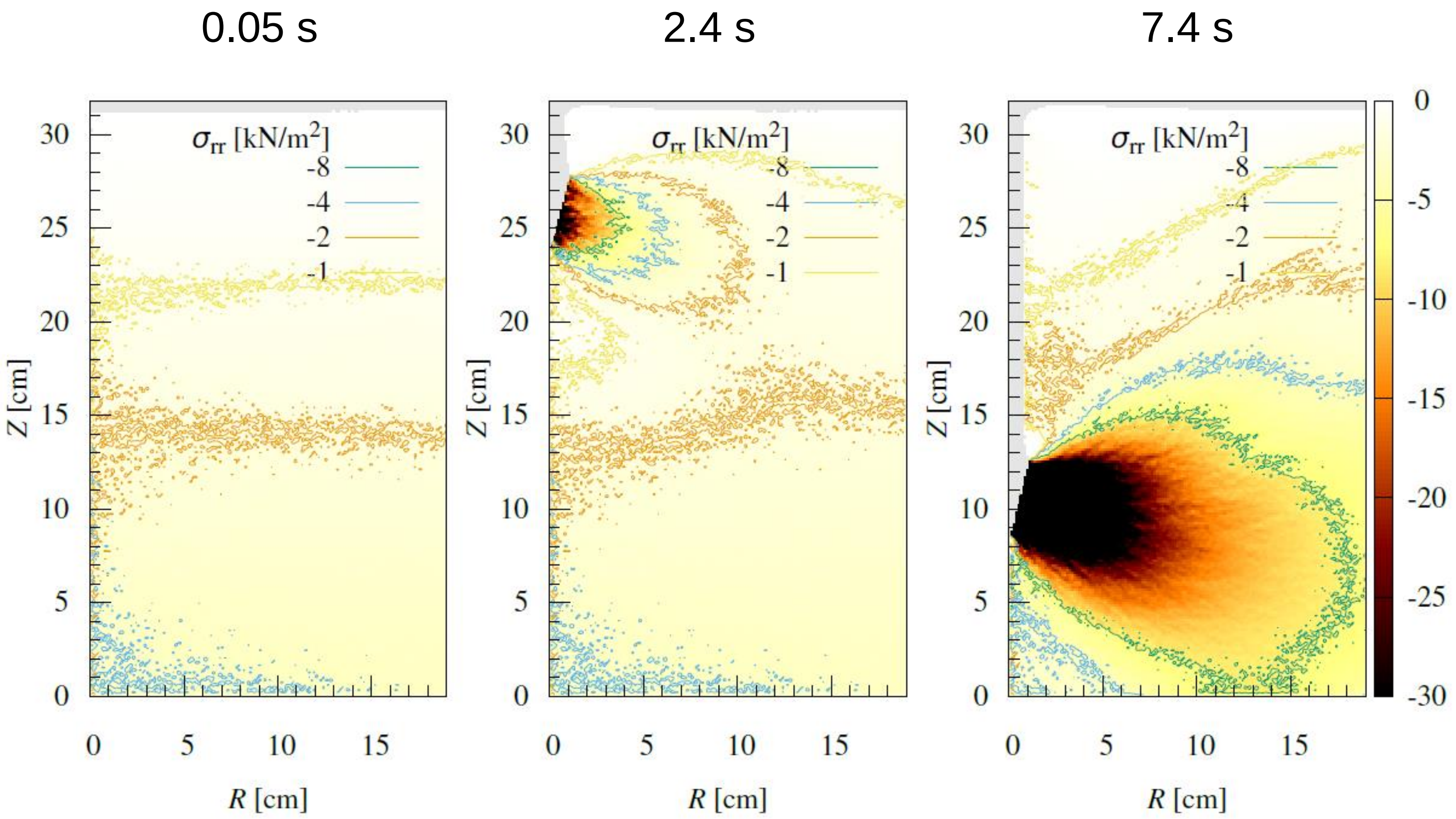


0.05 s

2.4 s

7.4 s

Evaluating vertical stress during CPT
Dense sample
σ_{rr} component



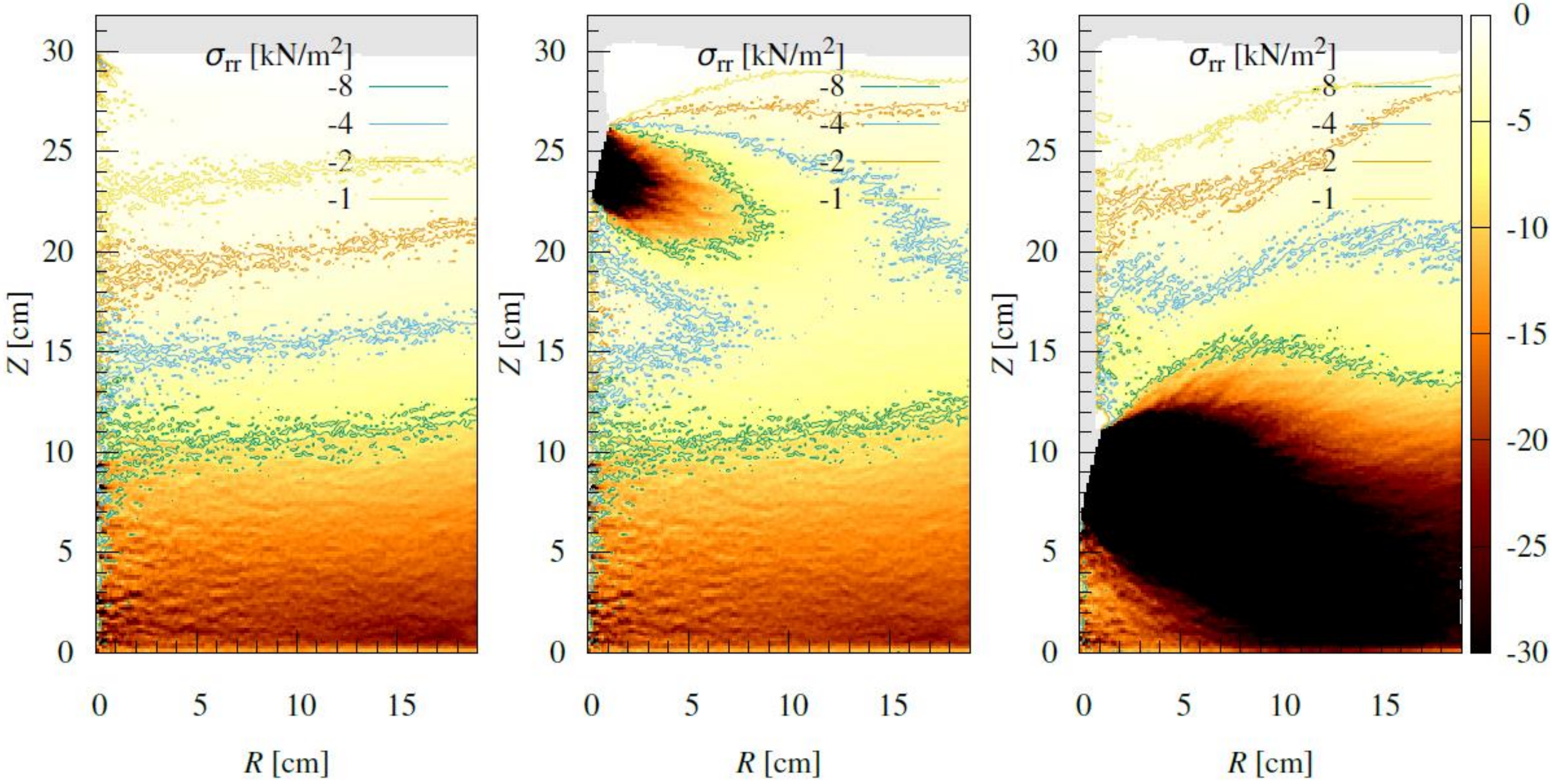
0.05 s

2.4 s

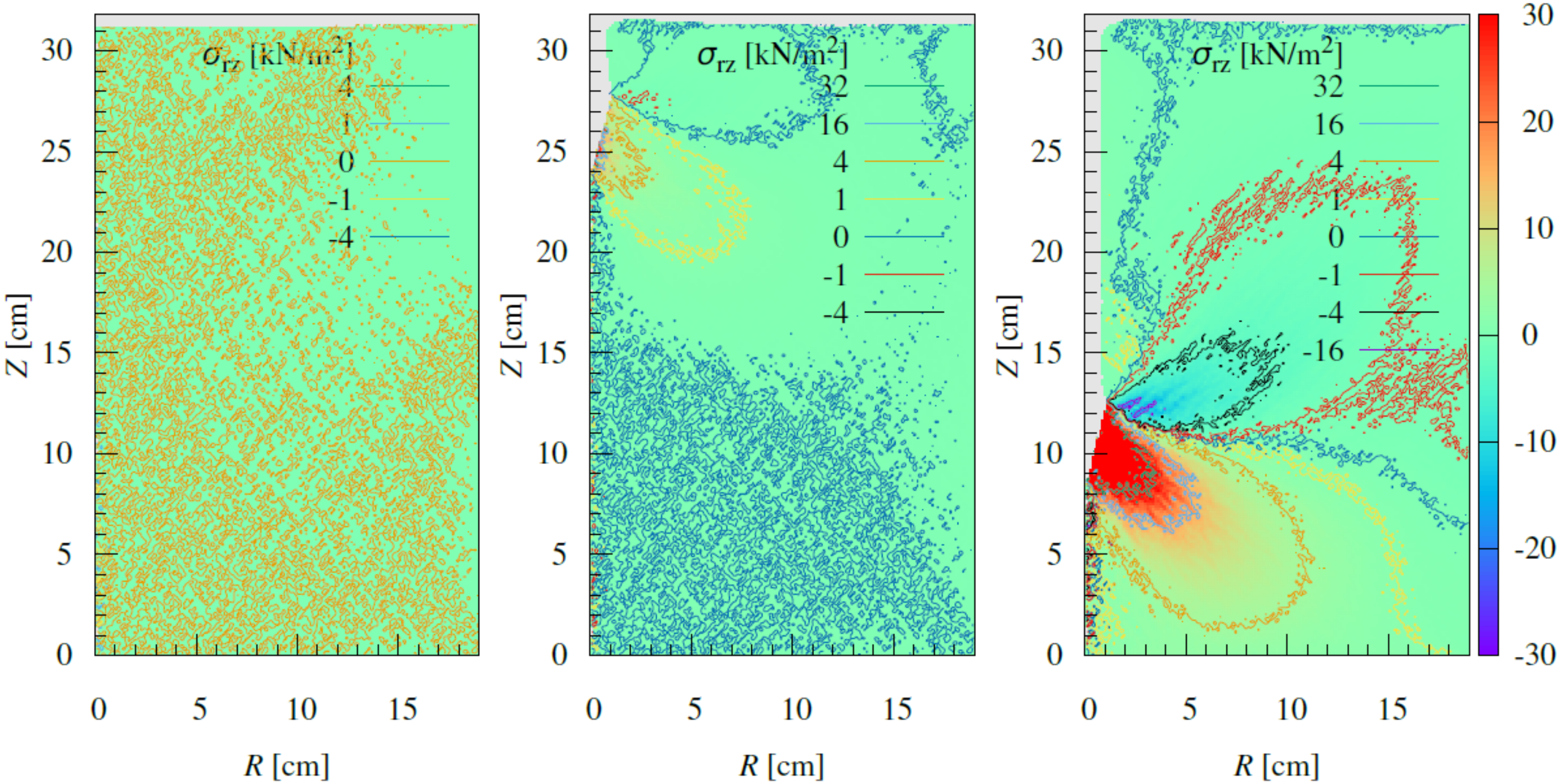
7.4 s

Evaluating vertical stress during CPT
Very dense sample
σ_{rr} component

0.05 s 2.4 s 7.4 s



Evaluating vertical stress during CPT
Dense sample
σ_{rz} component

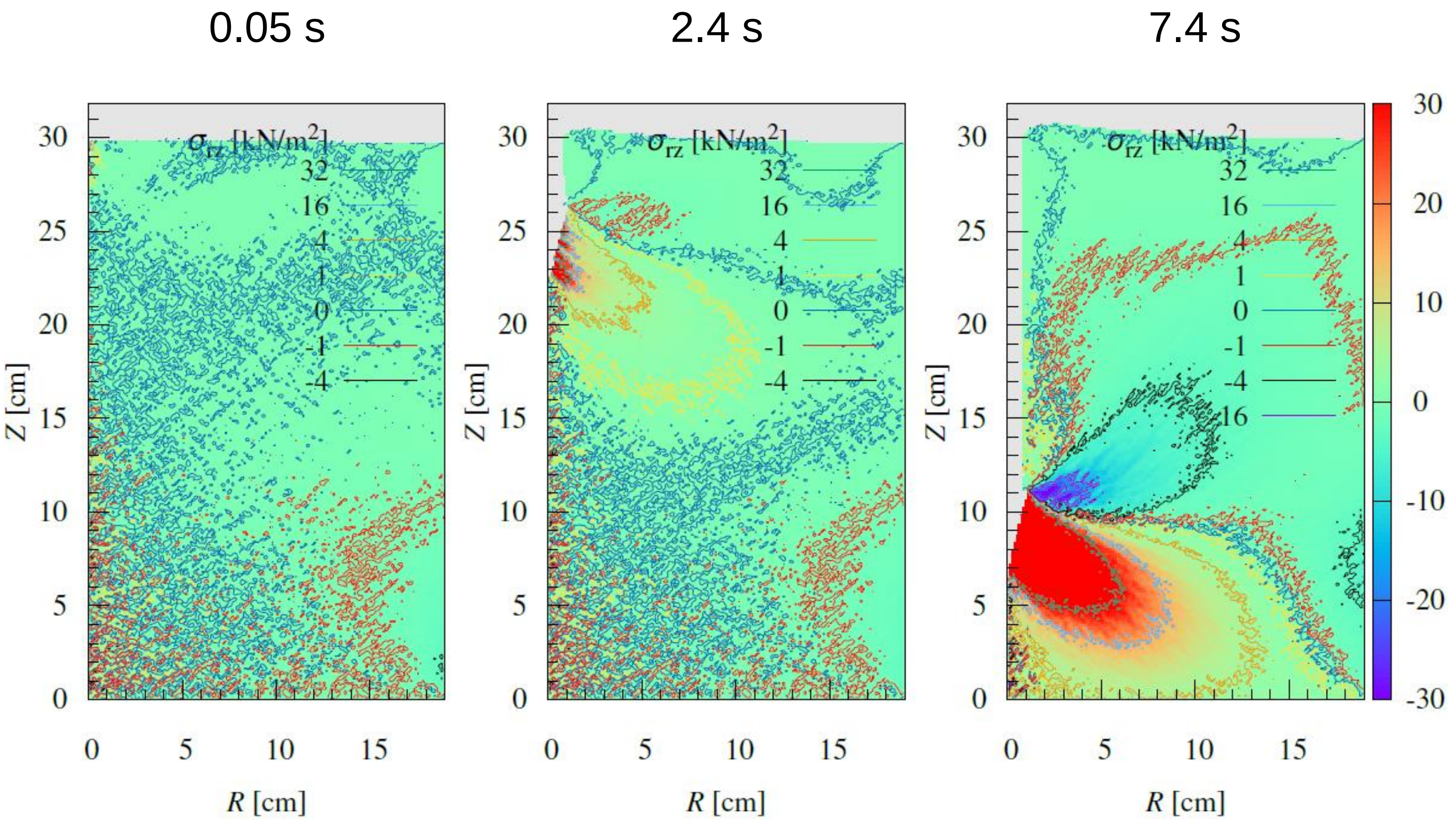


0.05 s

2.4 s

7.4 s

Evaluating vertical stress during CPT
Very dense sample
σ_{rz} component

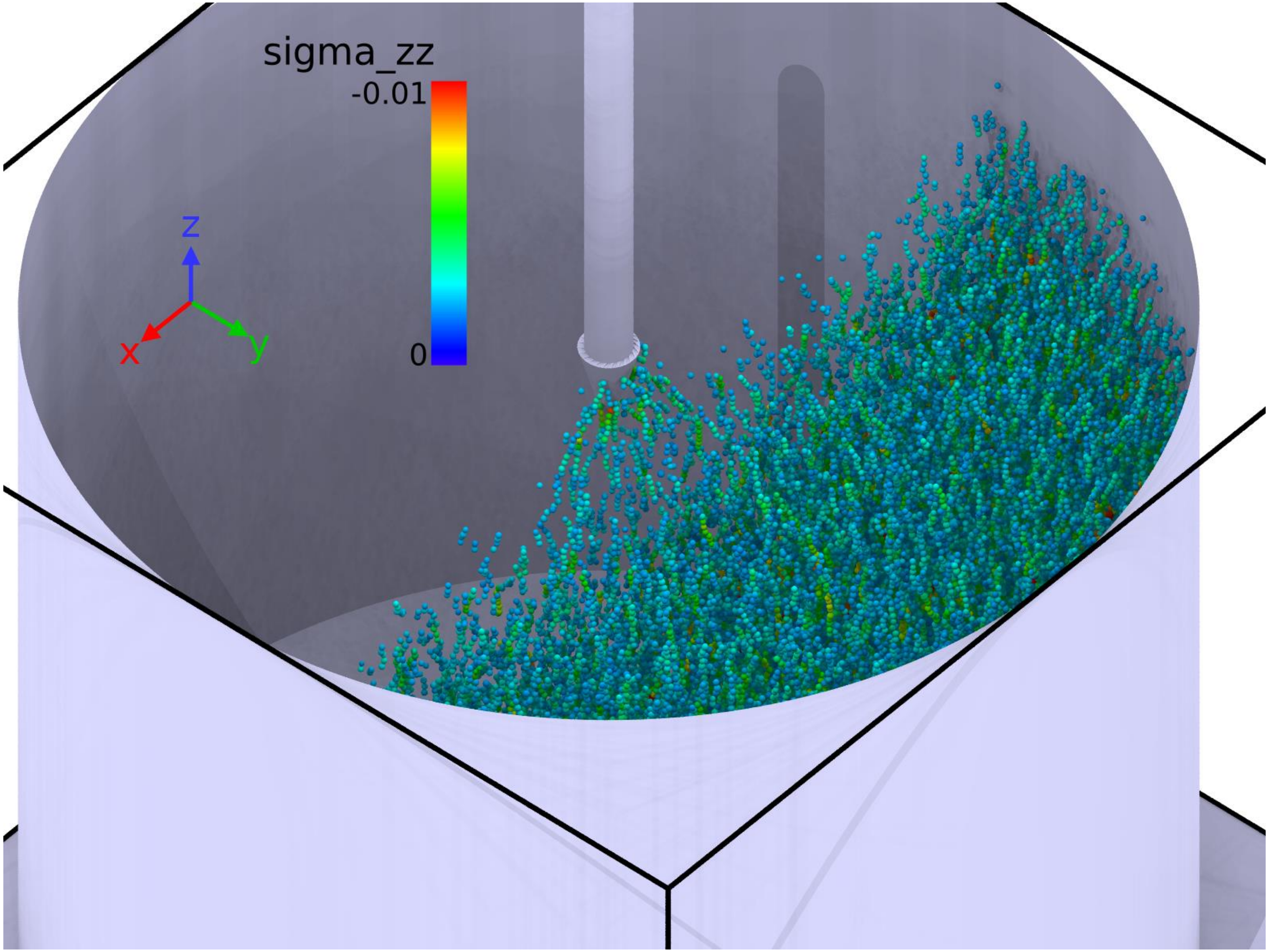


0.05 s

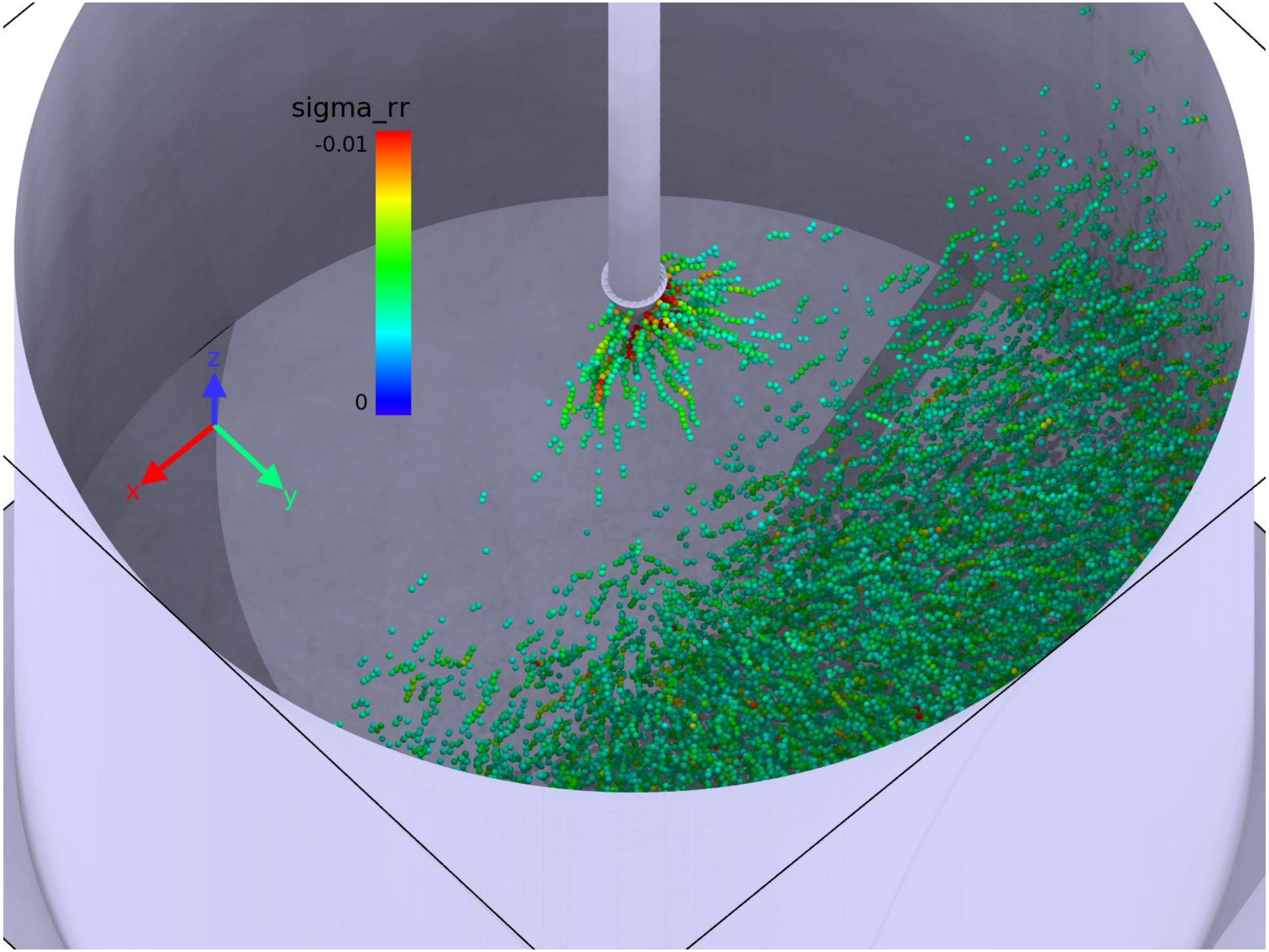
2.4 s

7.4 s

Force chains - σ_{zz}



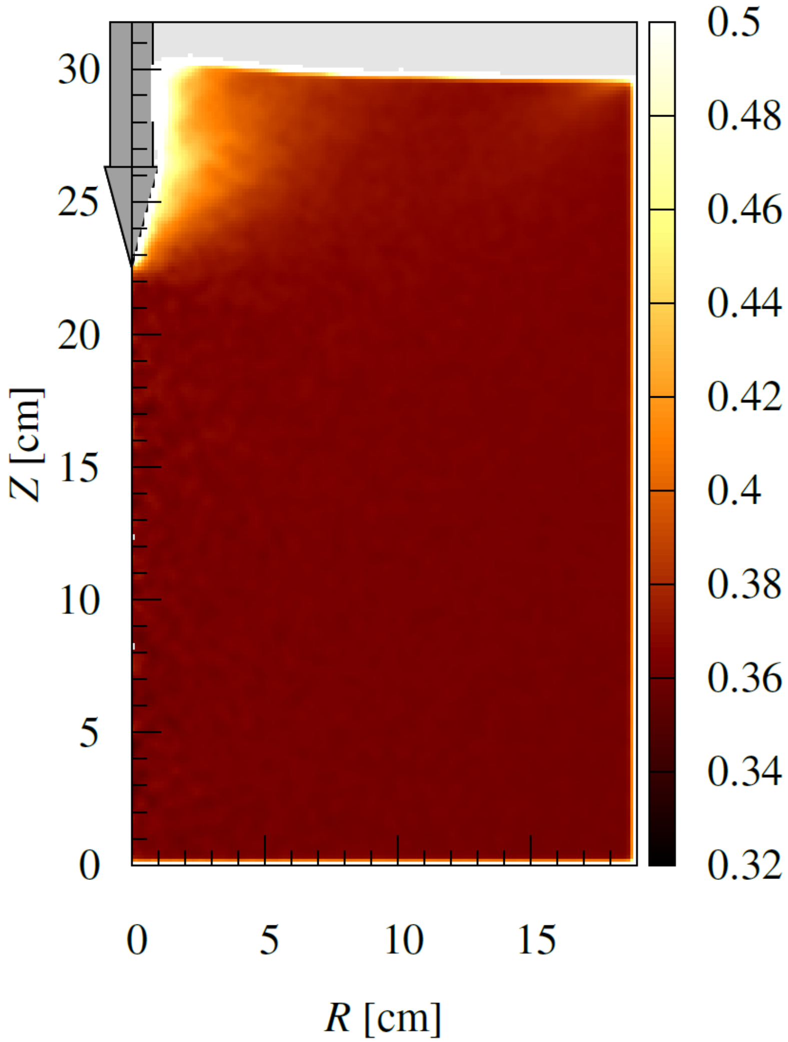
Force chains - σ_{rr}



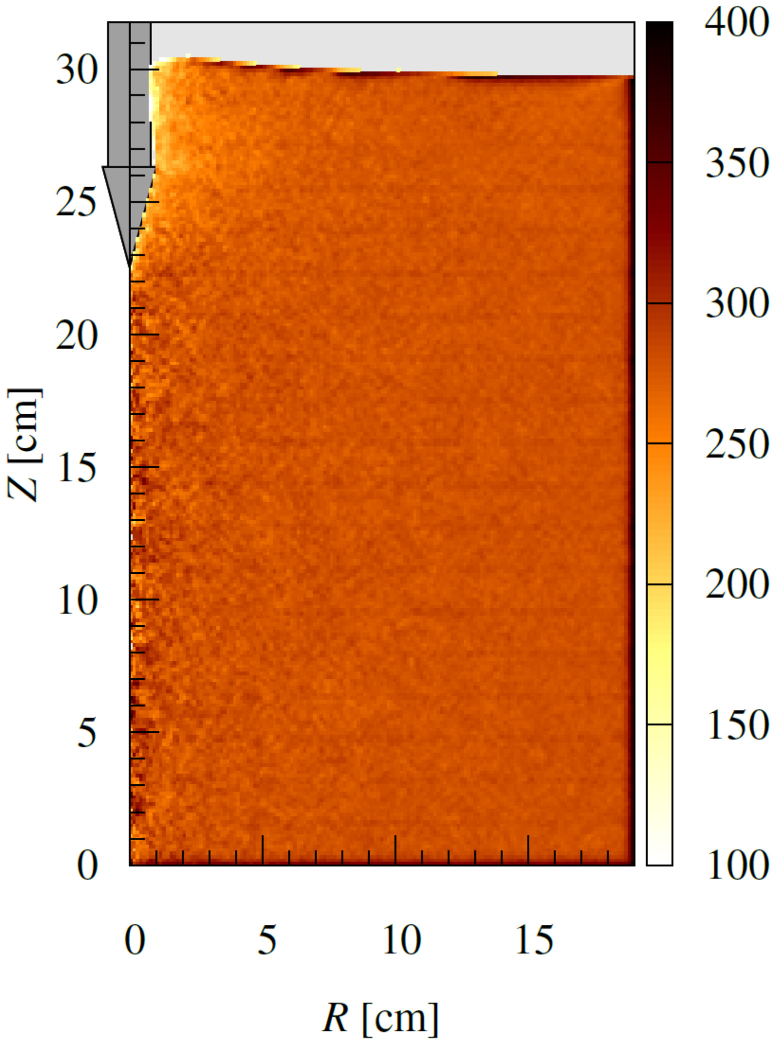
Local particle density

Very dense sample

Local porosity



Particle number density [cm^{-3}]



DEM simulations steps
Cone/wheel-subgrade interaction

Construct box and wheel of triangular facets

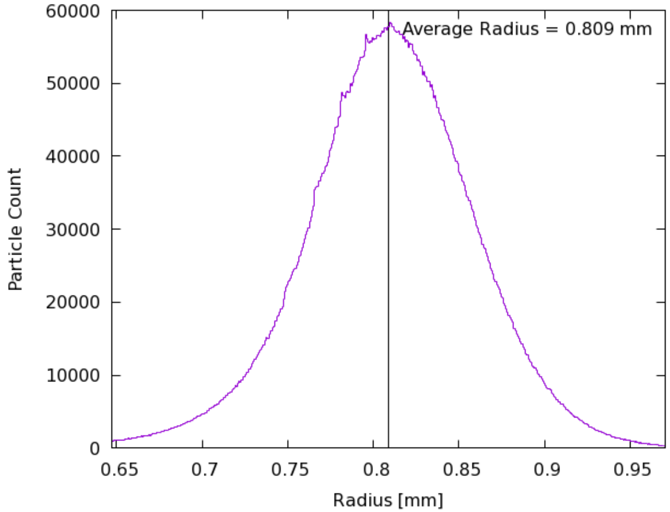
Settle particles in box

Settle wheel in box with settled particles

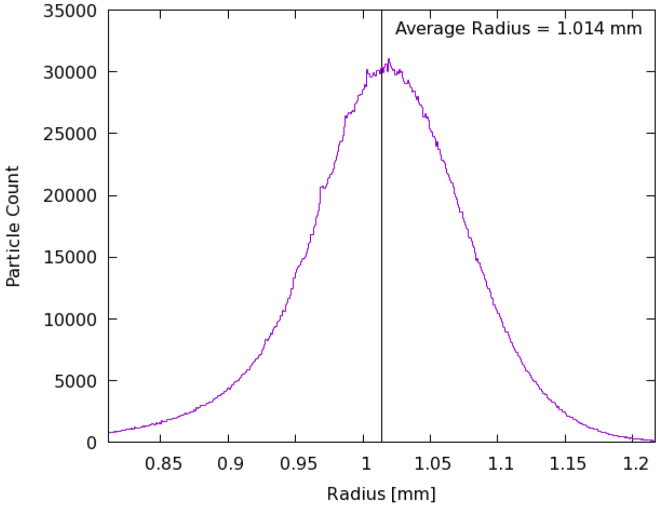
Execute simulations constrained to laminar motion:
1. Apply forward velocity (towed wheel)
2. Apply torque (driven wheel)
3. Prescribe translational velocity and slip, measure traction and pull (multiple slips = pull-slip curve)

DEM convergence study - particle size distributions

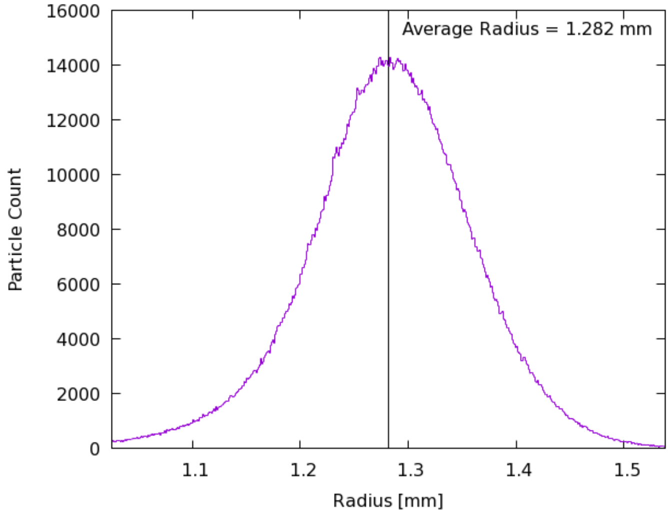
Particle size distribution, finest particles



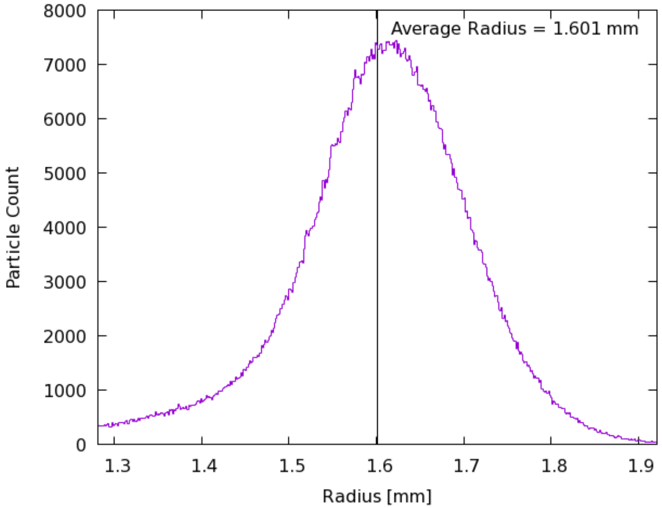
~2x lower number of particles



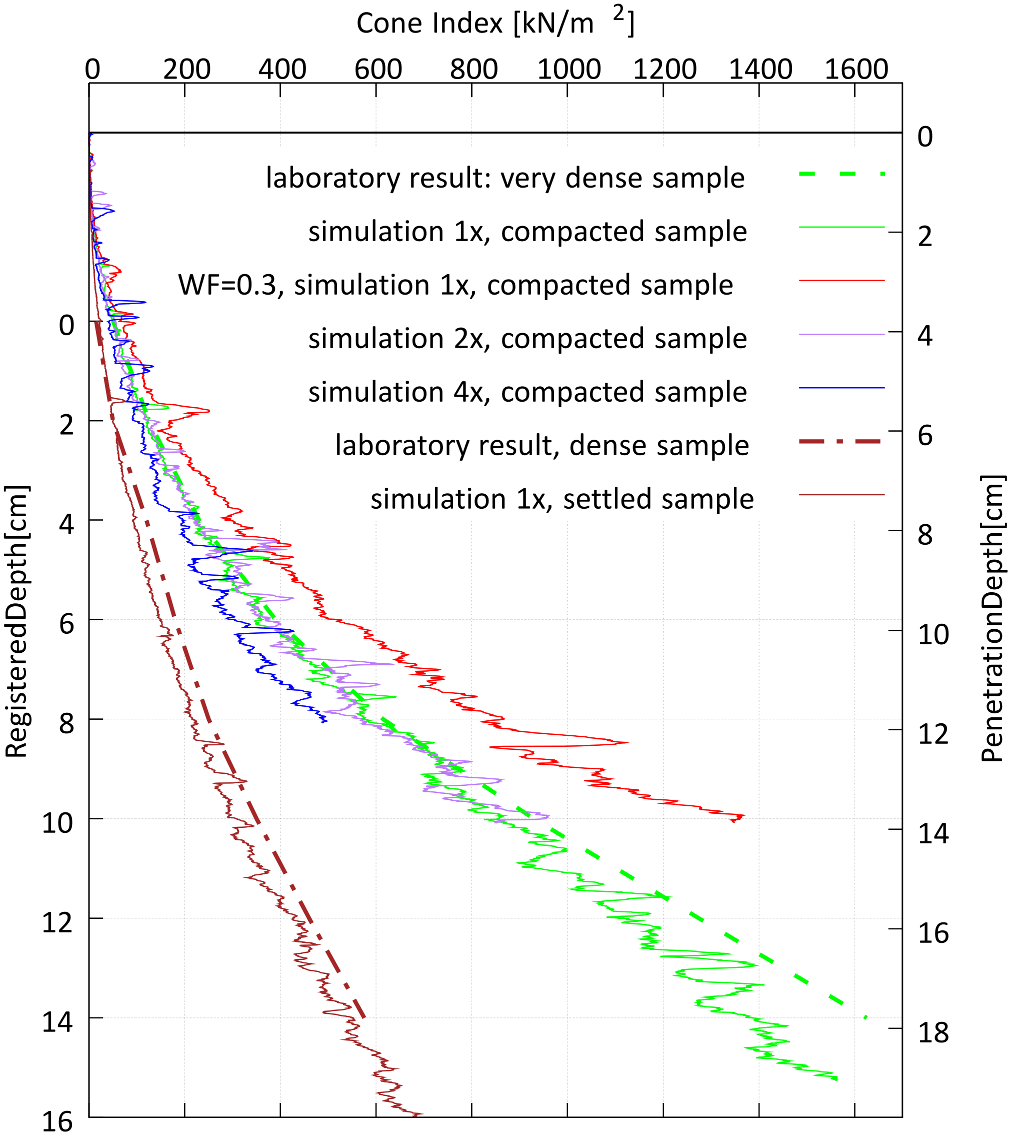
~4x lower number of particles



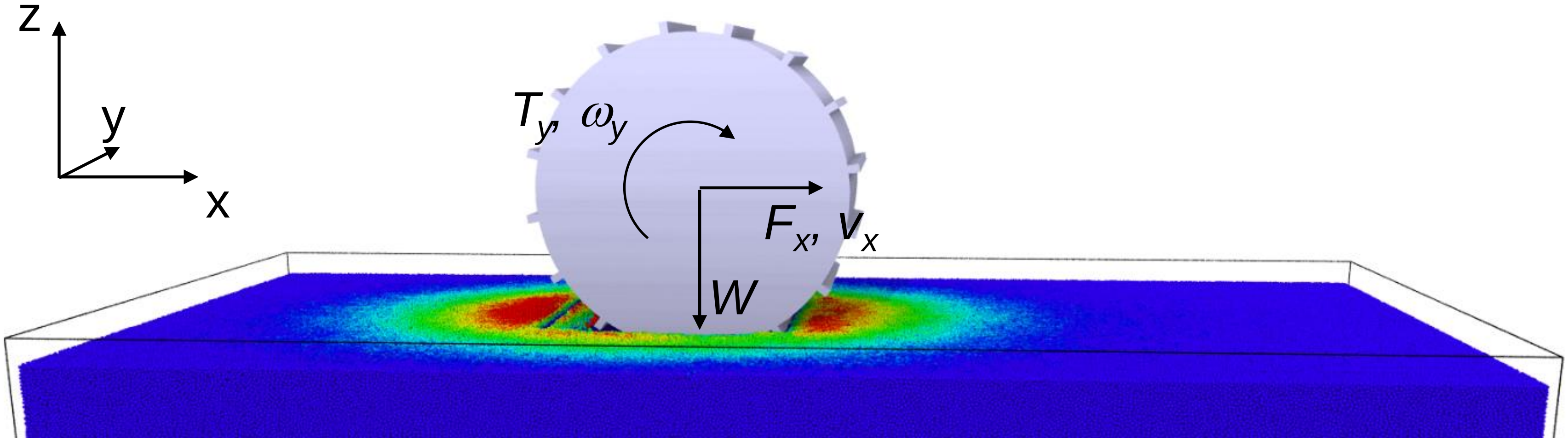
~8x lower number of particles



DEM convergence study



DEM model of a wheel in granular media: quantities of interest



Particles' colors represent height of the subgrade surface

Slip (powered wheel):

$$i = \frac{R\omega_y - v_x}{R\omega_y}$$

Skid (braked/towed wheel):

$$j = \frac{v_x - R\omega_y}{R\omega_y}$$

Drawbar pull force F_x (powered wheel):
force available to pull external load

Motion resistance:
resistance from subgrade + internal

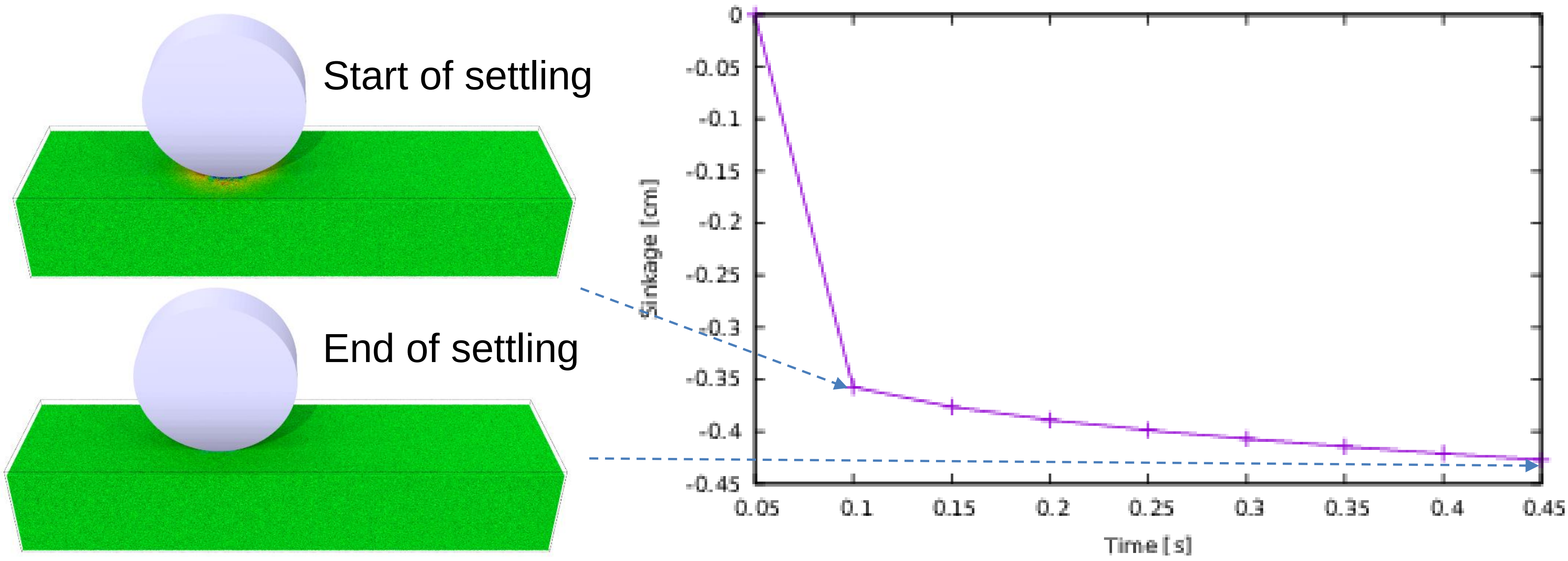
Traction coefficient:

$$k = \frac{T_y}{RW}$$

Sinkage:
depth to which wheel sinks into a subgrade

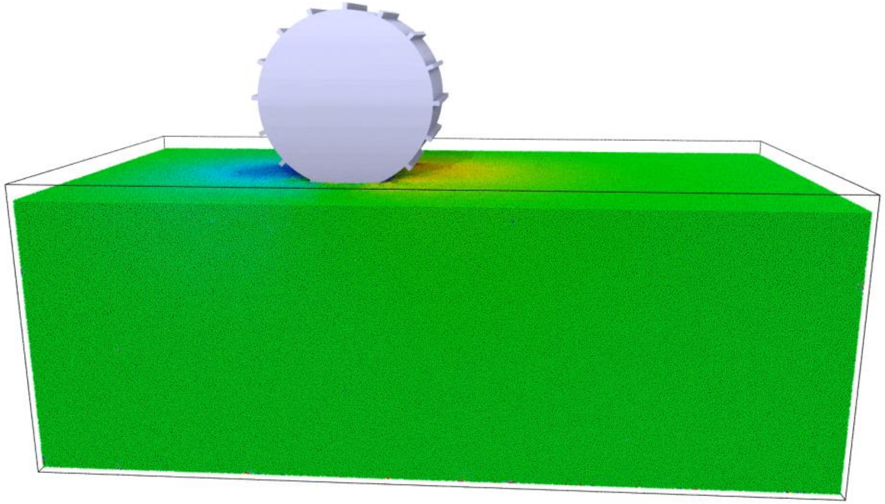
Wheel settling

1) Initial location of wheel is set to just touch subgrade surface.
2) Wheel is constrained to move in vertical direction only.
3) Gravity is applied.

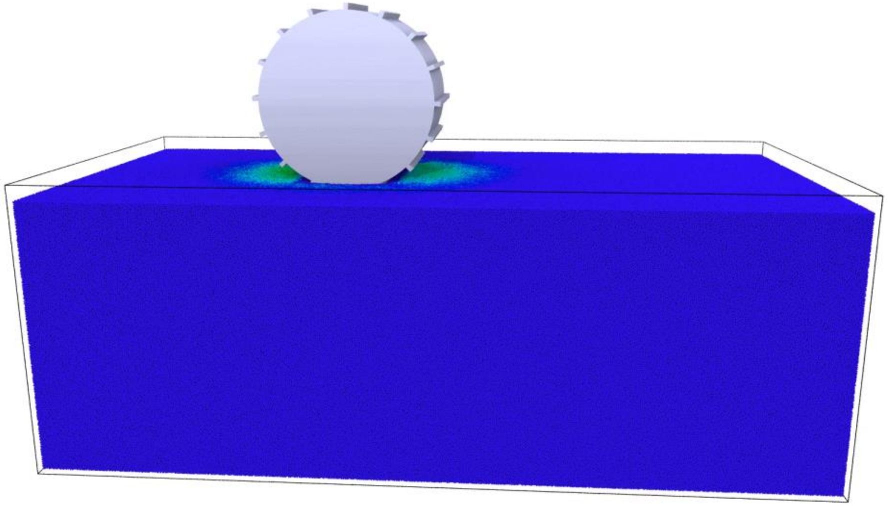


Wheel settling under gravity, after being placed on the subgrade surface. Left figures: particles' color depicts z-component of particle velocities: red is upward, blue is downward, green is zero. Right plot: sinkage of the wheel with time.

4” wheel driven by torque 100 lbf·ft

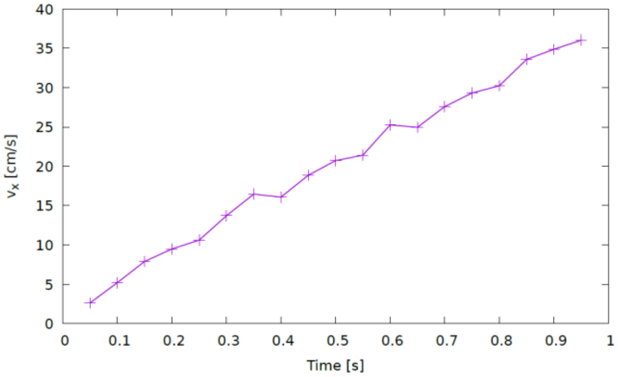


Particles’ color depicts x-component of particle velocity, red is forward, blue backward, green zero.

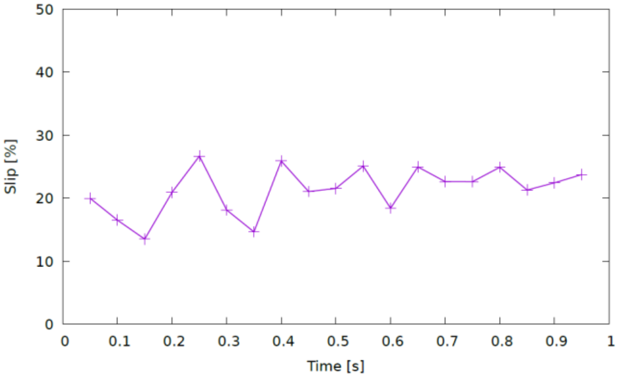


Color depicts particle height above the subgrade surface.

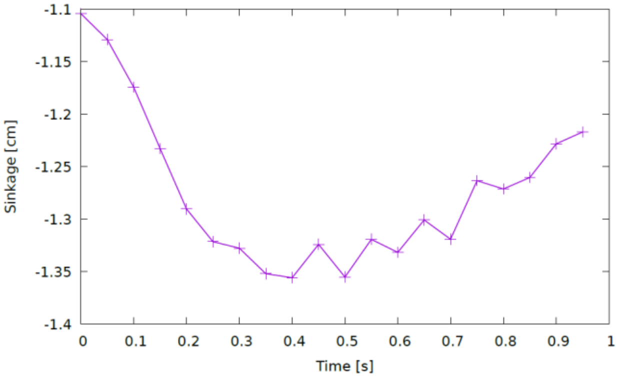
Forward velocity



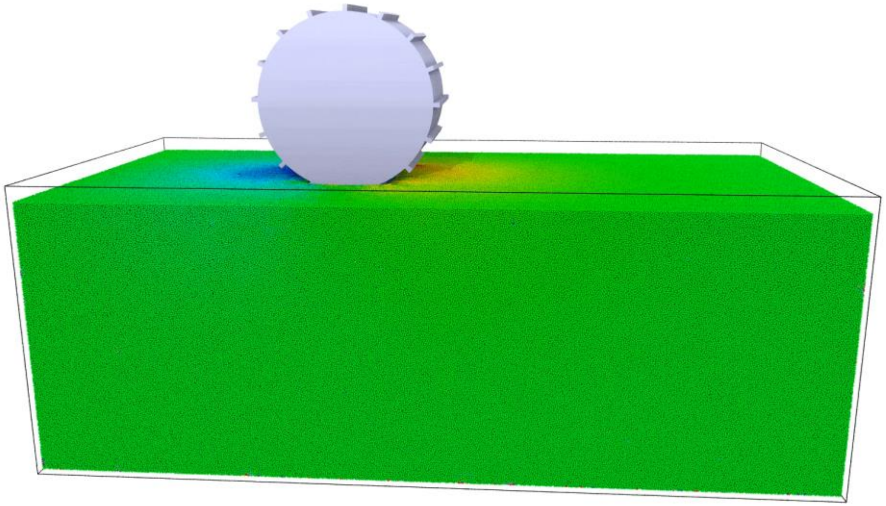
Slip



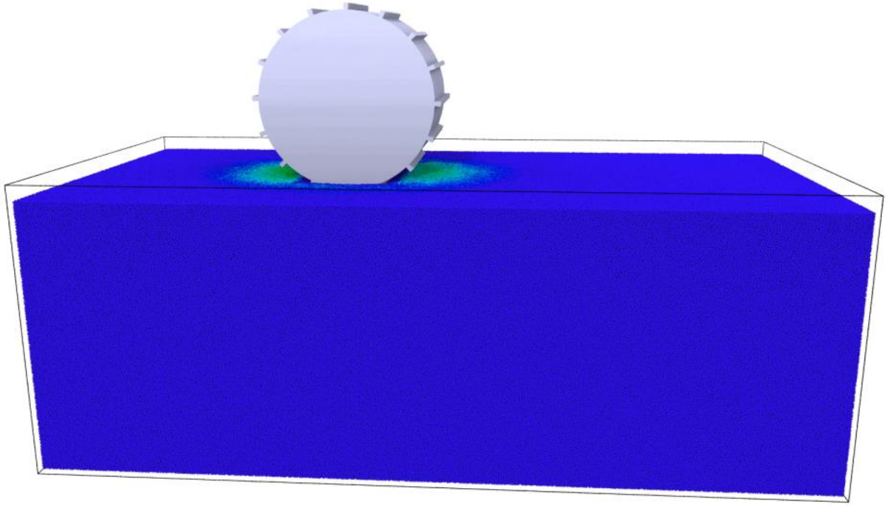
Sinkage



4” wheel driven by torque 30 lbf·ft

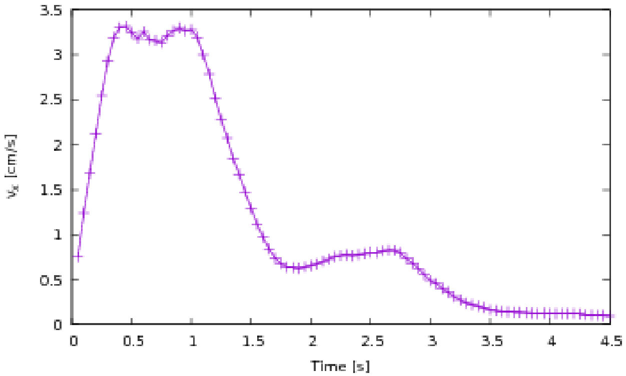


Particles’ color depicts x-component of particle velocity, red is forward, blue backward, green zero.

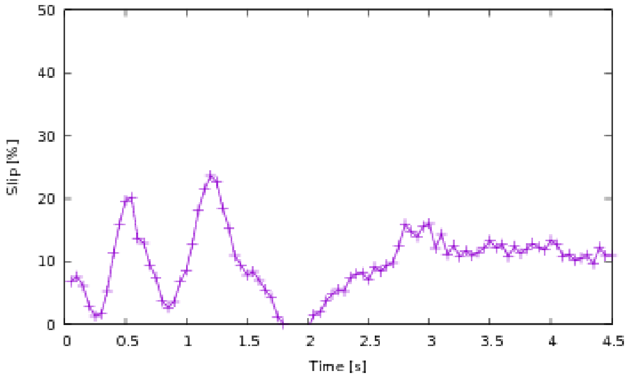


Color depicts particle height above the subgrade surface.

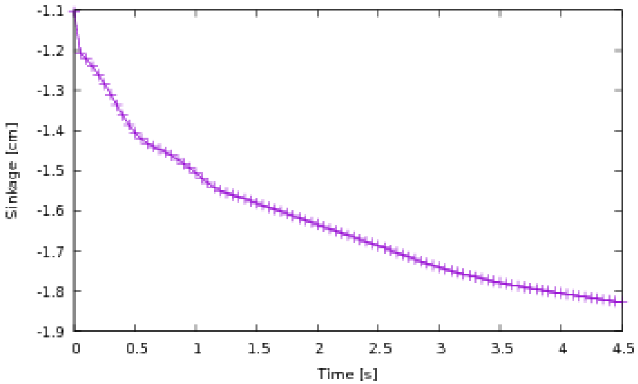
Forward velocity



Slip



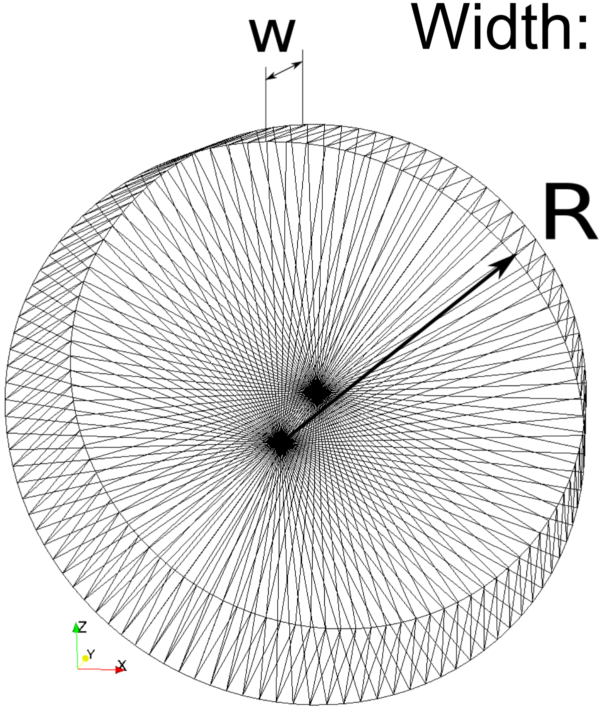
Sinkage



14.04” wheel

Smallest wheel in the DROVE database

Diameter: 14.04”
Width: 4.15”

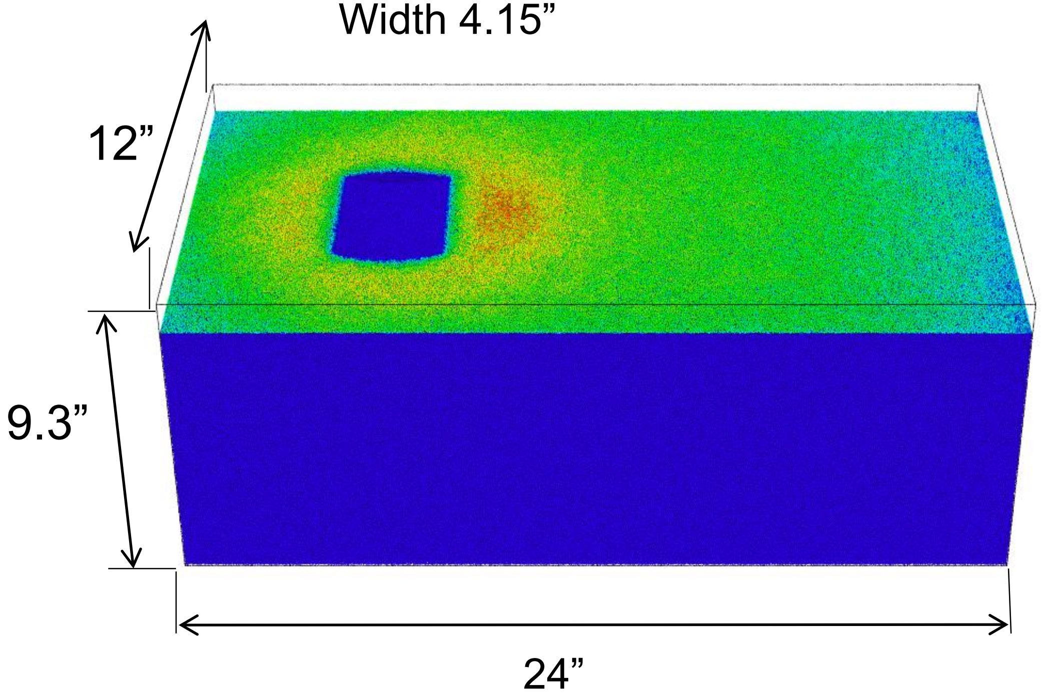


Carriage velocity: 66 in/s
Wheel rotation velocity: 82.5 in/s
Cone index: 416 kPa
Weight: 42 lbf
Sinkage / tire diameter: 1.4 %
Torque: 13 lbf·ft
DBP: 40.5 %

DEM simulations for slip-pull curve: dimensions

Smallest wheel in the DROVE database

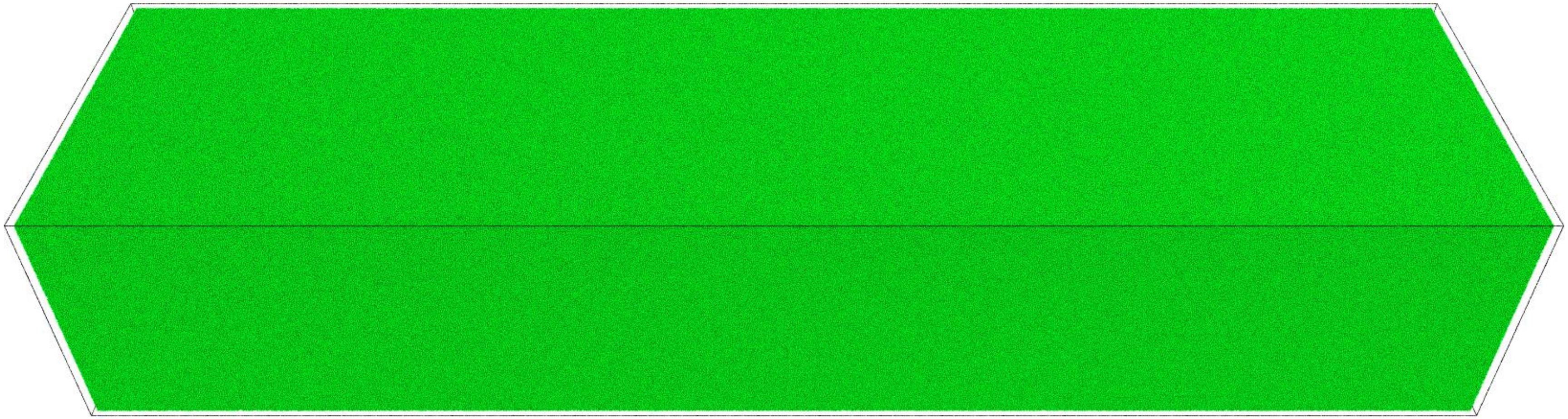
Wheel:
Diameter 14.04”
Width 4.15”



Preparation of larger particle bed for realistic size wheel

1) Particles are placed in space by filling tetrahedral mesh created by TetGen mesh generation package.

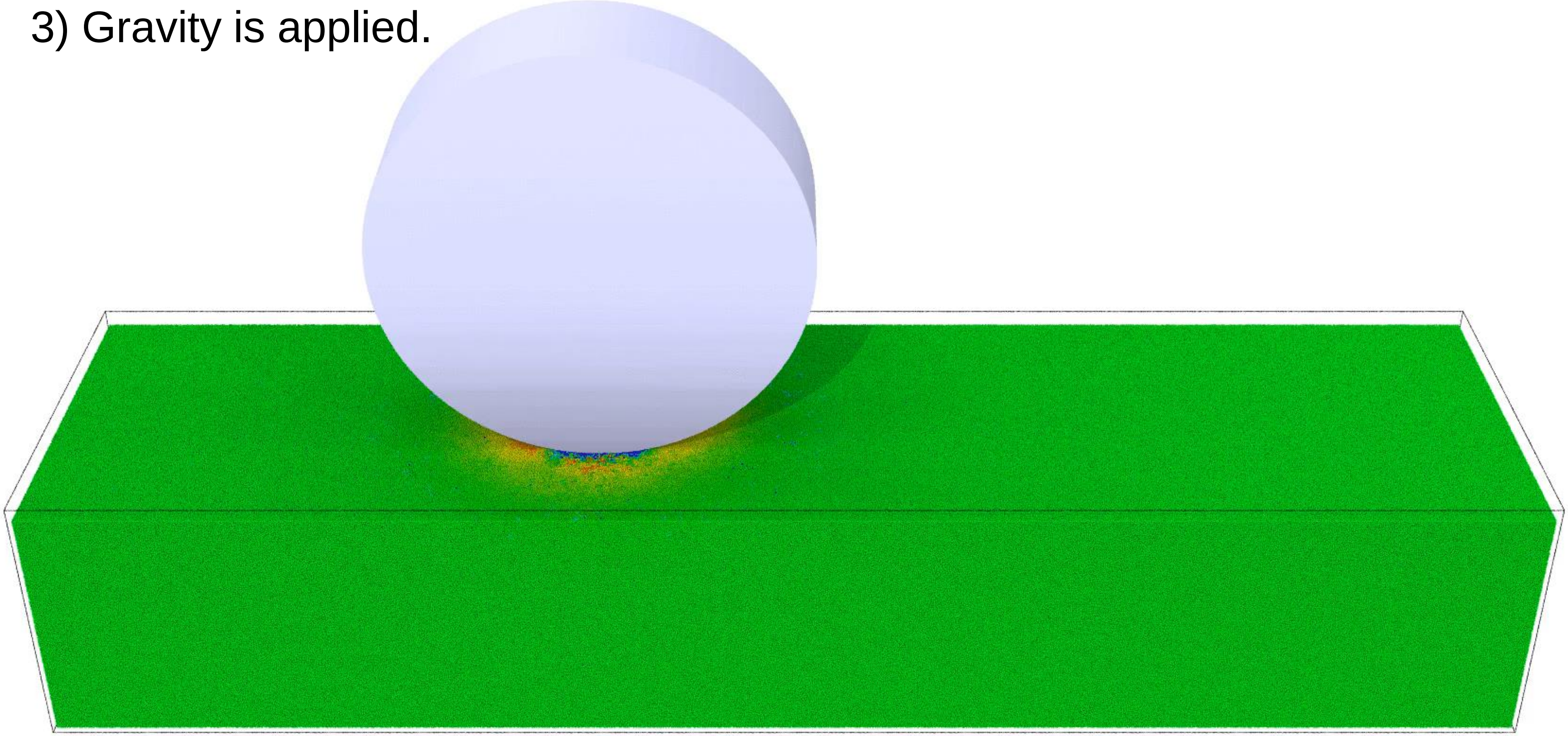
2) Particles are settled under gravity. Settling is complete when average kinetic energy decreases to chosen threshold.



Particle settling under gravity - after initial random placement within a box.
Particles' color depicts z-component of the particle velocity, red is upward, blue downward, green zero

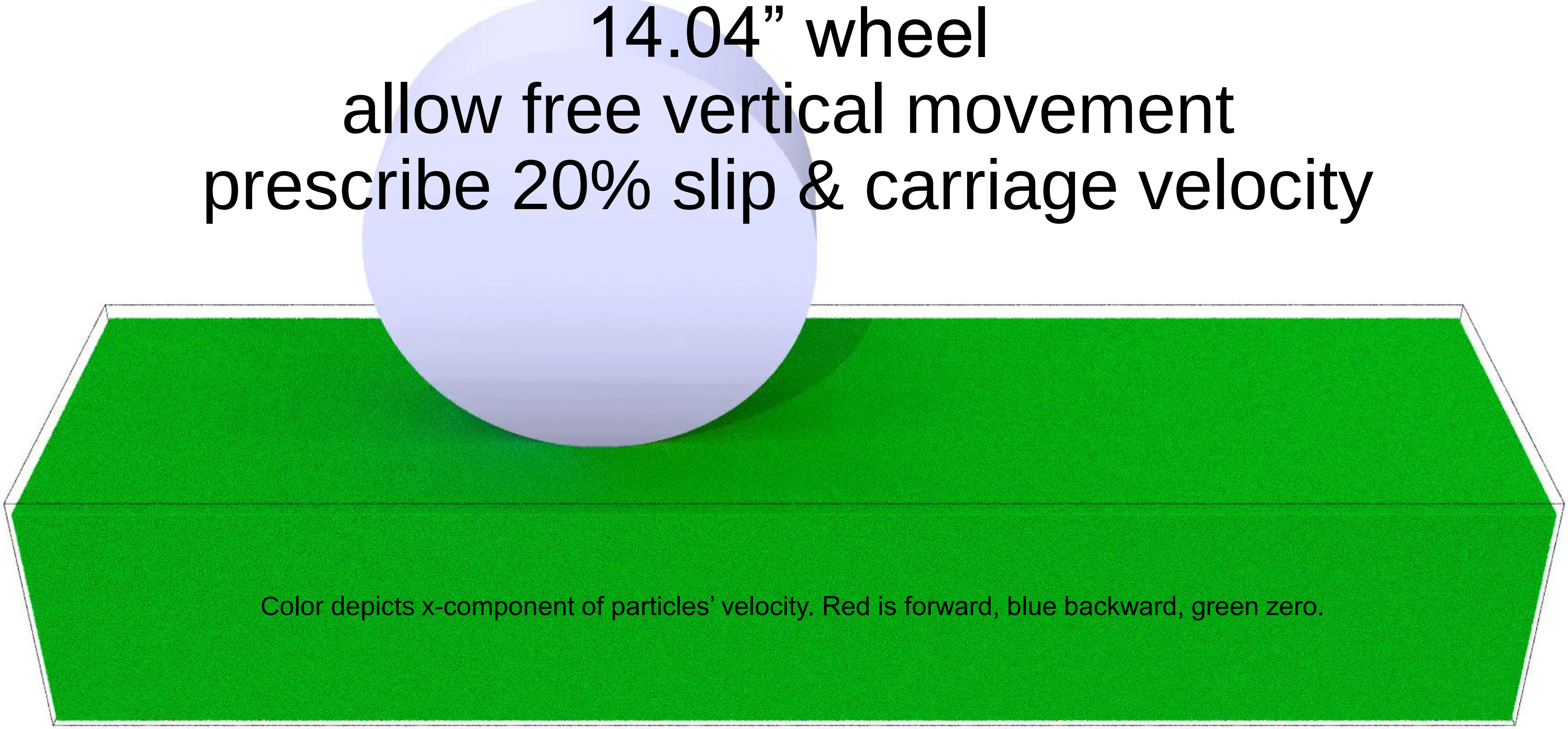
14.04” wheel
Settling under gravity

1) Initial location of wheel is set to just touch subgrade surface.
2) Wheel is constrained to move in vertical direction only.
3) Gravity is applied.



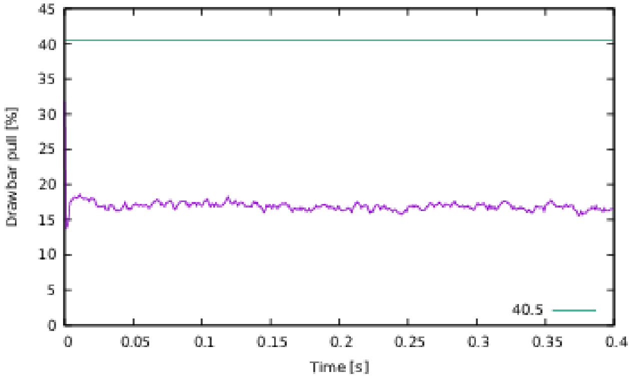
Wheel settling under gravity - after being placed on the top of particle bed. In the animation, particles’ color depicts z-component of the particle velocity: red is upward, blue downward, green zero.

14.04” wheel
allow free vertical movement
prescribe 20% slip & carriage velocity

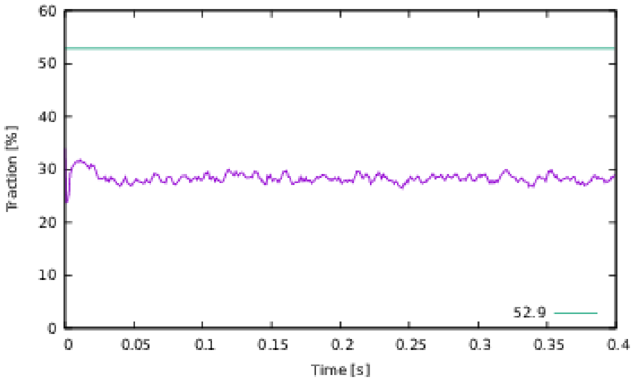


Color depicts x-component of particles’ velocity. Red is forward, blue backward, green zero.

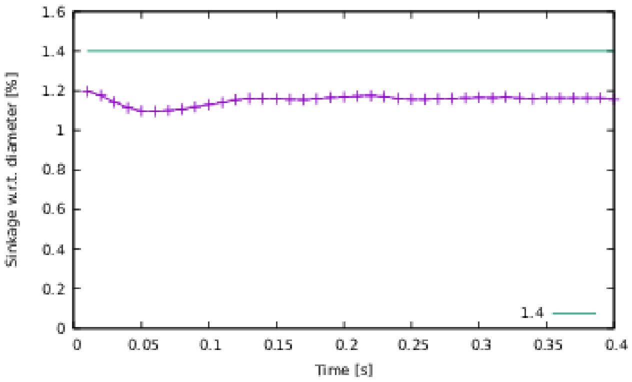
Drawbar pull



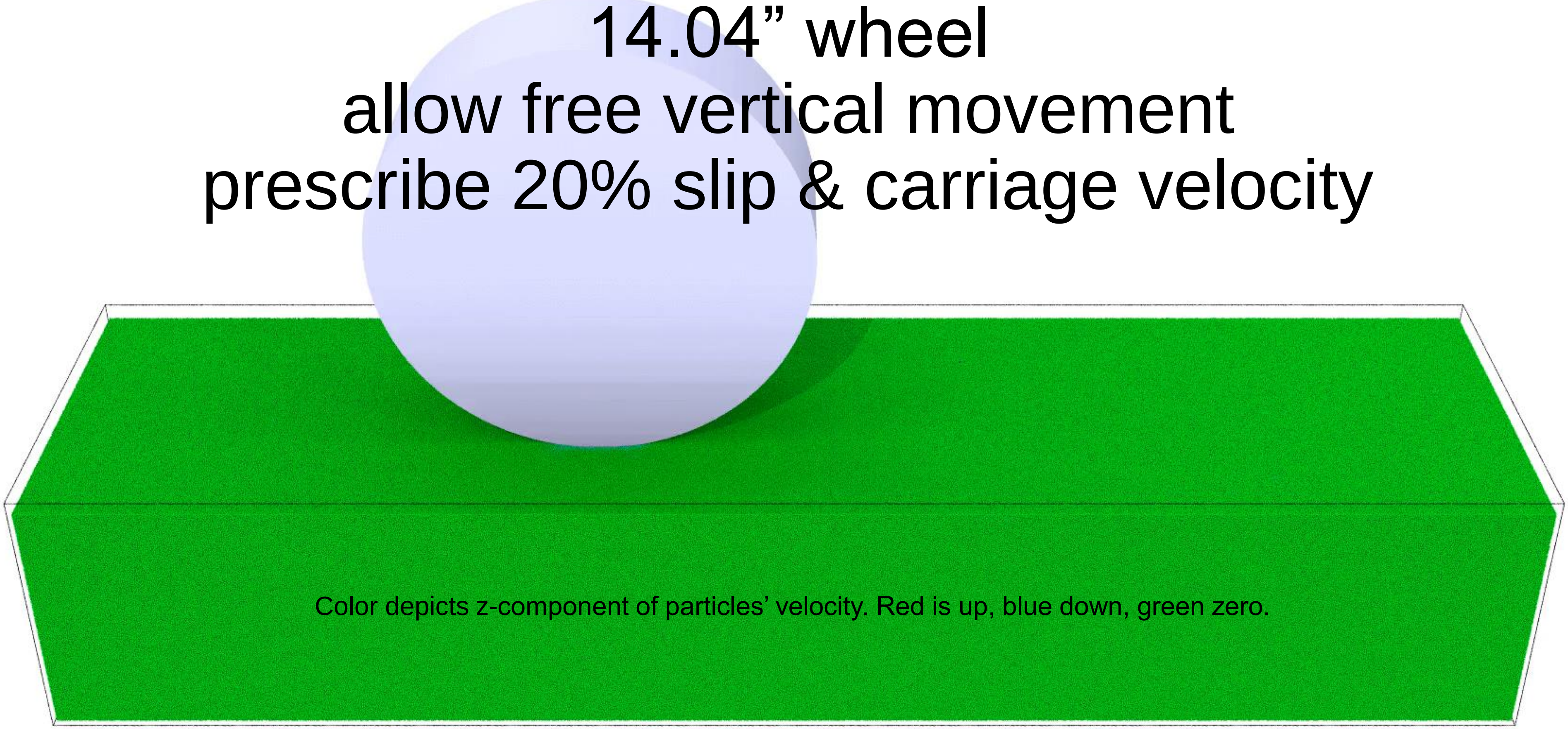
Traction



Sinkage

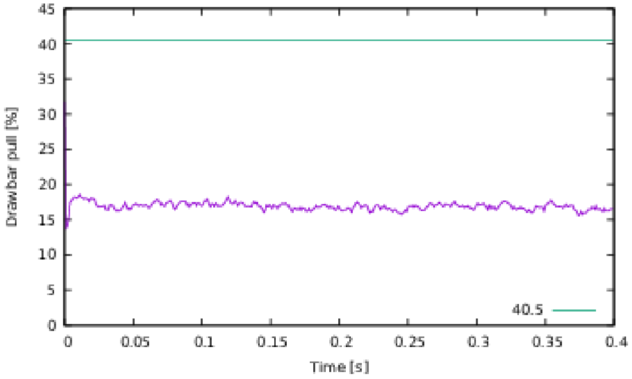


14.04” wheel
allow free vertical movement
prescribe 20% slip & carriage velocity

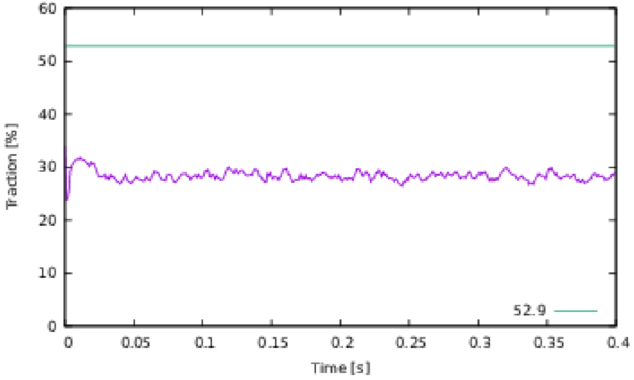


Color depicts z-component of particles’ velocity. Red is up, blue down, green zero.

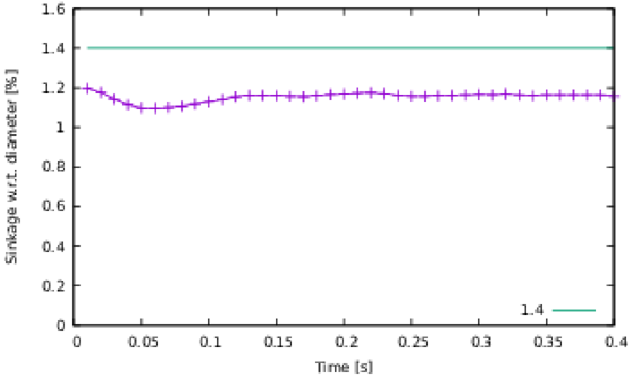
Drawbar pull



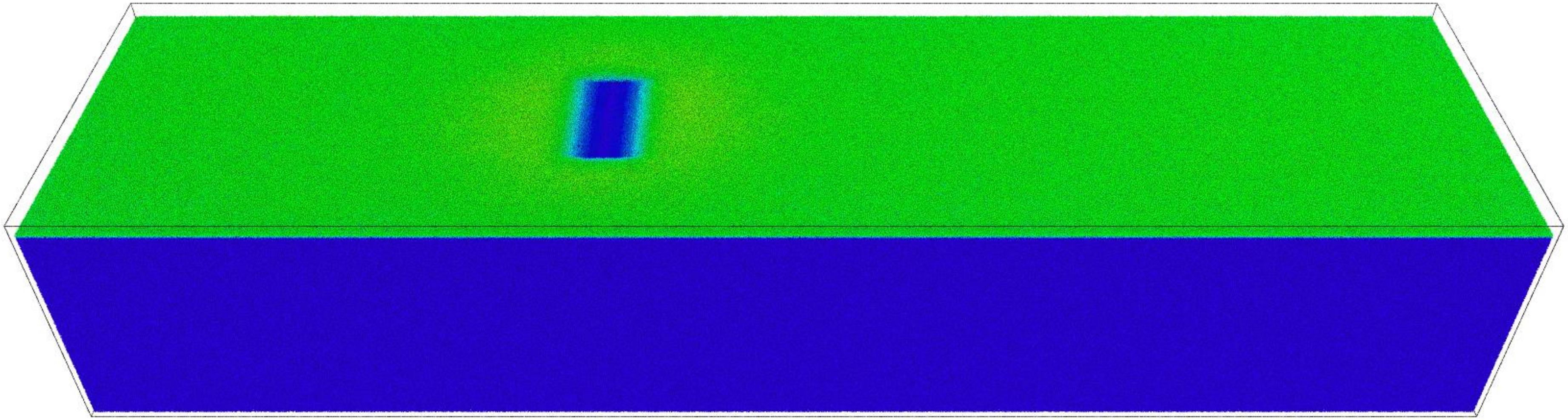
Traction



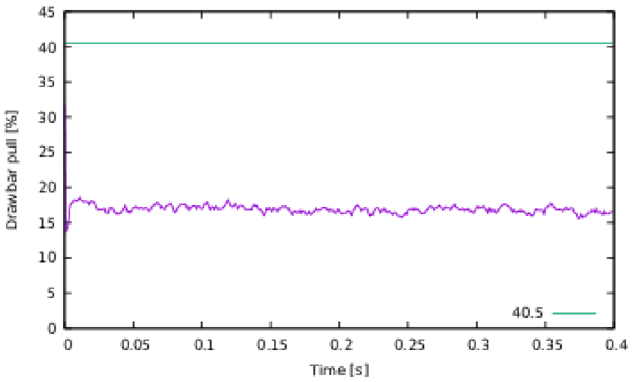
Sinkage



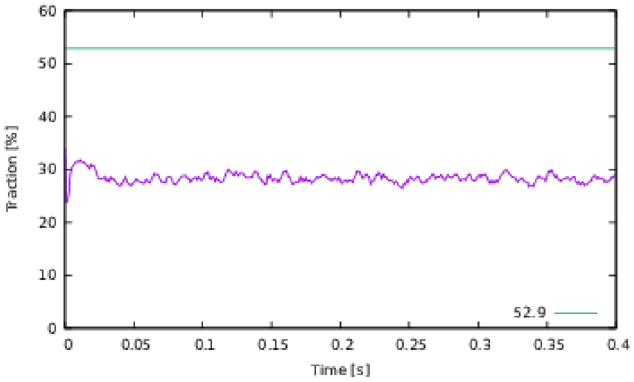
14.04” wheel



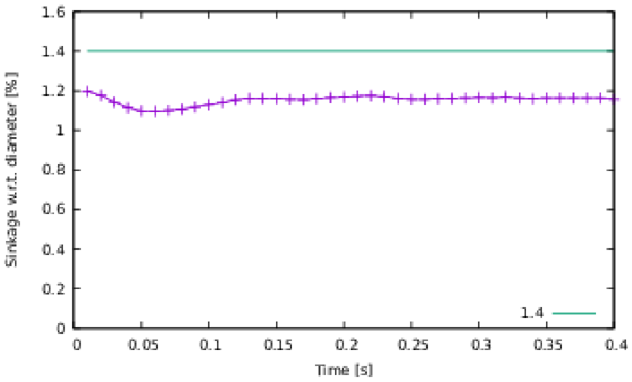
Color depicts particle height above the subgrade surface.



Drawbar pull



Traction

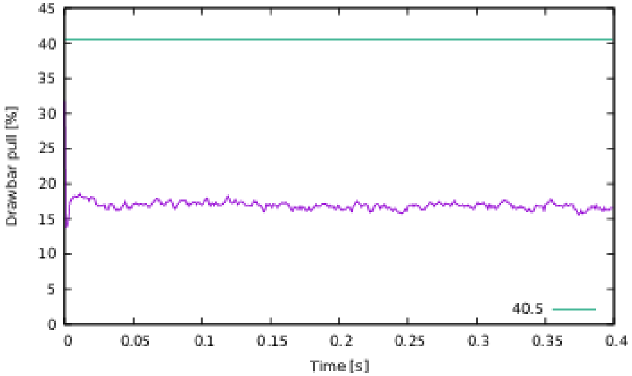


Sinkage

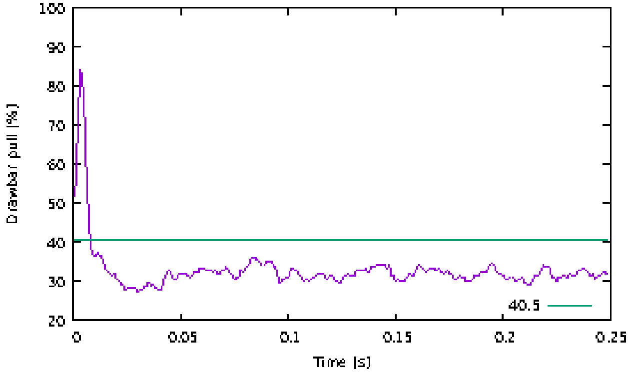
14.04” wheel
Calibration of DEM parameters to match experimental drawbar pull and traction

Drawbar pull:

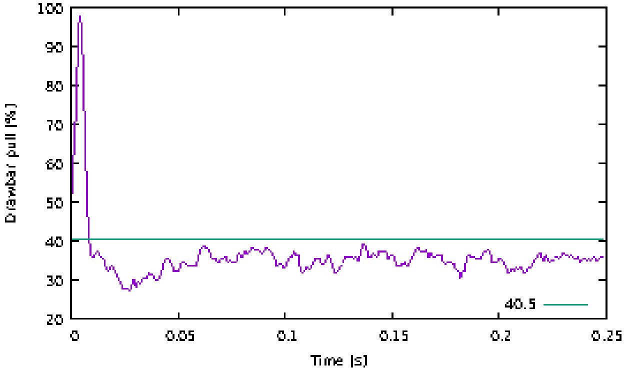
Particle-wall friction = 0.3
rolling friction = 0.0



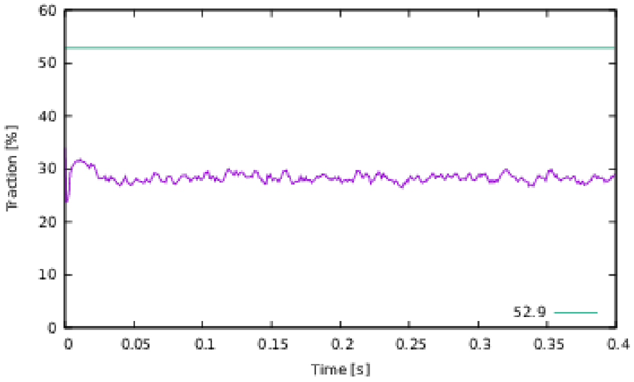
Sample density 97 lb/cu ft
Particle-wall friction = 0.7
rolling friction = 0.1

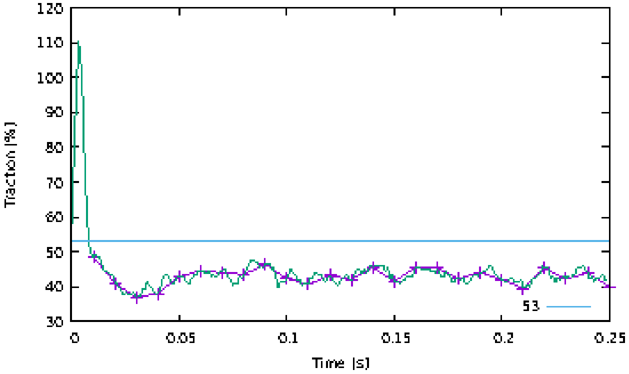


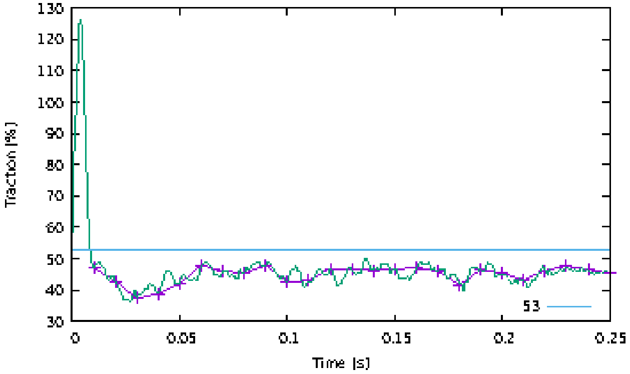
Particle solid density 1.5x larger
Sample density 146 lb/cu ft



Traction:

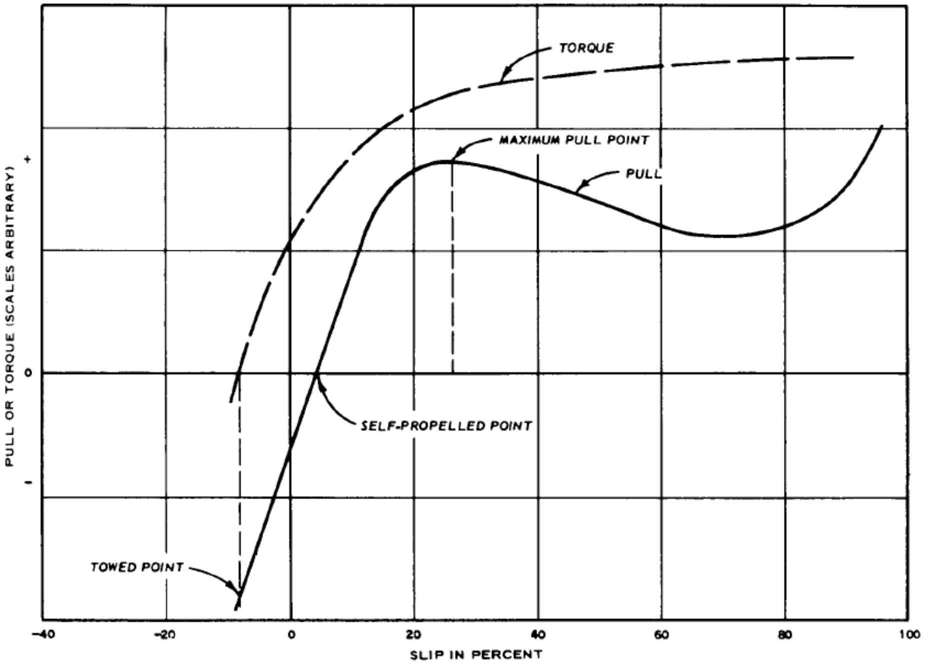




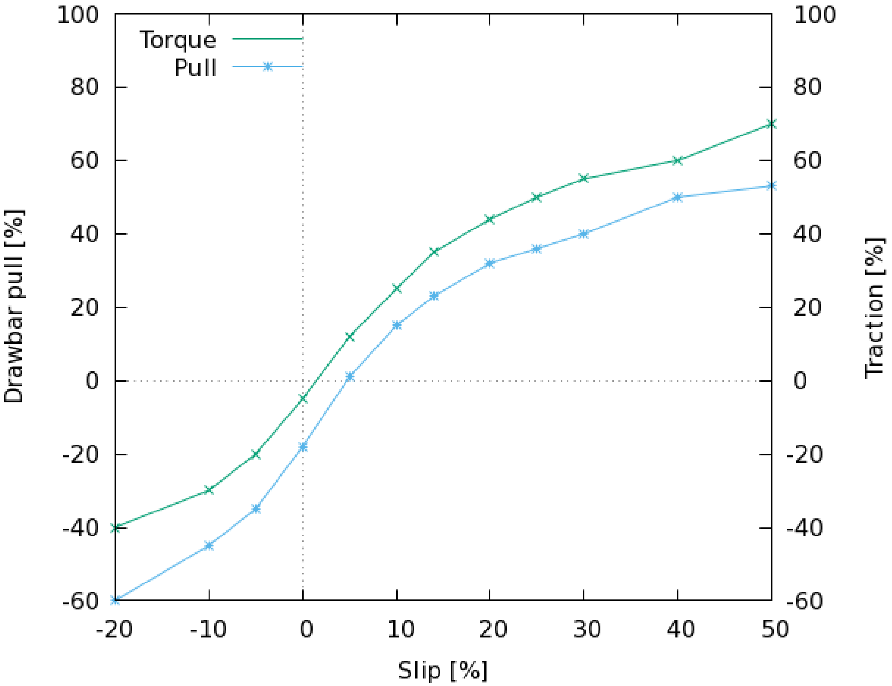


Sample lab test pull-slip curve vs. DEM 14.04” wheel simulations

Turnage, 1972



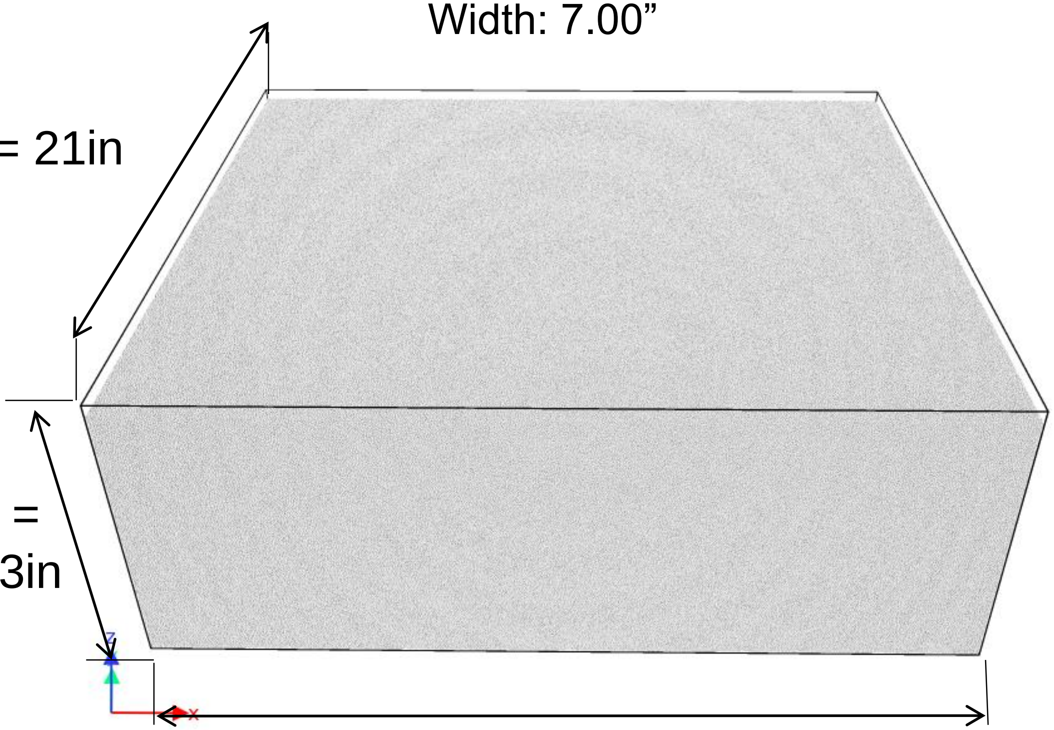
DEM simulations



DEM model of a wheel interaction with granular media - dimensions

Smallest low-deflection wheel from the DROVE database

Solid rubber wheel
Diameter: 28.06”
Width: 7.00”

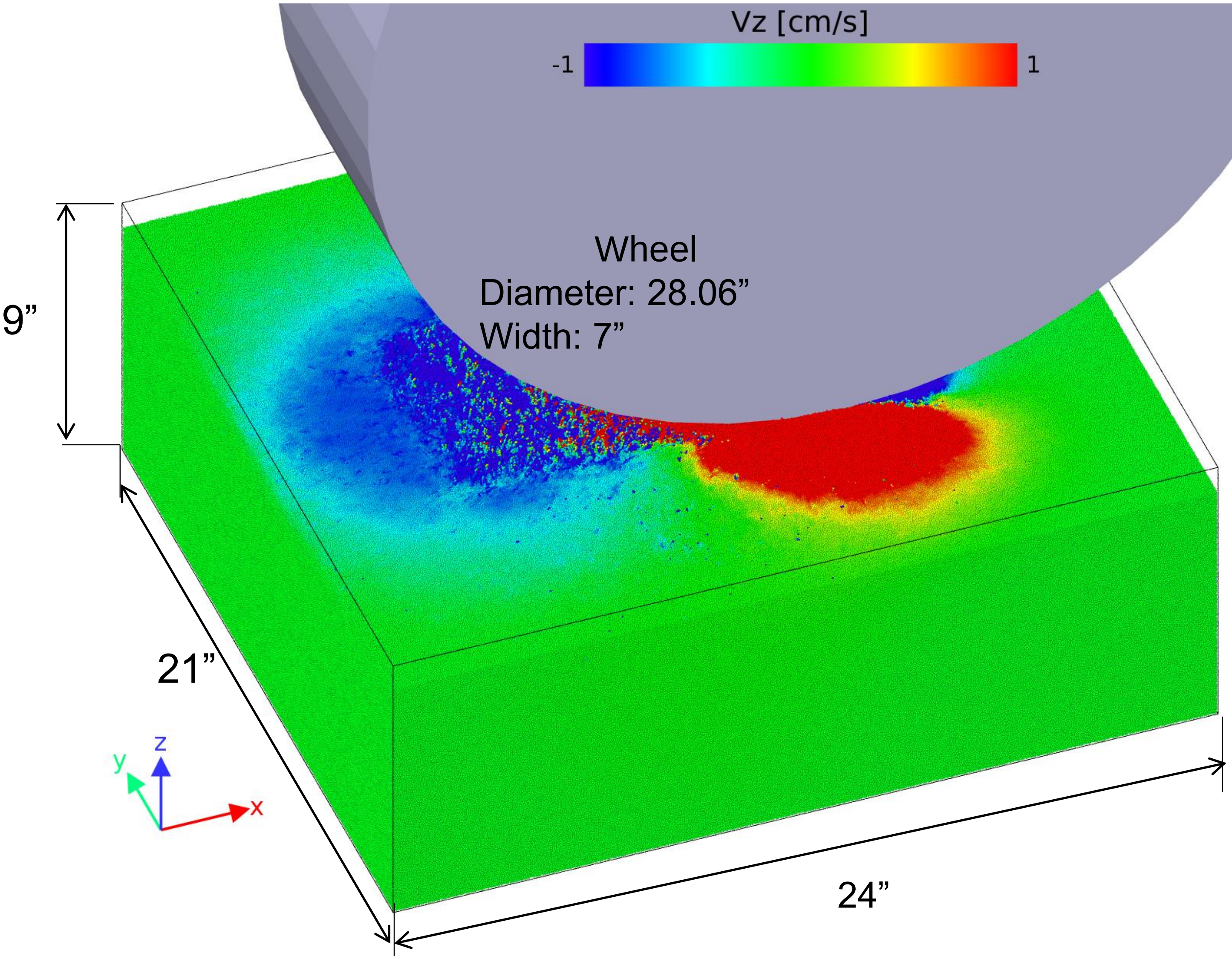


d = 21in

h = 9.3in

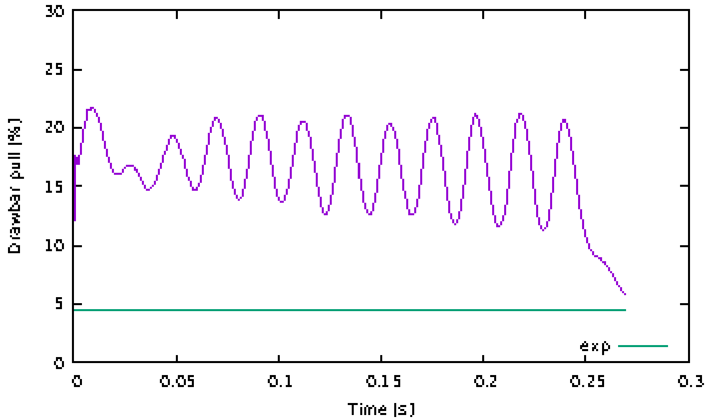
L = 24in

Smallest solid rubber wheel from DROVE - coarse wheel surface facets

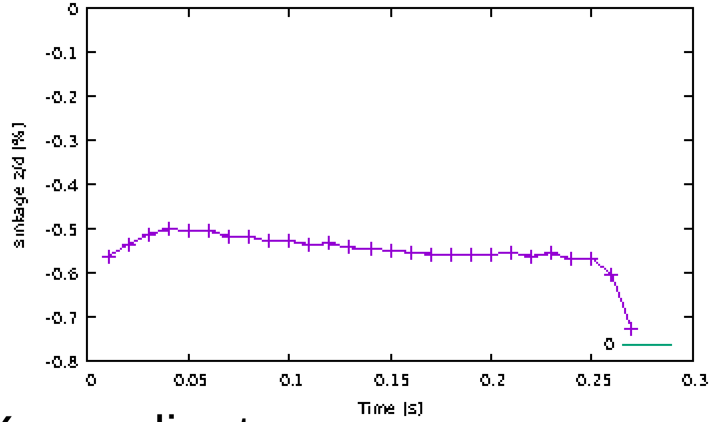


28.06” wheel
smallest solid rubber wheel in DROVE database: drawbar pull, traction, and sinkage

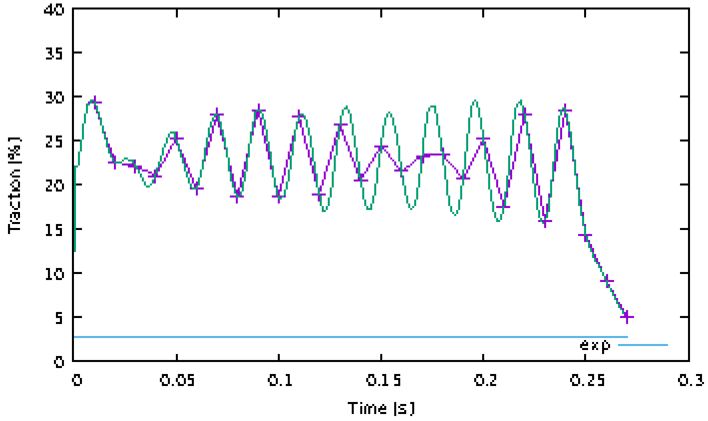
Drawbar pull:



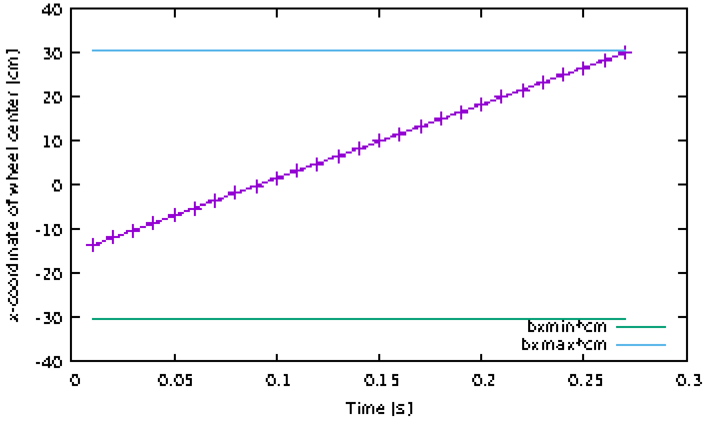
Sinkage:



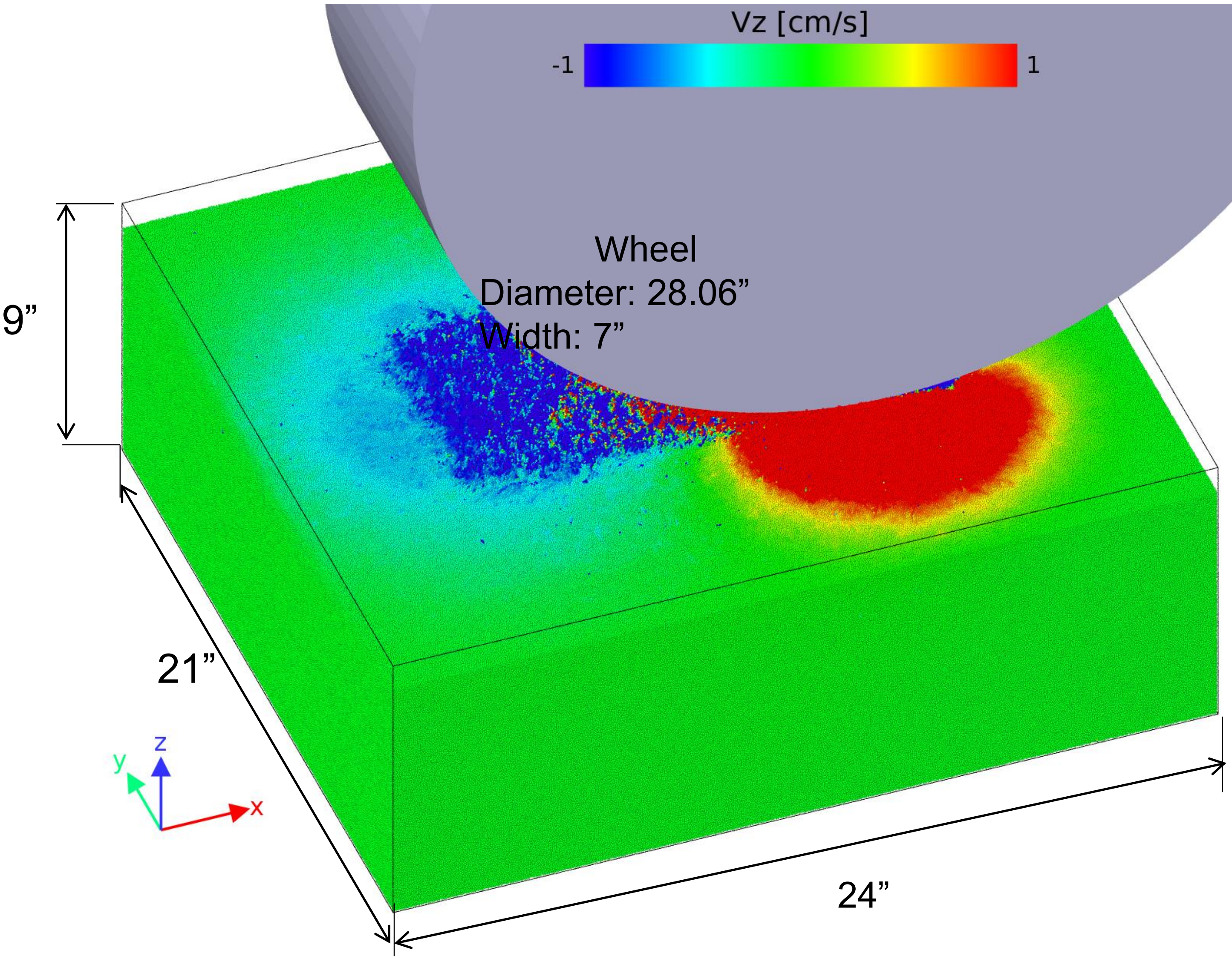
Traction:



X-coordinate:

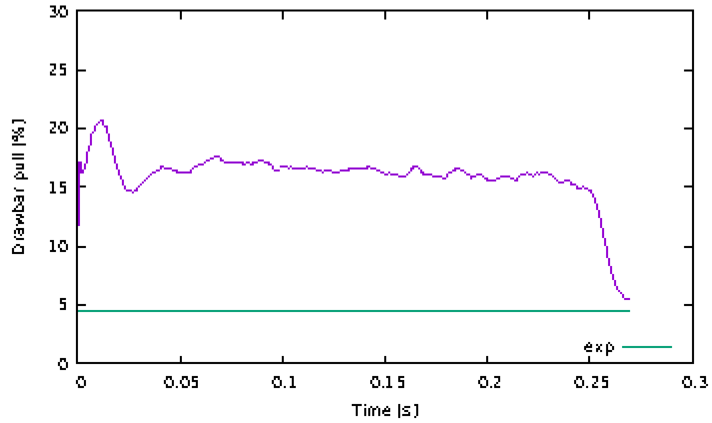


Smallest solid rubber wheel from DROVE - refined wheel surface facets

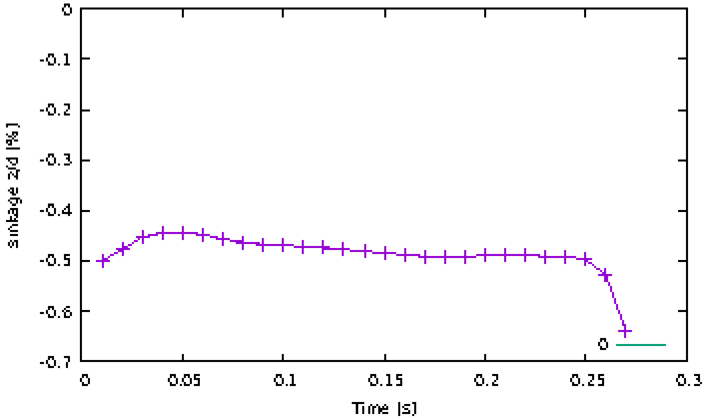


28.06” wheel
smallest solid rubber wheel in DROVE database: drawbar pull, traction, and sinkage

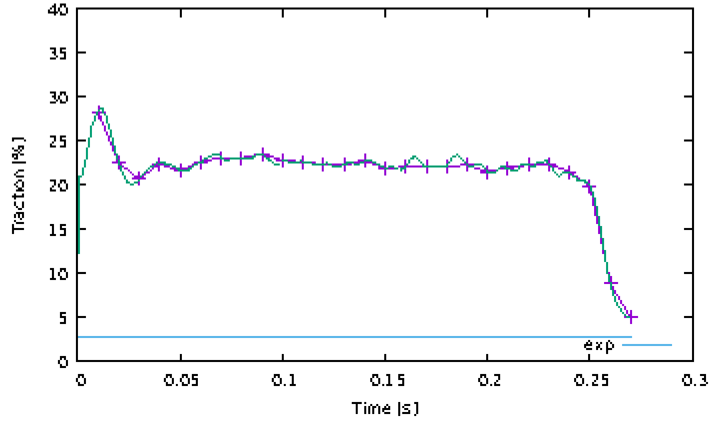
Drawbar pull:



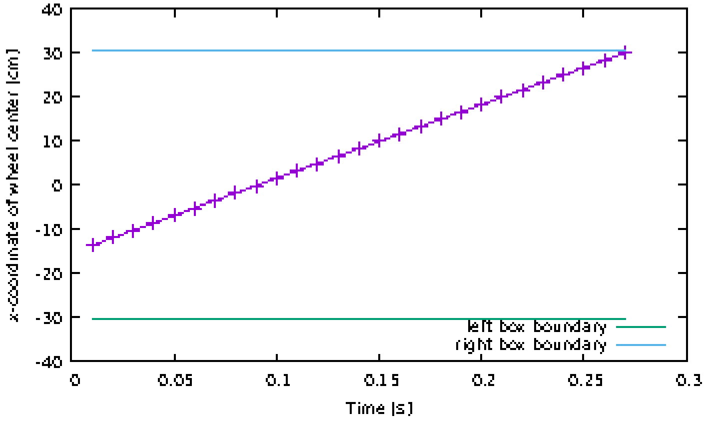
Sinkage:



Traction:

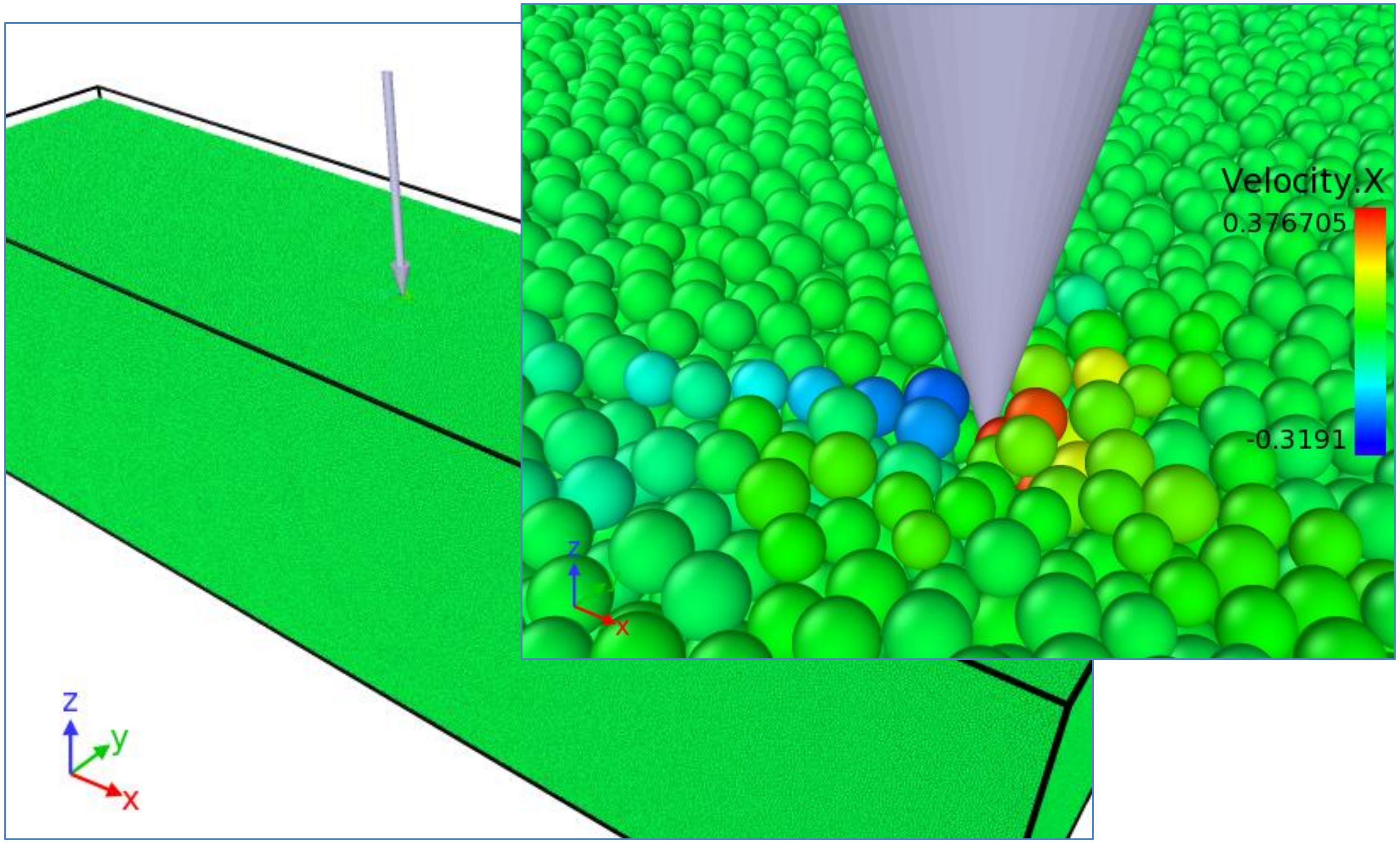


X-coordinate:



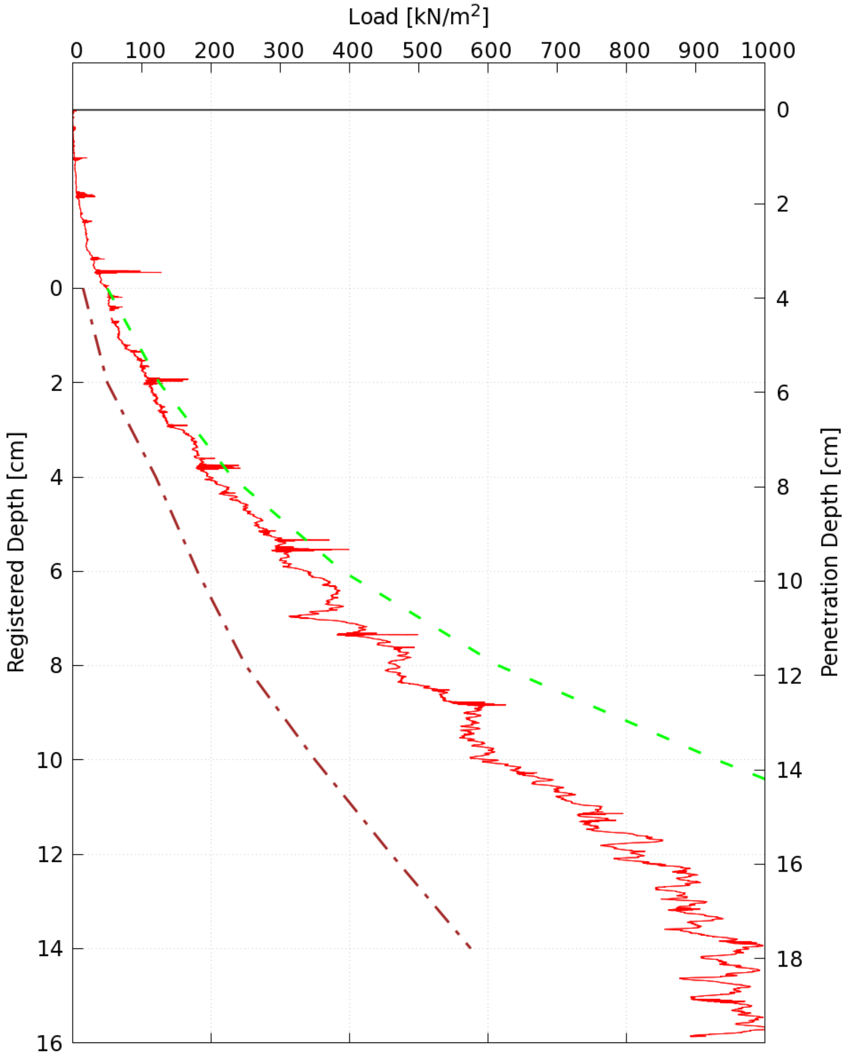
Cone penetrometer test
large particle beds

Shadow @ MSU HPCC,
200 cores, ~3 hours per 0.05 s step.

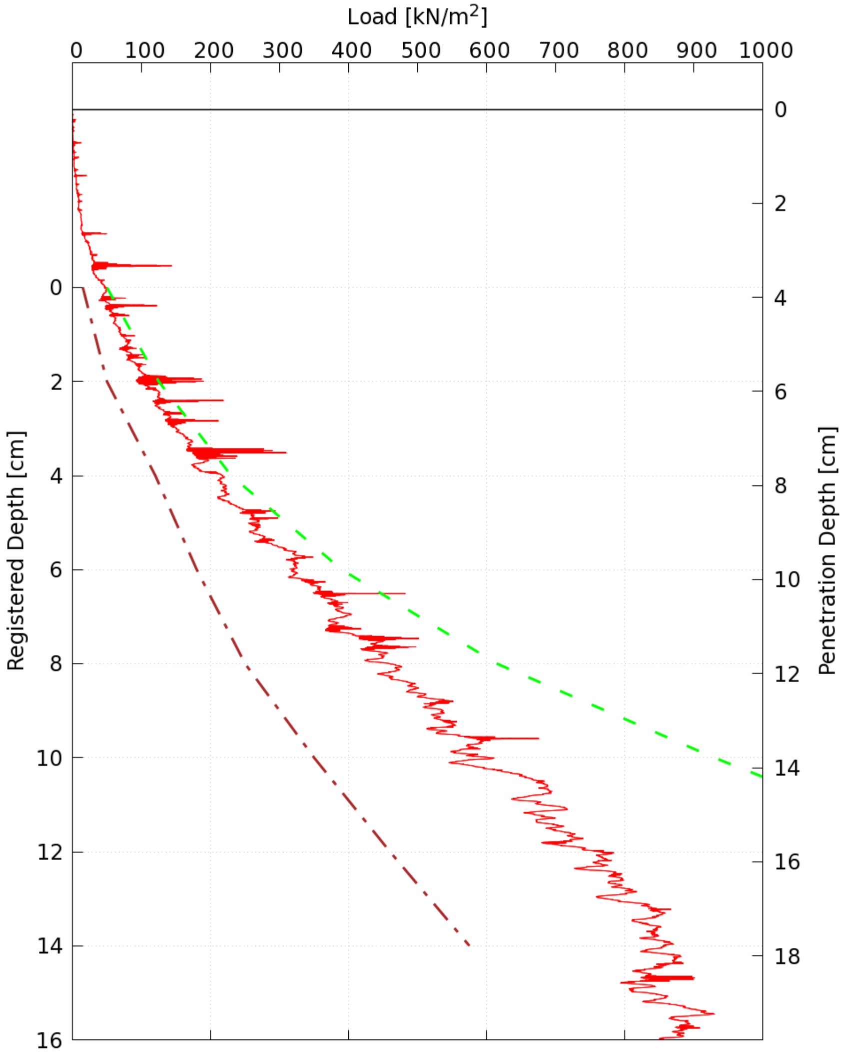


Cone penetrometer test large particle beds

24 x 21 x 8.75 in^3



48 x 21 x 8.75 in^3



Conclusions

Coupled DEM-LBM model of shear thickening in fluid-particle suspensions demonstrates capability to model fluid-soil interaction

Discrete Element Method can qualitatively predict pull-slip relationship for a wheel in granular media

Calibration and validation of DEM parameters is of utmost importance

ERDC HPCMP computational resources provide invaluable tool for large scale DEM/LBM studies

Acknowledgments

DEM code origin: ERDC - John Peters, David Horner, Alex Carrillo

LBM code origin: MSU - Sergio Felicelli, Hebi Yin

LBM parallelization, HDF5 output and restart, DEM and LBM visualization: Bohumir Jelinek

DEM calibration: Clay Goodman

Experimental guide, DROVE database: George Mason, Farshid Vahedifard, Jody Priddy

LBM-DEM coupling: Bohumir Jelinek, Daniel Johnson