Chrono::Parallel

Overview of the Chrono::Parallel module

What is Chrono::Parallel?

A software library for OpenMP-based parallel simulation of Chrono models

- Middleware: can be embedded in third parties software
- Open source with BSD license
- Library developed in C++ (requires C++11)
- Cross-platform: compiles on GNU GCC, MSVC, etc.

Relationship to Chrono::Engine

- Chrono-Parallel relies on Chrono for all its modeling capabilities
- Supports a subset of Chrono modeling elements:
  - Rigid bodies with frictional contact (DEM-C or DEM-P)
  - Kinematic joints (revolute, spherical, translational, etc.)
  - Force elements (spring-dampers, actuators, etc.)
  - 1-D shafts and associated elements and constraints (shaft-body connection, gears, motors, etc.)
- No support for FEA
- Implements only the *Implicit Euler Linearized* time-stepper

- Chrono-Parallel uses different data structures and algorithms

Data structures and algorithms

Chrono-Parallel uses structures of arrays (SOA) as opposed to arrays of structures (AOS)

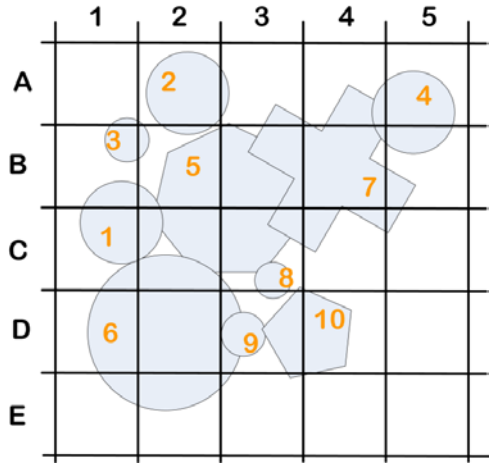
- OpenMP parallel for loops

- Thrust (with OMP backend)
  - parallel algorithms library (sort, scan, reductions, etc.)
  - Interface similar to the C++ STL
  - https://code.google.com/p/thrust/

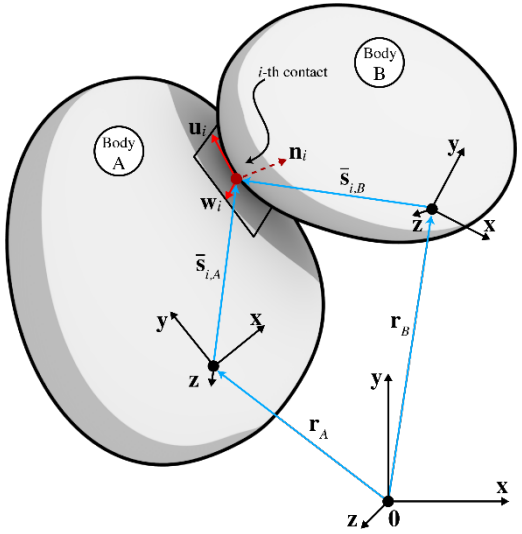
- Blaze
  - High-performance (dense and) sparse matrix operations
  - Smart Expression Template implementation
  - https://code.google.com/p/blaze-lib/

Collision detection

- Broad phase
  - Based on binning with AABBs
  - Adaptive 2-level hierarchical grid



- Narrow phase
  - Different options:
    - MPR (Minkovski Portal Refinement)
    - GJK (Gilbert-Johnson-Keerthi)
    - SAT (Separating Axis Theorem)
  - Hybrid option (SAT with fallback to MPR)



User code

- New type of ChSystem:

```
ChSystemParallelNSC system;
```

or

```
ChSystemParallelSMC system;
```

- Create elements in the mechanical system using Chrono::Engine functions

- Specify solver settings by directly accessing the structures

```
ChSystemParallel::GetSettings()->solver
```

and

```
ChSystemParallel::GetSettings()->collision
```

- Advance simulation by invoking

```
chrono::ChSystem::DoStepDynamics()
```

or

```
chrono::opengl::ChOpenGLWindow::DoStepDynamics()
```

User code – solver settings (DEM-C)

```
system.GetSettings()->perform_thread_tuning = false;

system.GetSettings()->solver.solver_mode = SolverMode::SLIDING;
system.GetSettings()->solver.max_iteration_normal = 0;
system.GetSettings()->solver.max_iteration_sliding = 200;
system.GetSettings()->solver.max_iteration_spinning = 0;
system.GetSettings()->solver.max_iteration_bilateral = 50;
system.GetSettings()->solver.tolerance = 0.1;
system.GetSettings()->solver.alpha = 0;
system.GetSettings()->solver.contact_recovery_speed = 10000;

system.ChangeSolverType(SolverType::APGD);

system.GetSettings()->collision.narrowphase_algorithm = NarrowPhaseType::NARROWPHASE_HYBRID_MPR;
system.GetSettings()->collision.collision_envelope = 0.01;
system.GetSettings()->collision.bins_per_axis = vec3(10, 10, 10);
```

User code – solver settings (DEM-P)

```
system.GetSettings()->perform_thread_tuning = false;

system.GetSettings()->solver.max_iteration_bilateral = 50;
system.GetSettings()->solver.tolerance = 0.1;

system.GetSettings()->solver.contact_force_model = ChSystemSMC::ContactForceModel::Hertz
system.GetSettings()->solver.tangential_displ_mode = ChSystemSMC::TangentialDisplacementModel::MultiStep;

system.GetSettings()->collision.narrowphase_algorithm = NarrowPhaseType::NARROWPHASE_HYBRID_MPR;
system.GetSettings()->collision.bins_per_axis = vec3(10, 10, 10);
```

Chrono utilities for granular dynamics

Chrono utilities

- Samplers for granular dynamics
  - Uniform grid, Poisson-disk sampling, hexagonal close packing
  - Sampling of different domains (box, sphere, cylinder)
  - Allows 2D sampling (rectangle, disk)
- Generators for granular dynamics
  - Create particles, using a given sampler, randomly selecting from a mixture of ingredients with prescribed expectation
  - Mixture ingredient: multivariate normal distributions for particle size and contact material properties

- Convenience functions for creating bodies with simple geometry (contact and graphics)
- Utilities for file I/O, output for POV-Ray post-processing, etc.
- Utilities for validation using golden files, data filtering, etc.

- Classes and free functions implemented in the `chrono::utils` namespace

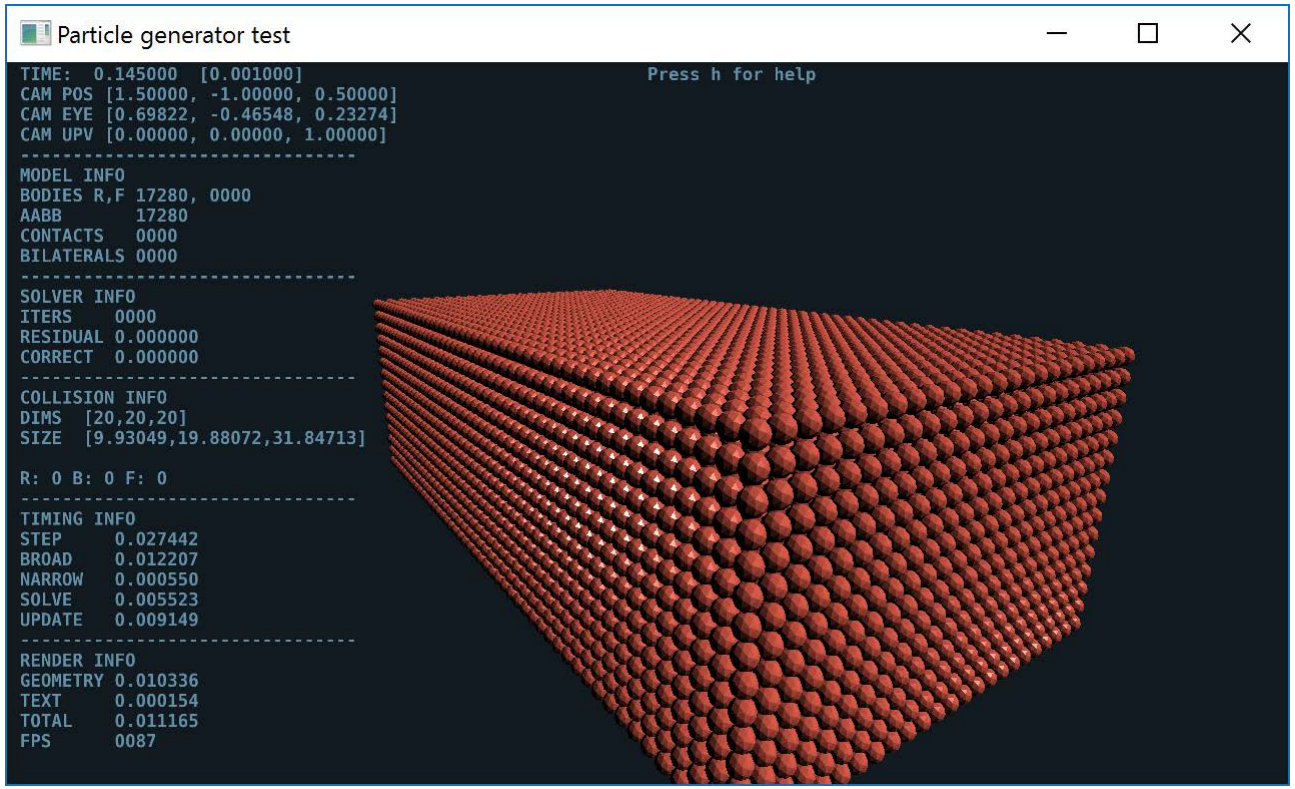
Volume sampling

- `chrono::utils::PDSampler`
  - generates points in 3D domains (box, sphere, or cylinder) using Poisson Disk Sampling. The sampler produces a set of points uniformly distributed in the specified domain such that no two points are closer than a specified distance.
  - based on "Fast Poisson Disk Sampling in Arbitrary Dimensions" by Robert Bridson http://people.cs.ubc.ca/~rbridson/docs/bridson-siggraph07-poissondisk.pdf

- `chrono::utils::GridSampler`
  - generates points in 3D or 2D domain with constant grid spacing
  - grid spacing can be different in the 3 directions

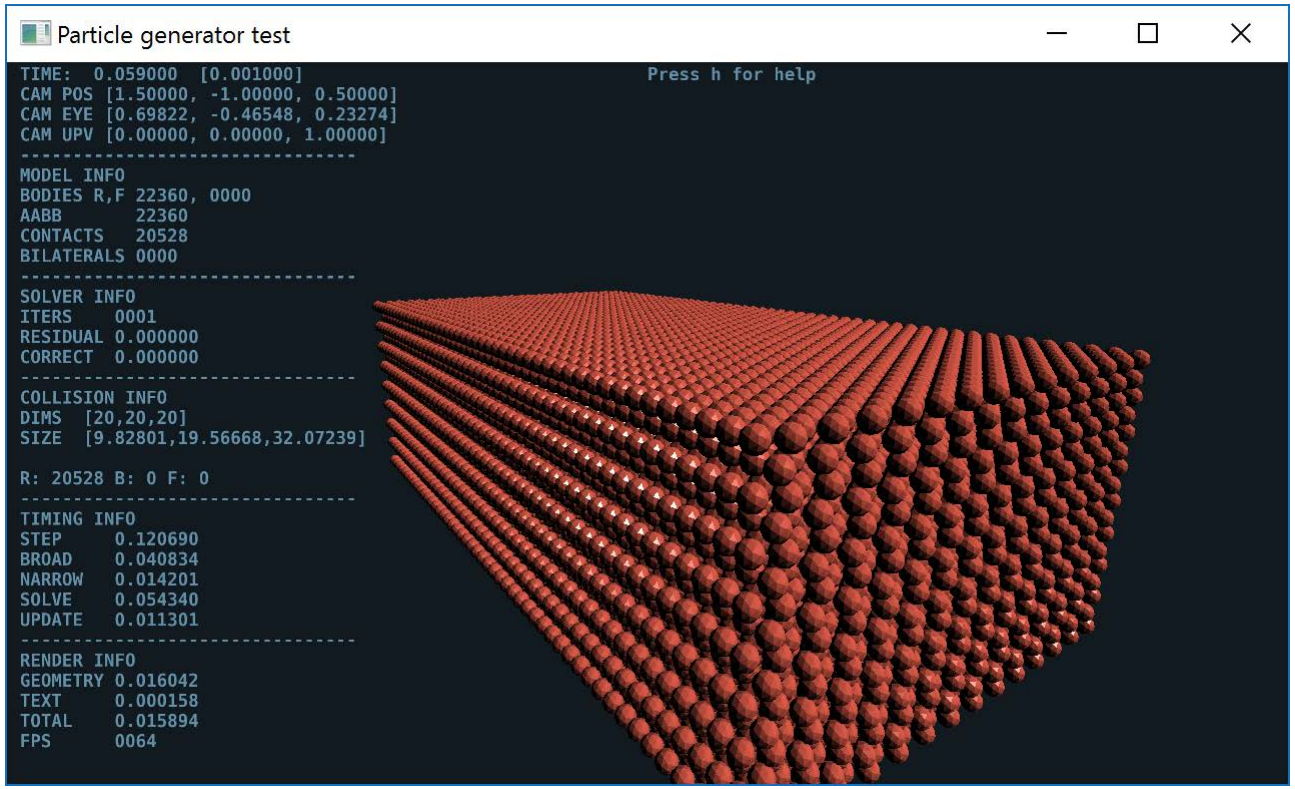
- `chrono::utils::HCPSampler`
  - generates points in a hexagonally close packed structure

Sampling – regular grid

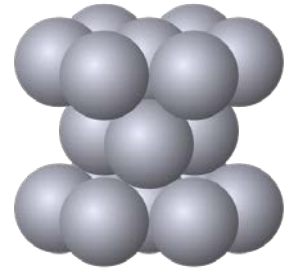



```
utils::Generator gen(system);

std::shared_ptr<utils::MixtureIngredient> m1 = gen.AddMixtureIngredient(utils::SPHERE, 1.0);
m1->setDefaultSize(radius_g);

double r = 1.05 * radius_g;
gen.createObjectsBox(utils::REGULAR_GRID, 2 * r, ChVector<>(0, 0, 0), ChVector<>(1, 0.5, 0.3));
```

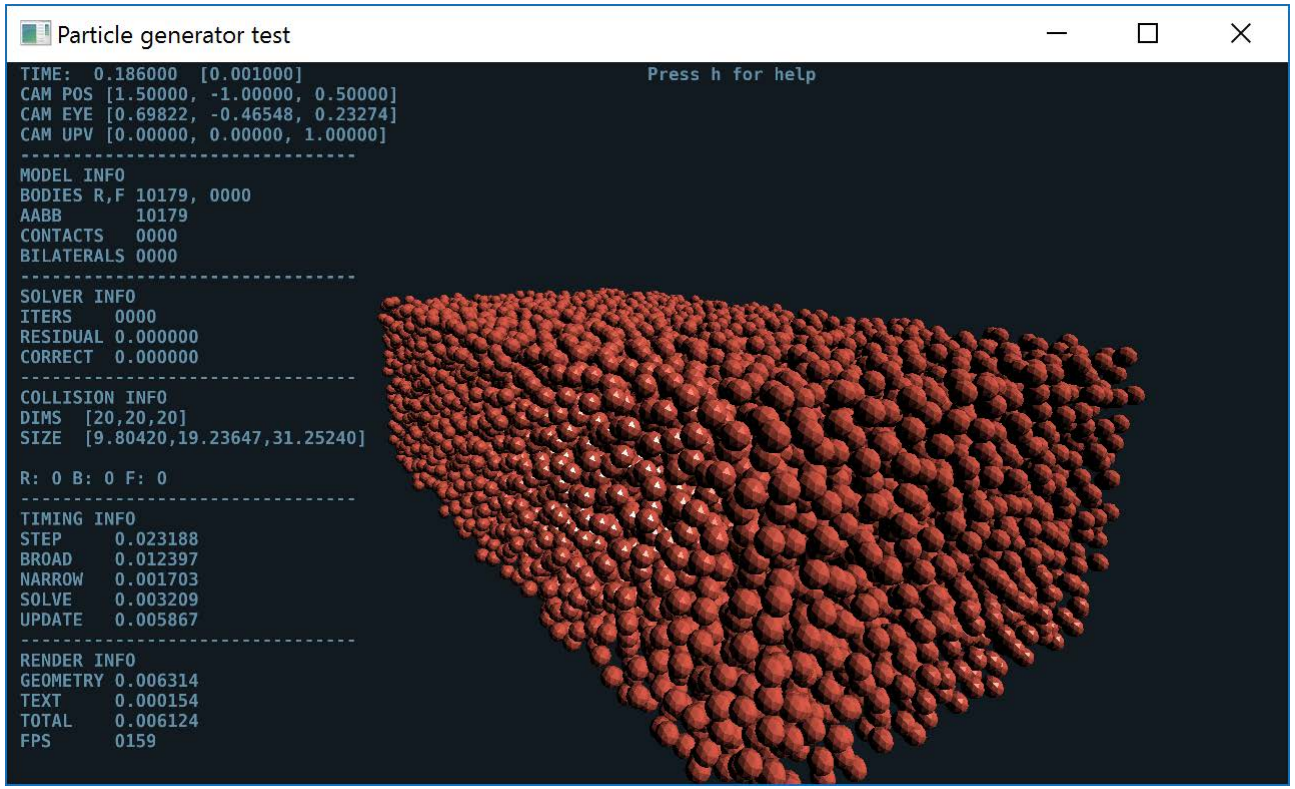
Sampling – hexagonal close packing




```
utils::Generator gen(system);

std::shared_ptr<utils::MixtureIngredient> m1 = gen.AddMixtureIngredient(utils::SPHERE, 1.0);
m1->setDefaultSize(radius_g);

double r = 1.05 * radius_g;
gen.createObjectsBox(utils::HCP_PACK, 2 * r, ChVector<>(0, 0, 0), ChVector<>(1, 0.5, 0.3));
```

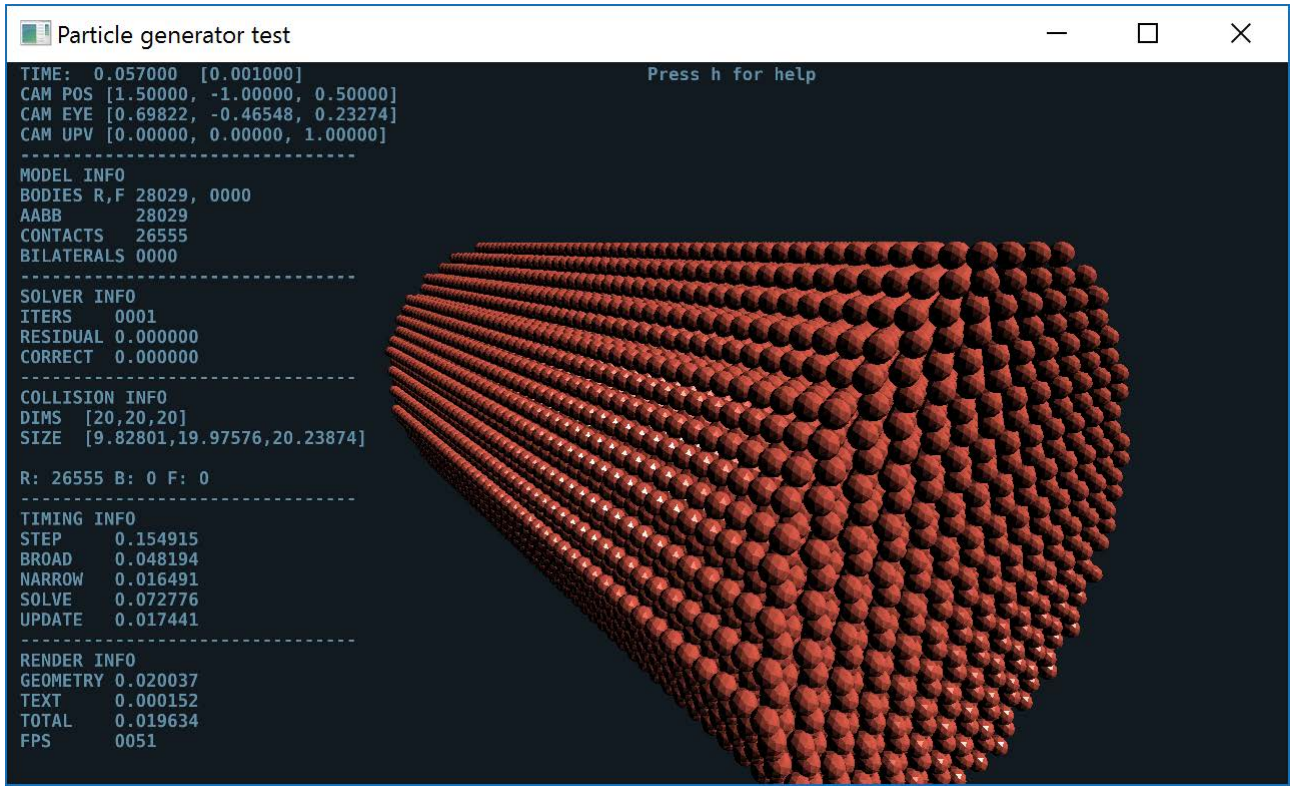


Sampling – Poisson disc




```
utils::Generator gen(system);

std::shared_ptr<utils::MixtureIngredient> m1 = gen.AddMixtureIngredient(utils::SPHERE, 1.0);
m1->setDefaultSize(radius_g);

double r = 1.05 * radius_g;
gen.createObjectsBox(utils::POISSON_DISK, 2 * r, ChVector<>(0, 0, 0), ChVector<>(1, 0.5, 0.3));
```

Sampling of cylindrical volume



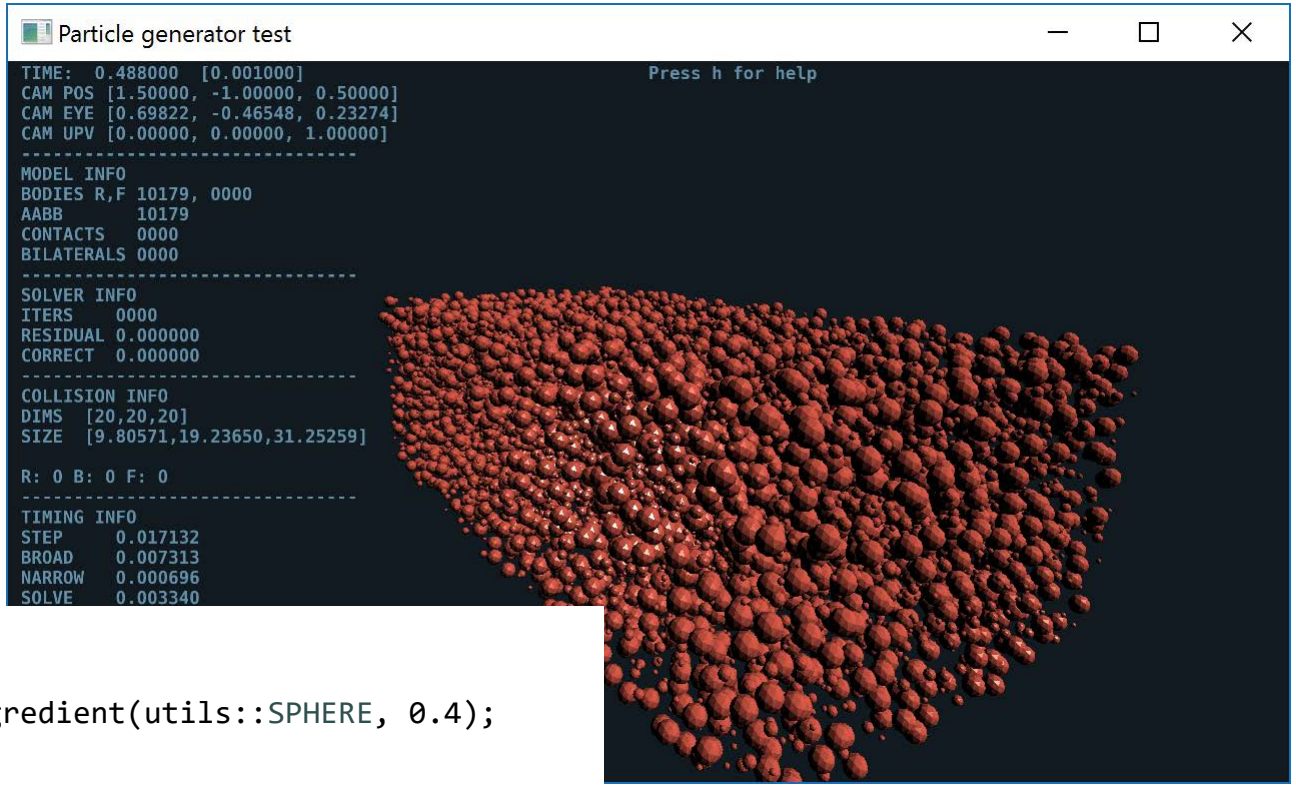

```
utils::Generator gen(system);

std::shared_ptr<utils::MixtureIngredient> m1 = gen.AddMixtureIngredient(utils::SPHERE, 1.0);
m1->setDefaultSize(radius_g);

double r = 1.05 * radius_g;
gen.createObjectsCylinderX(utils::HCP_PACK, 2 * r, ChVector<>(0, 0, 0), 0.5, 1);
```

Mixtures of ingredients

- `chrono::utils::MixtureIngredient`
  - models an ingredient of given shape (`chrono::utils::MixtureType`) in a granular material mixture
  - specifies object size/scaling (constant or drawn from user-defined distribution)
  - specifies material properties (constant or drawn from user-defined distributions)
  - defines the ratio for this particular ingredient in a mixture
  - uses truncated normal distributions

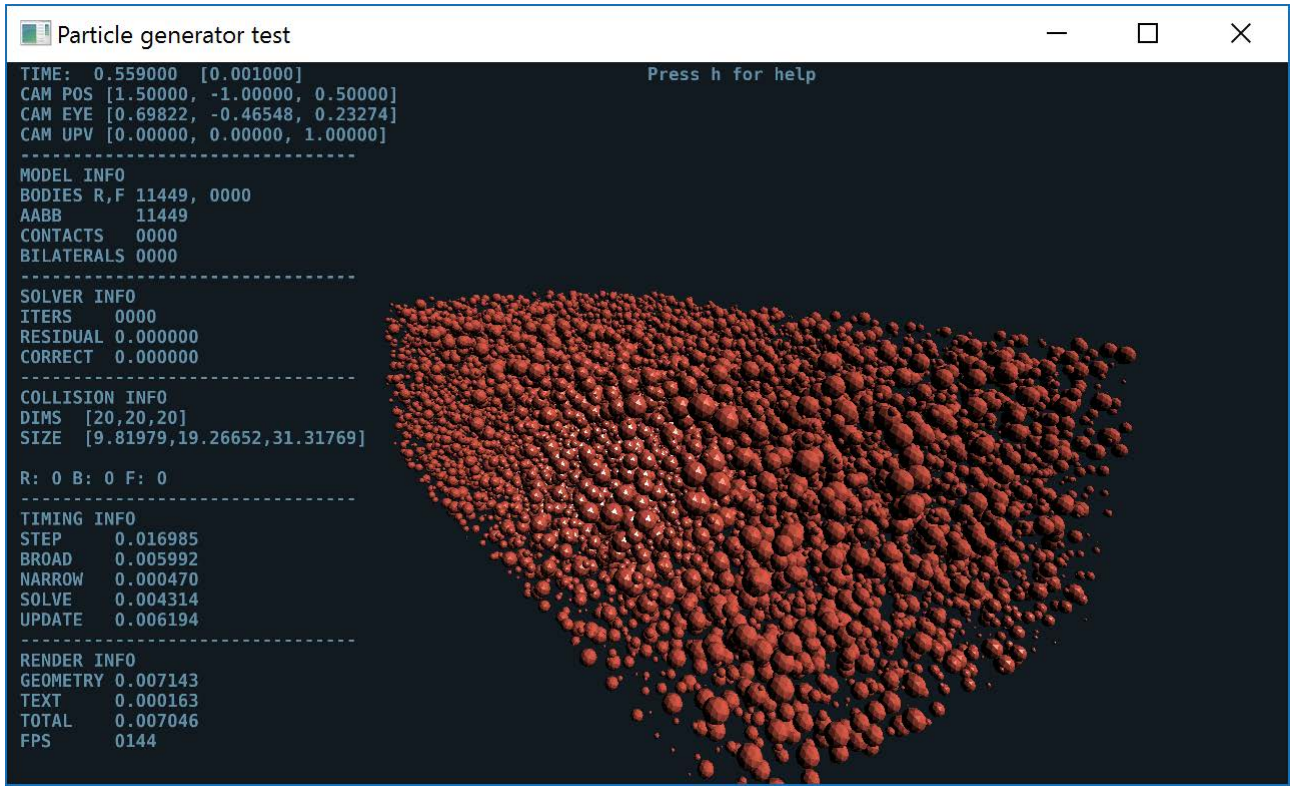
- `chrono::utils::Generator`
  - generates objects in a specified volume (box or cylinder), drawing from a uniform distribution over a mixture of ingredients
  - particle locations are generated with a user-specified sampling method (REGULAR_GRID, HCP_PACK, POISSON_DISK)
  - allows degenerate sampling volumes (i.e., rectangle or circle)

Mixing different sizes (pre-set)



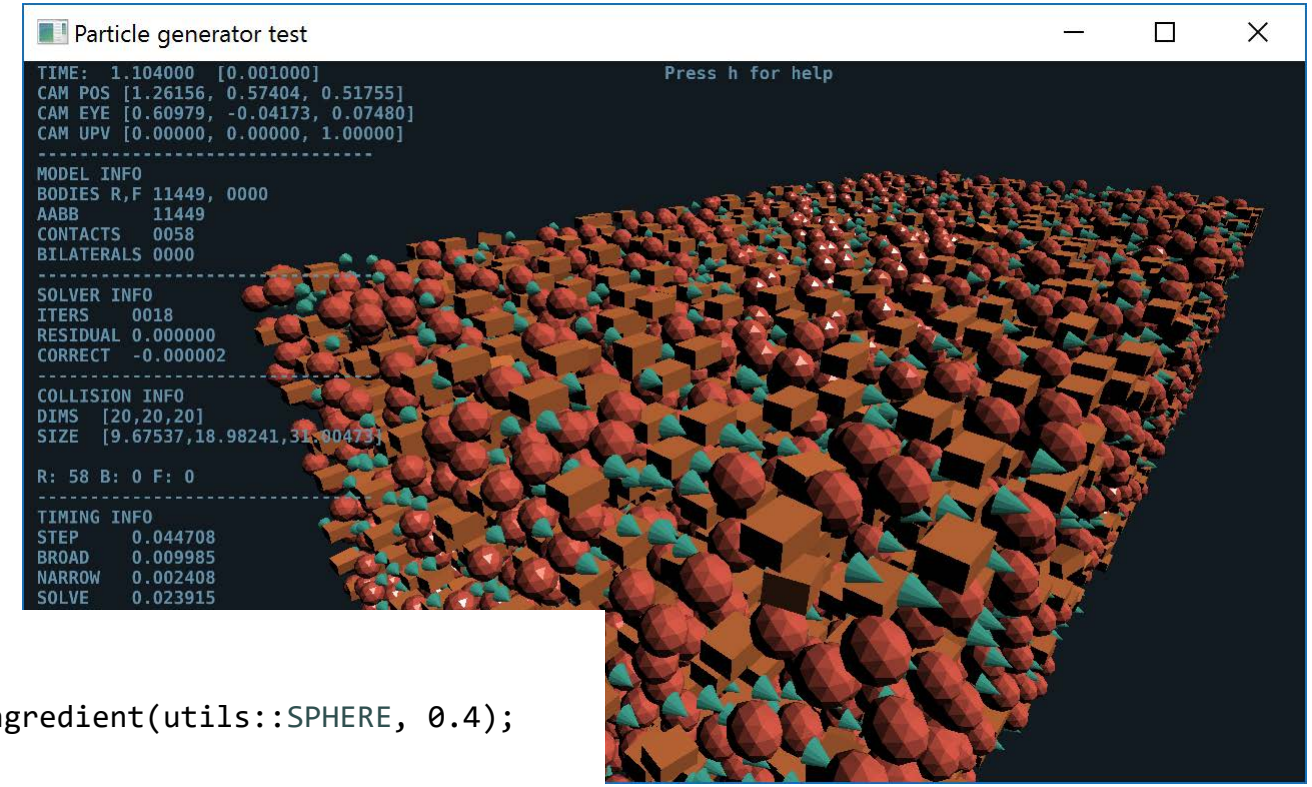

```
utils::Generator gen(system);

std::shared_ptr<utils::MixtureIngredient> m1 = gen.AddMixtureIngredient(utils::SPHERE, 0.4);
m1->setDefaultDensity(rho_g);
m1->setDefaultSize(radius_g);
std::shared_ptr<utils::MixtureIngredient> m2 = gen.AddMixtureIngredient(utils::SPHERE, 0.3);
m2->setDefaultDensity(rho_g);
m2->setDefaultSize(0.5 * radius_g);
std::shared_ptr<utils::MixtureIngredient> m3 = gen.AddMixtureIngredient(utils::SPHERE, 0.3);
m3->setDefaultDensity(rho_g);
m3->setDefaultSize(0.25 * radius_g);

double r = 1.01 * radius_g;
gen.createObjectsBox(utils::POISSON_DISK, 2 * r, ChVector<>(0, 0, 0), ChVector<>(1, 0.5, 0.3));
```

Mixing different sizes (from distribution)



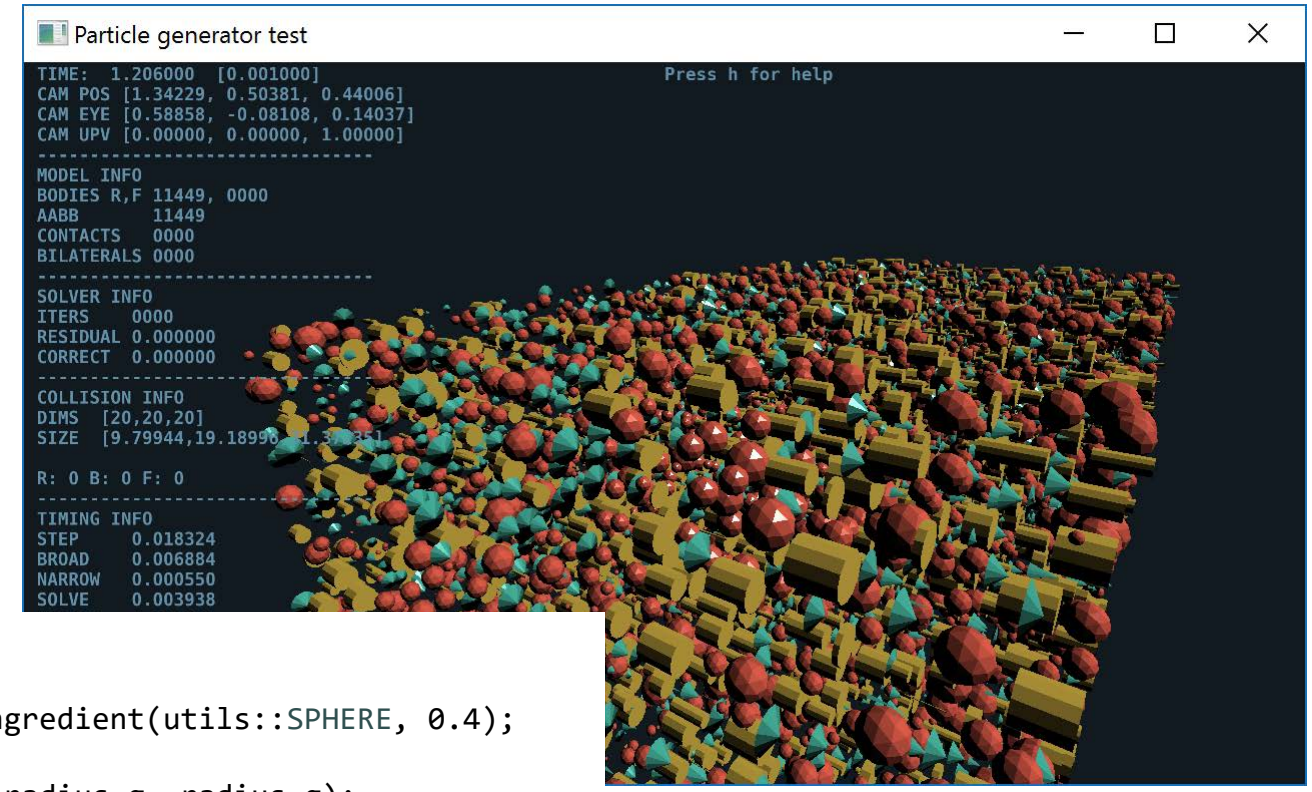

```
utils::Generator gen(system);

std::shared_ptr<utils::MixtureIngredient> m1 = gen.AddMixtureIngredient(utils::SPHERE, 1.0);
m1->setDefaultDensity(rho_g);
m1->setDistributionSize(0.5 * radius_g, 0.5 * radius_g, 0.01 * radius_g, radius_g);

double r = 1.01 * radius_g;
gen.createObjectsBox(utils::POISSON_DISK, 2 * r, ChVector<>(0, 0, 0), ChVector<>(1, 0.5, 0.3));
```

Mixing different shapes




```
utils::Generator gen(system);

std::shared_ptr<utils::MixtureIngredient> m1 = gen.AddMixtureIngredient(utils::SPHERE, 0.4);
m1->setDefaultDensity(rho_g);
m1->setDefaultSize(radius_g);
std::shared_ptr<utils::MixtureIngredient> m2 = gen.AddMixtureIngredient(utils::BOX, 0.3);
m2->setDefaultDensity(rho_g);
m2->setDefaultSize(ChVector<>(radius_g, 0.7 * radius_g, 0.5 * radius_g));
std::shared_ptr<utils::MixtureIngredient> m3 = gen.AddMixtureIngredient(utils::CONE, 0.3);
m3->setDefaultDensity(rho_g);
m3->setDefaultSize(ChVector<>(0.5 * radius_g, radius_g, 0.75 * radius_g));

double r = 1.01 * radius_g;
gen.createObjectsBox(utils::POISSON_DISK, 2 * r, ChVector<>(0, 0, 0), ChVector<>(1, 0.5, 0.3));
```

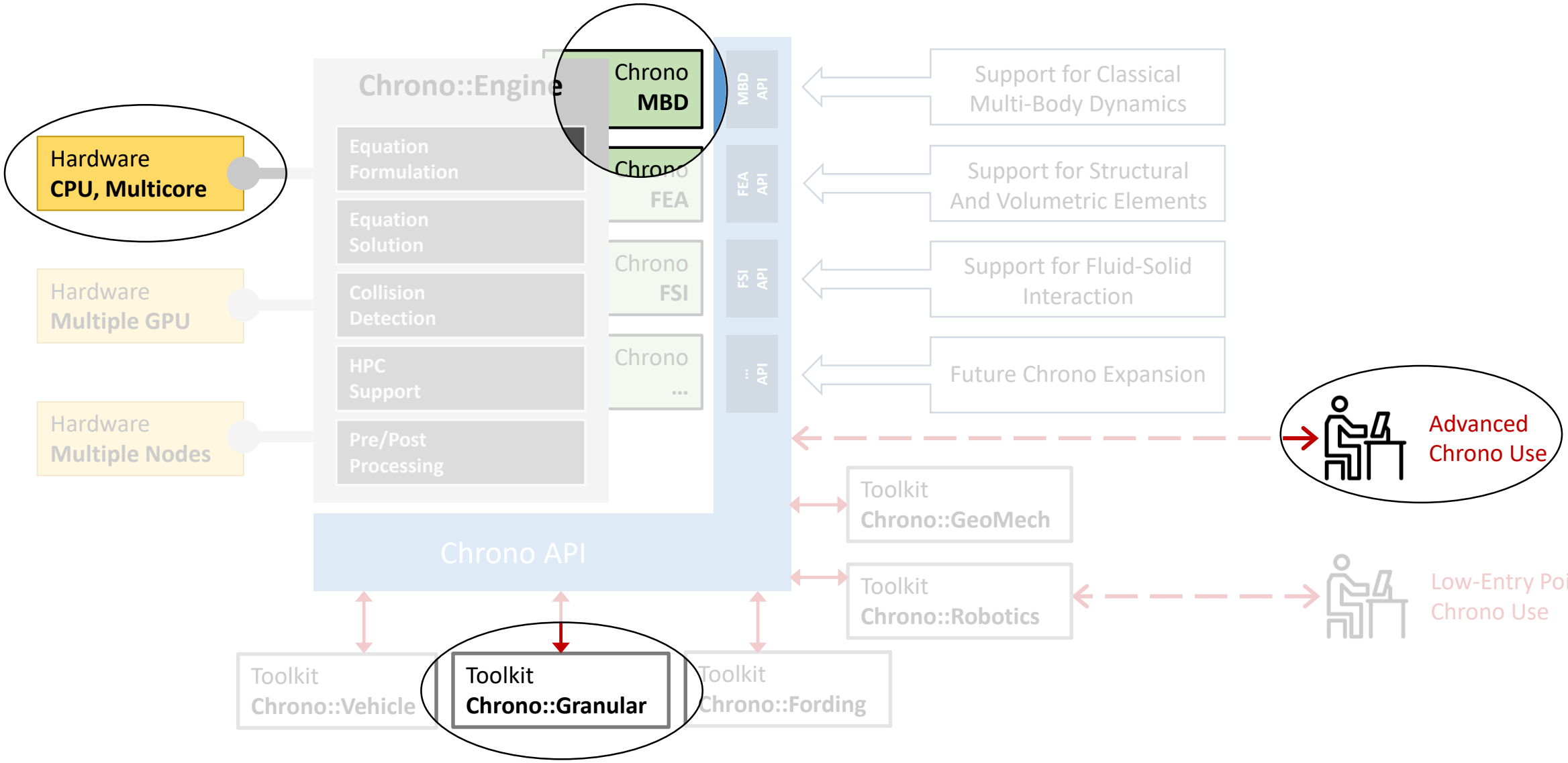
Mixing shapes and sizes




```
utils::Generator gen(system);

std::shared_ptr<utils::MixtureIngredient> m1 = gen.AddMixtureIngredient(utils::SPHERE, 0.4);
m1->setDefaultDensity(rho_g);
m1->setDistributionSize(0.5 * radius_g, 0.5 * radius_g, 0.01 * radius_g, radius_g);
std::shared_ptr<utils::MixtureIngredient> m2 = gen.AddMixtureIngredient(utils::CONE, 0.3);
m2->setDefaultDensity(rho_g);
m2->setDistributionSize(0.5 * radius_g, 0.5 * radius_g, 0.01 * radius_g, radius_g);
std::shared_ptr<utils::MixtureIngredient> m3 = gen.AddMixtureIngredient(utils::CYLINDER, 0.3);
m3->setDefaultDensity(rho_g);
m3->setDistributionSize(0.5 * radius_g, 0.5 * radius_g, 0.01 * radius_g, radius_g);

double r = 1.01 * radius_g;
gen.createObjectsBox(utils::POISSON_DISK, 2 * r, ChVector<>(0, 0, 0), ChVector<>(1, 0.5, 0.3));
```

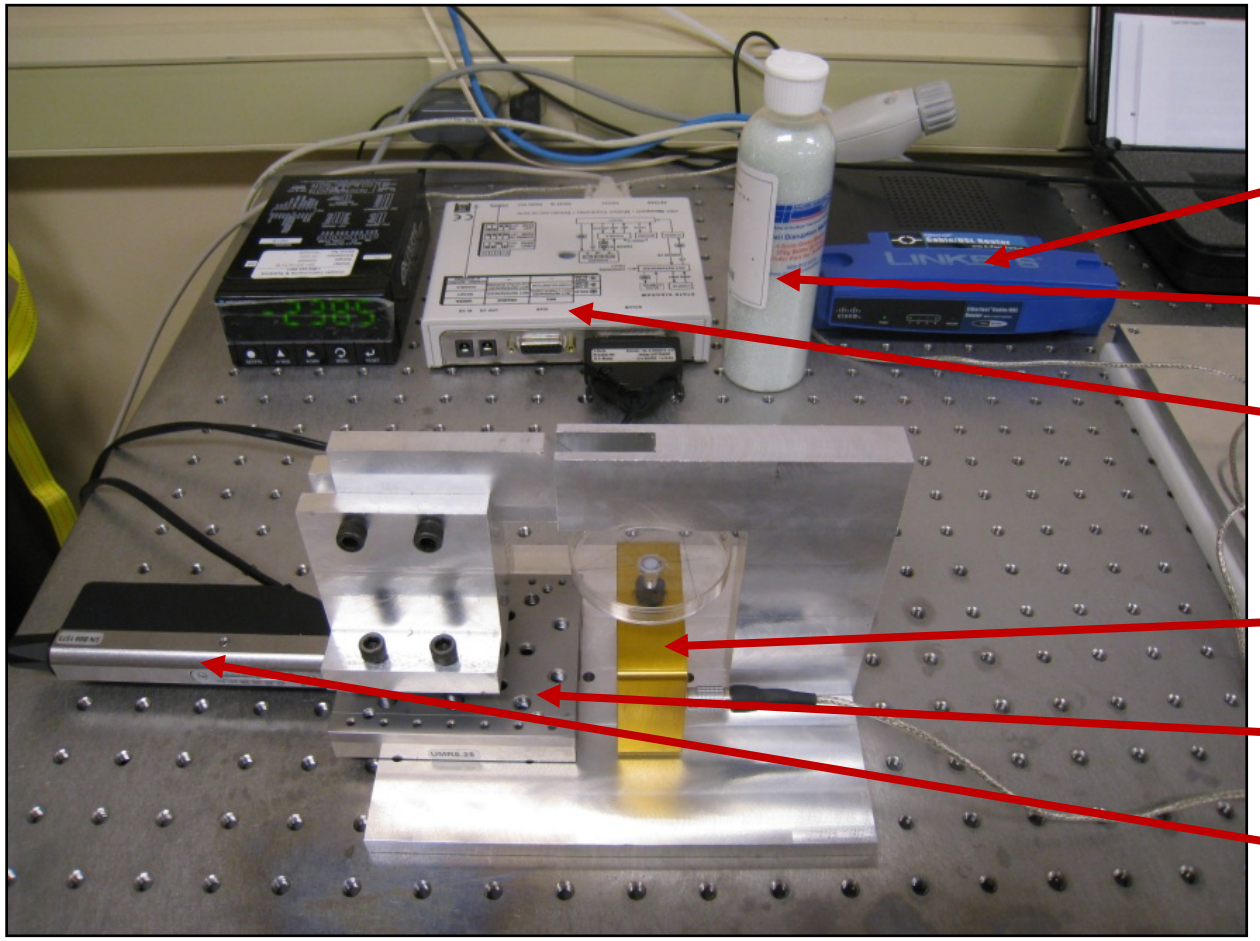
Validation studies for granular dynamics

Chrono structure



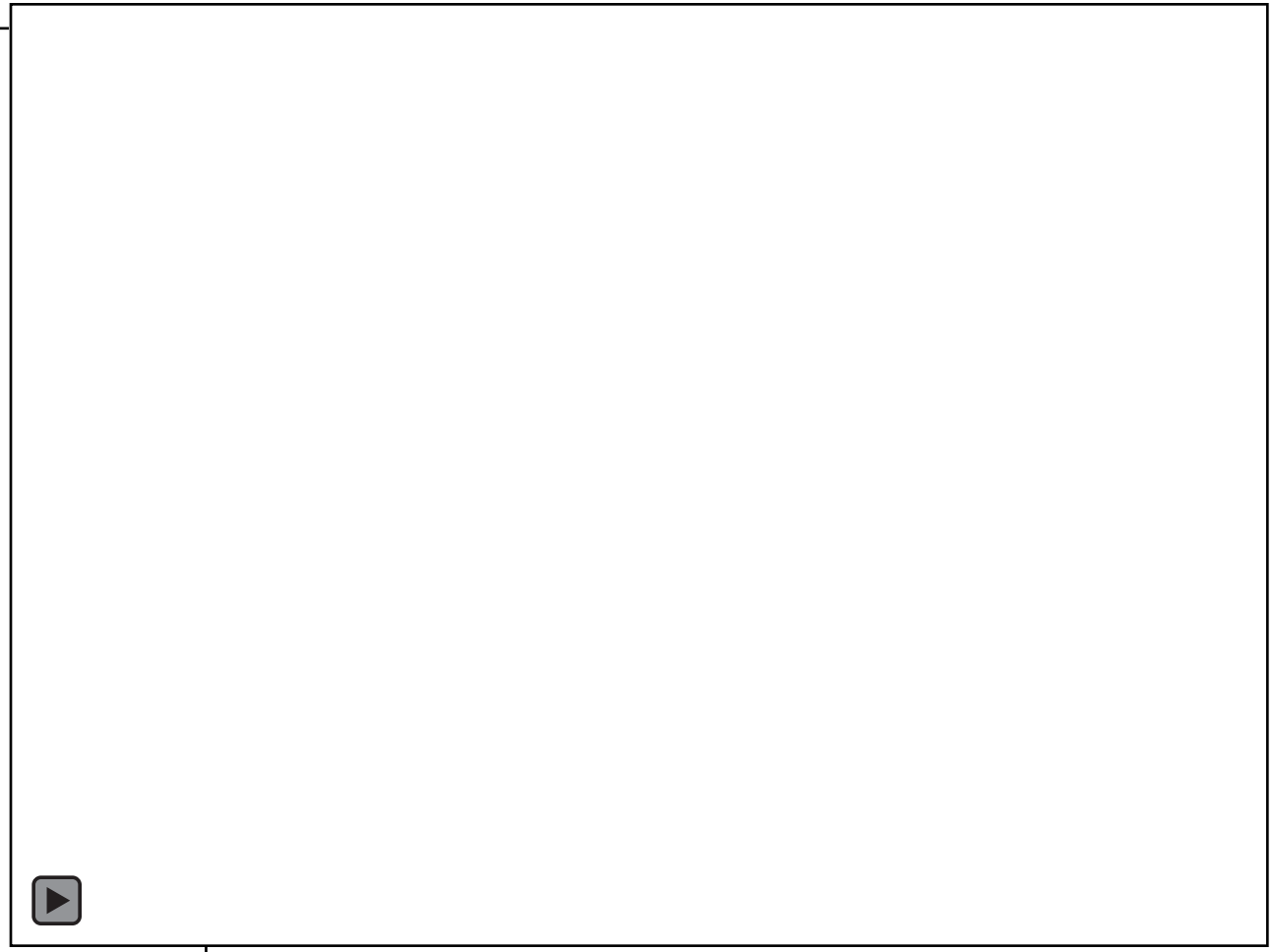
Validation Studies
Mass flow rate experiment

Experimental setup



"On the Modeling, Simulation, and Visualization of Many-Body Dynamics Problems with Friction and Contact," T. Heyn, PhD Thesis, 2013

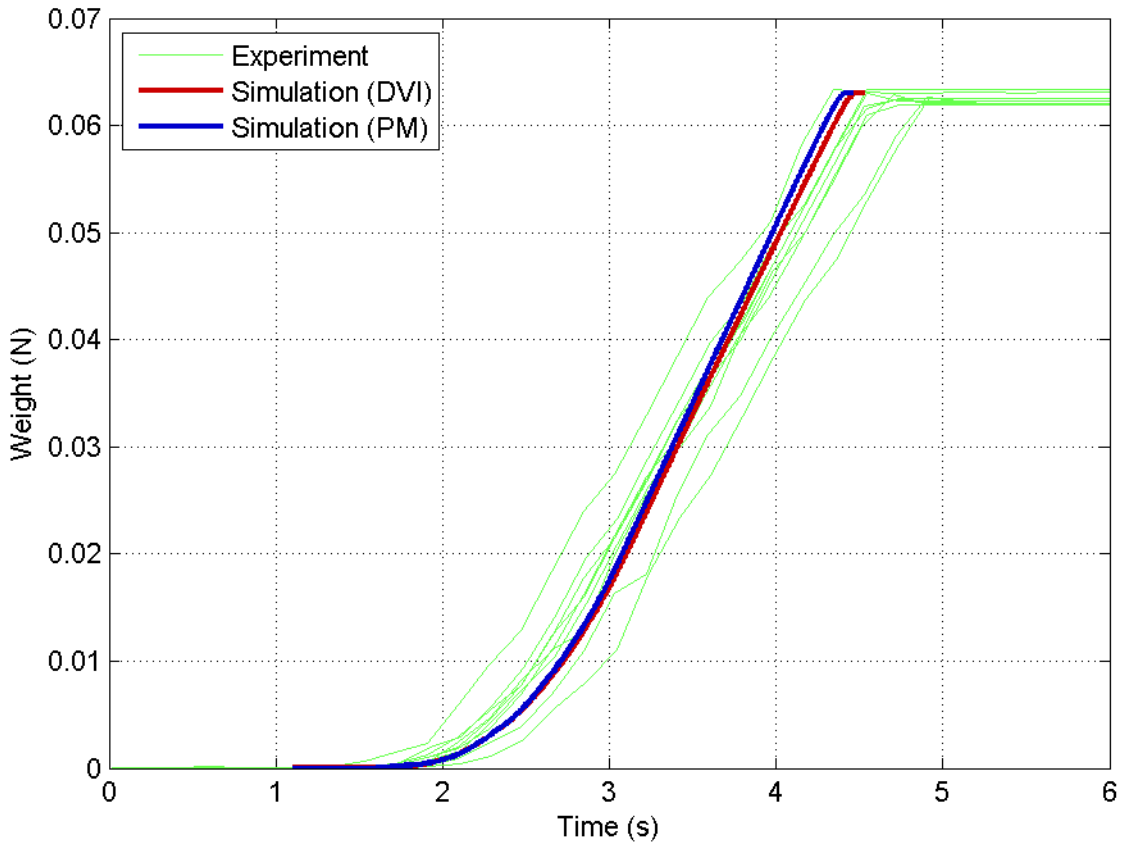
Flow Rate – 500 micron spheres



Simulation results and validation

- Total mass of granular material: 6.38 g
- Width of opening: 9.4 mm
- Opening speed: 1 mm/s
- Maximum opening gap: 2 mm

- Simulation with Chrono::Parallel



"A Comparison of Penalty and Complementarity Approaches to Discrete Element Method Simulations," R. Serban, D. Melanz, P. Jayakumar, D. Negrut, in preparation, 2016

Method comparison

Problem

- 39,000 particles
- 2 mm gap size
- 40 OpenMP threads
- $r = 0.25 \cdot 10^{-3}$ m
- $\mu = 0.3$

Complementarity

- Step-size: 10^{-4} s
- Cost per step: 0.423 s
  - Collision detection: 0.054 s
  - Update: 0.010 s
  - Solver: 0.359 s
- Average number contacts: 140,000

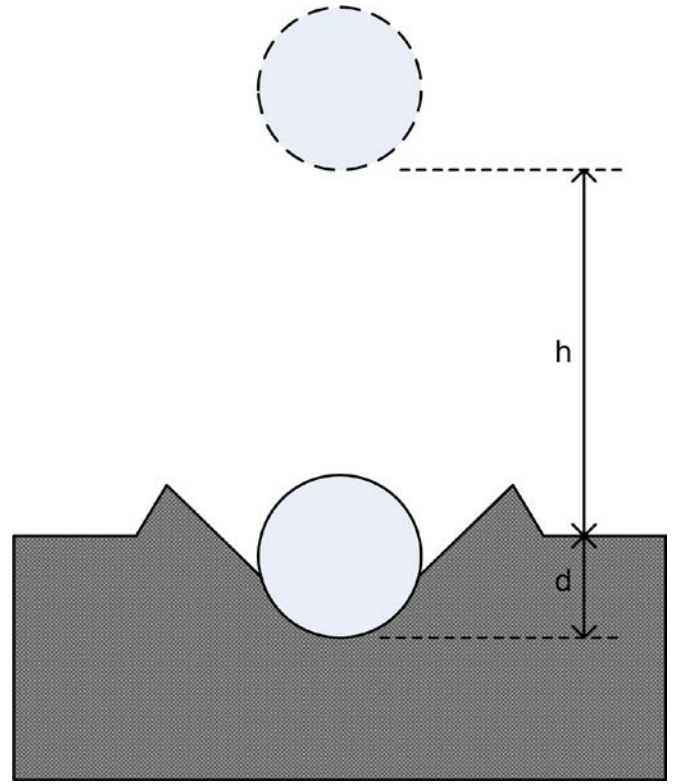
Penalty

- Step-size: 10^{-5} s
- Cost per step: 0.054 s
  - Collision detection: 0.026 s
  - Update: 0.010 s
  - Solver: 0.016 s
- Average number contacts: 118,400

Validation Studies
Low-speed impact cratering

Experimental setup

- Experiment:
  - Measured penetration of spherical projectiles into loose non-cohesive granular media
  - Parameters: ρ_b, D_b, h, ρ_g, μ
- Simulations:
  - ρ_g =1.51 g/cm^3, D_b=2.54 cm, μ=0.3, and 1 mm grains
  - h={5,10,20} cm, ρ_b={0.28,0.7,2.2} g/cm^3



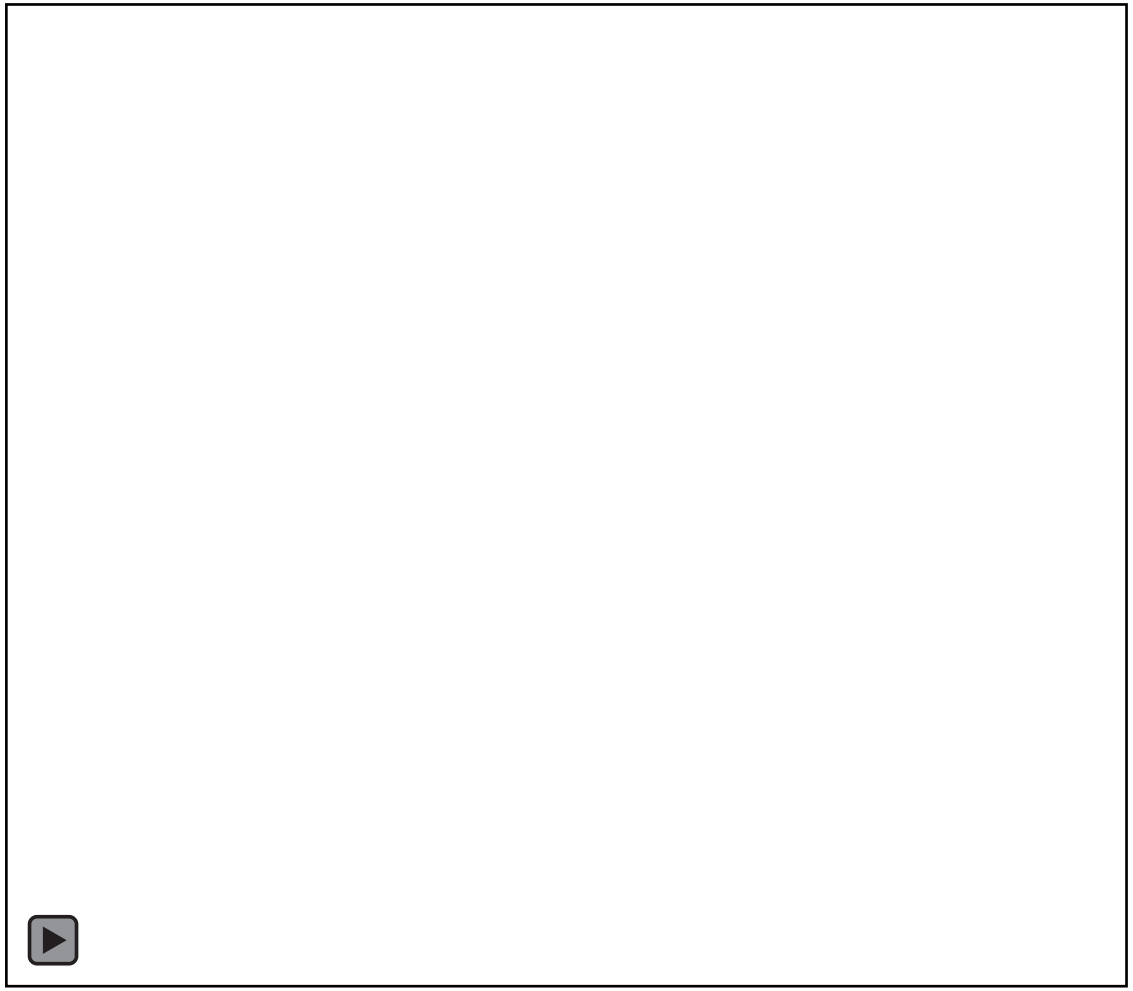
"Low-speed impact craters in loose granular media," J. S. Uehara, M. A. Ambroso, R. P. Ojha, D. J. Durian, Phys. Rev. Lett., 90:194301, 2003.
"Scaling of impact craters in unconsolidated granular materials," D. Dowling, T. Dowling, American Journal of Physics, 81, 2013

Impact simulation

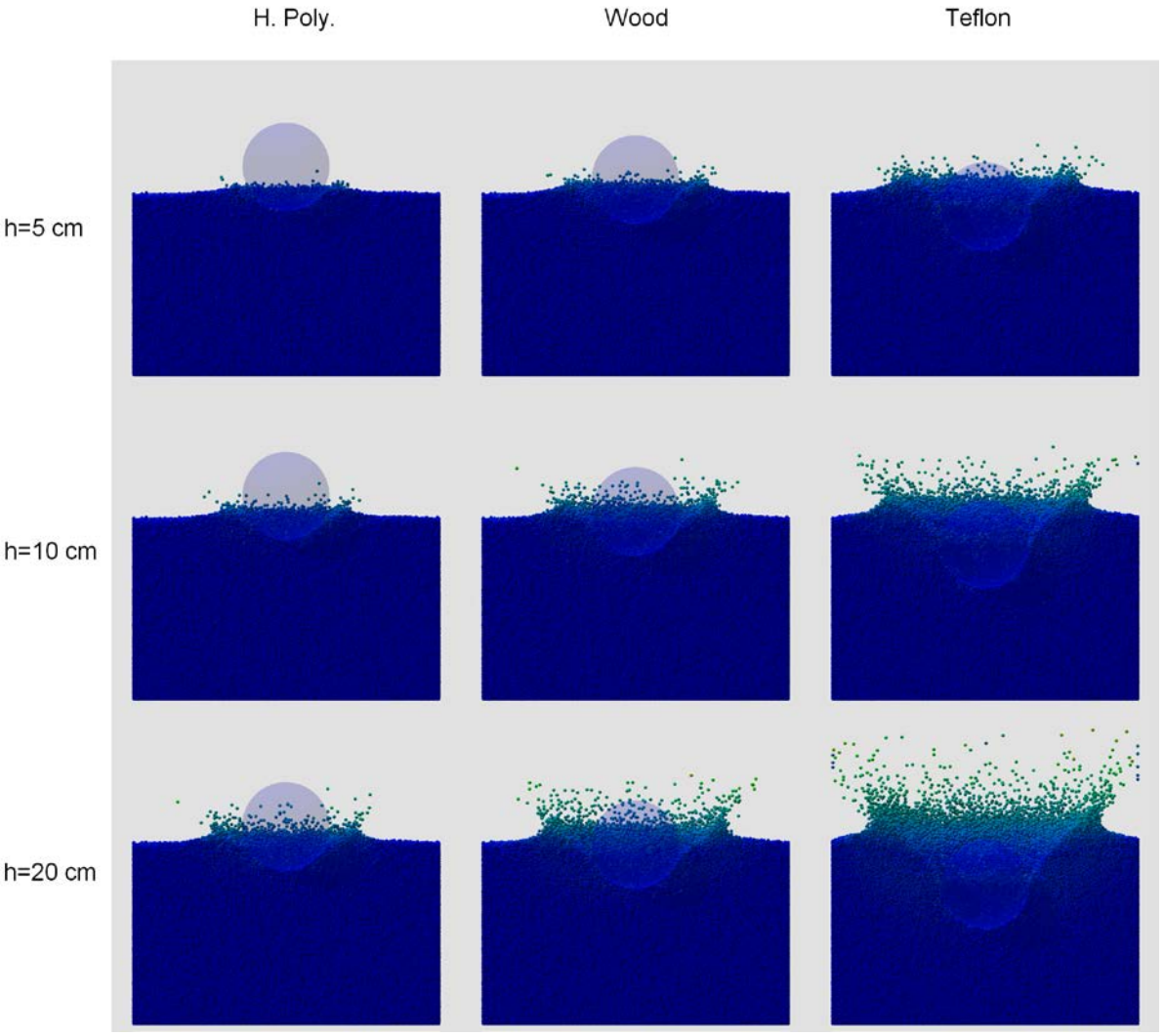
Simulation parameters (PM)

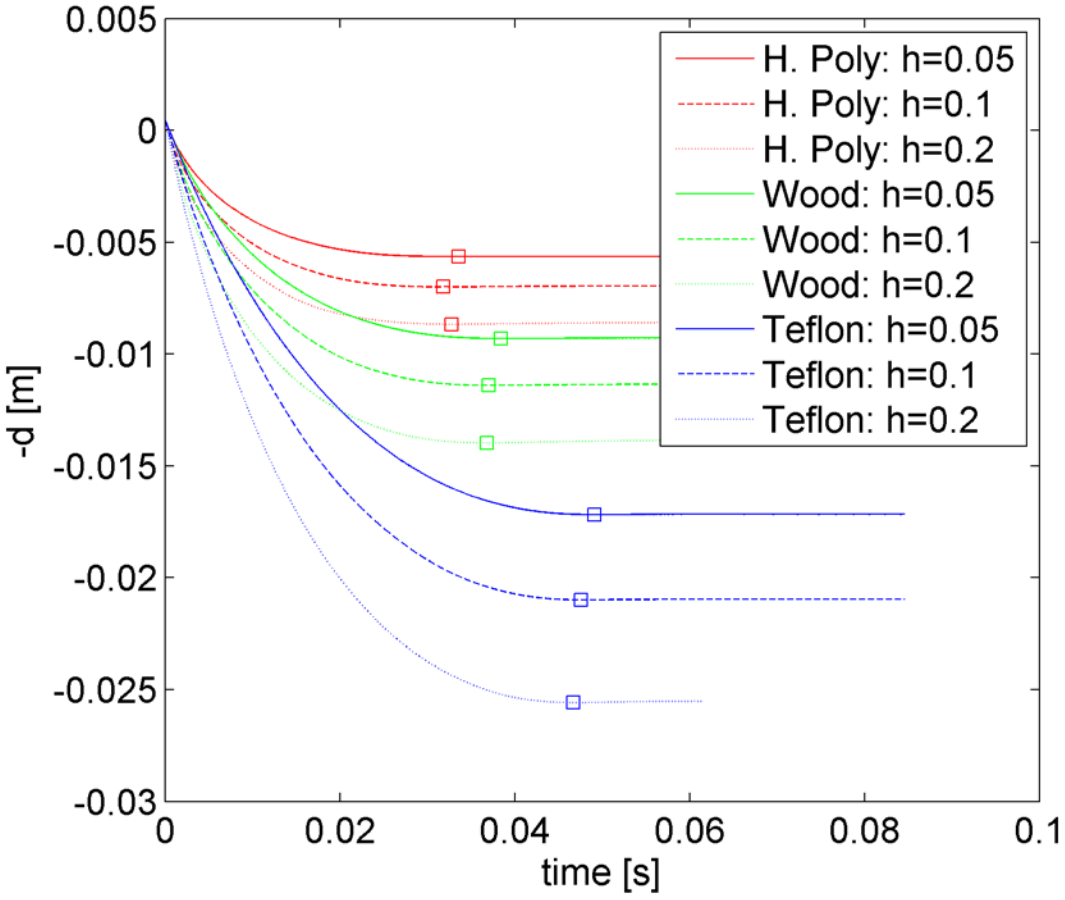
- 379,000 spheres
- r = 0.5 mm
- ρ = 1500 kg/m^3
- E = 10^8 Pa
- μ = 0.3

- Simulation with Chrono::Parallel



Deepest penetration

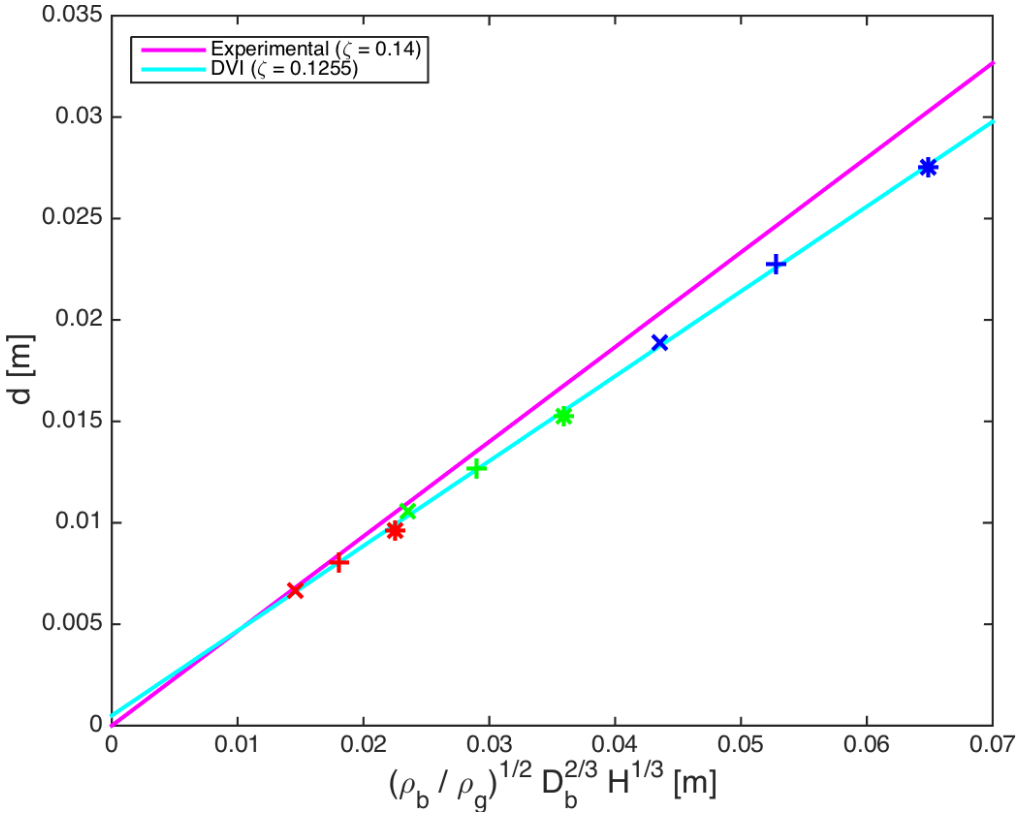




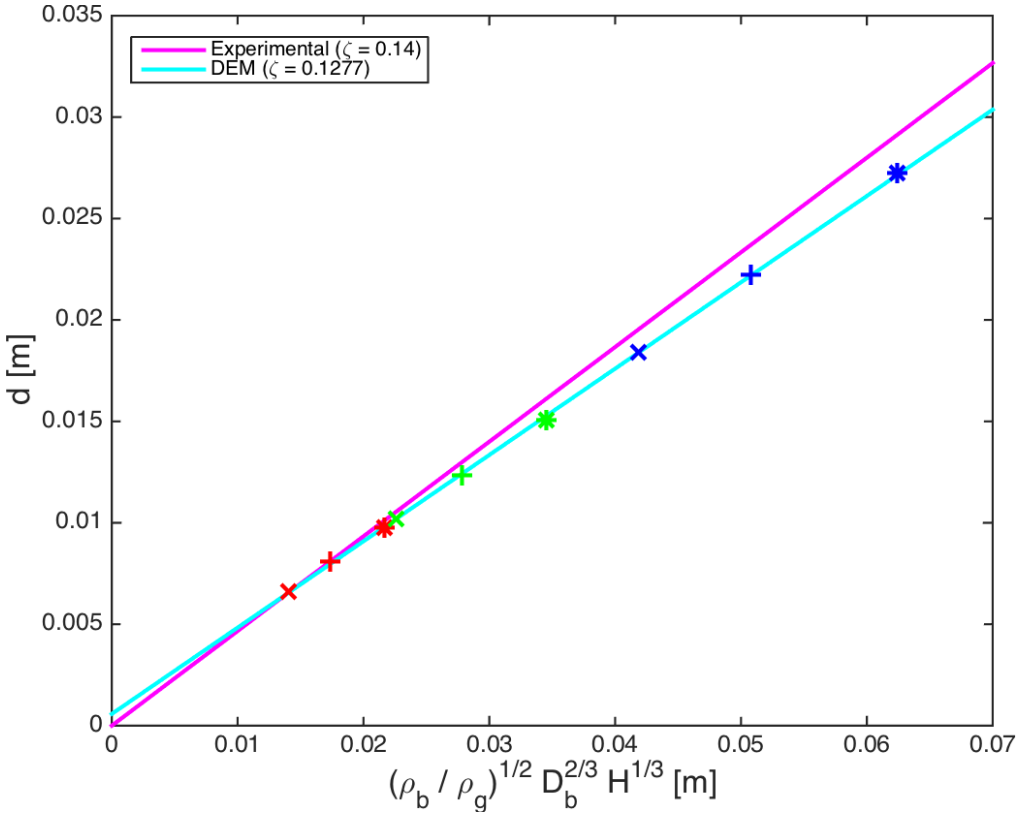
Simulation results and validation

$$d = \frac{\zeta}{\mu}\left(\frac{\rho_b}{\rho_g}\right)^{1/2} D_b^{2/3} H^{1/3}$$

Complementarity $\zeta = 0.1255$



Penalty $\zeta = 0.1277$



"A Comparison of Penalty and Complementarity Approaches to Discrete Element Method Simulations," R. Serban, D. Melanz, P. Jayakumar, D. Negrut, in preparation, 2016

Method comparison

Problem

- $\rho = 700\ kg/m^3$
- $h = 0.1\ m$
- 64 OpenMP threads

Complementarity

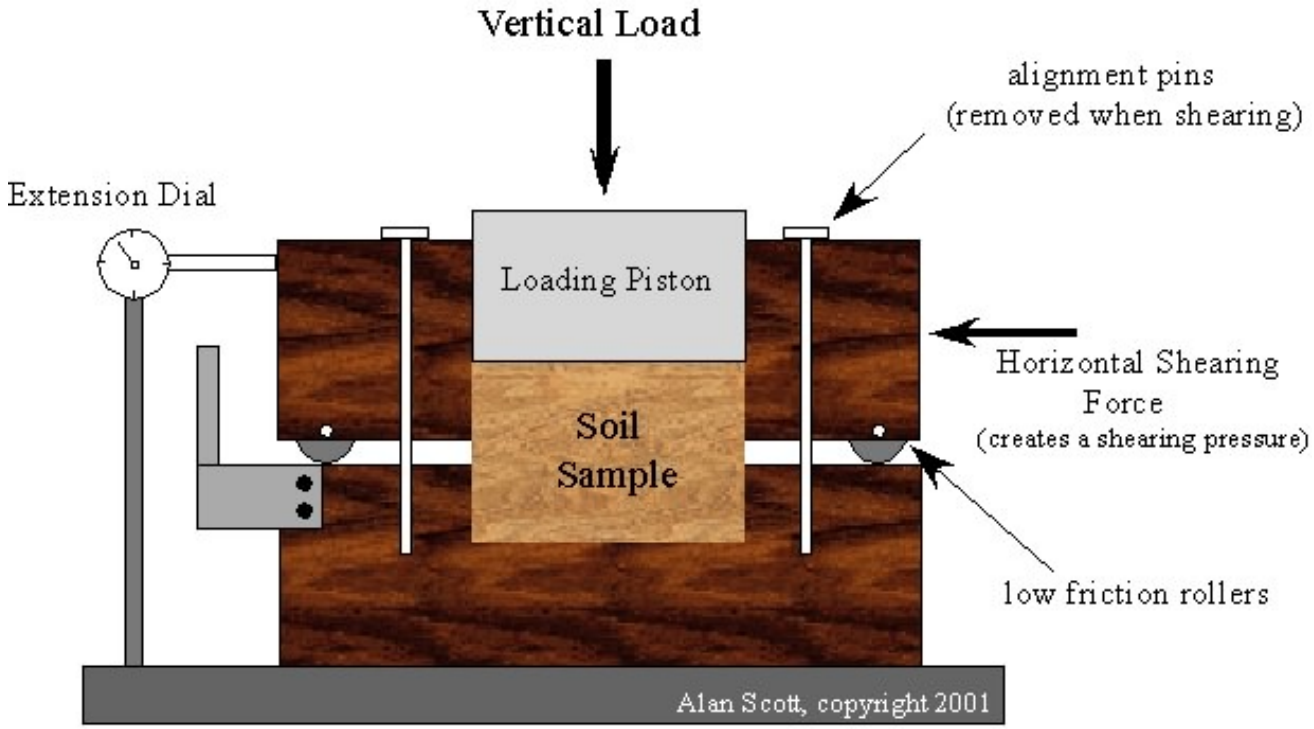
- Step-size: 10^{-4} s
- Cost per step: 3.471 s
  - Collision detection: 0.087 s
  - Update: 0.012 s
  - Solver: 3.372 s
- Average number contacts: 1.37 millions

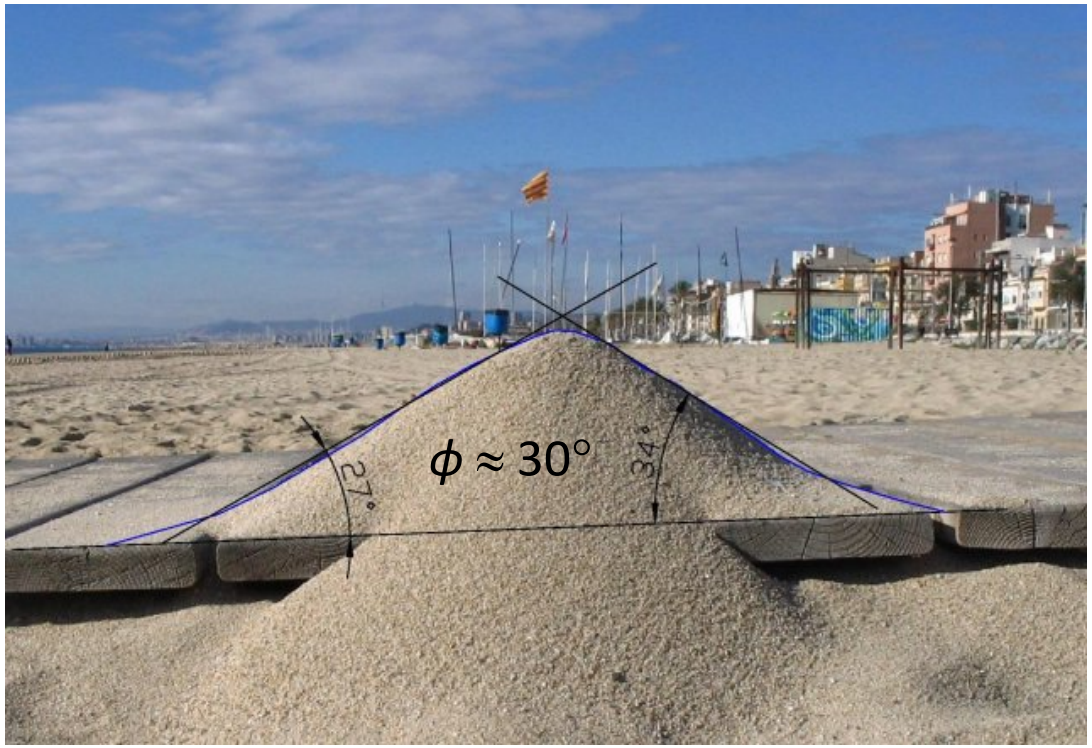
Penalty

- Step-size: 10^{-5} s
- Cost per step: 0.144 s
  - Collision detection: 0.061 s
  - Update: 0.010 s
  - Solver: 0.072 s
- Average number contacts: 1.04 millions

Validation Studies
Low-speed direct-shear test

Direct Shear test

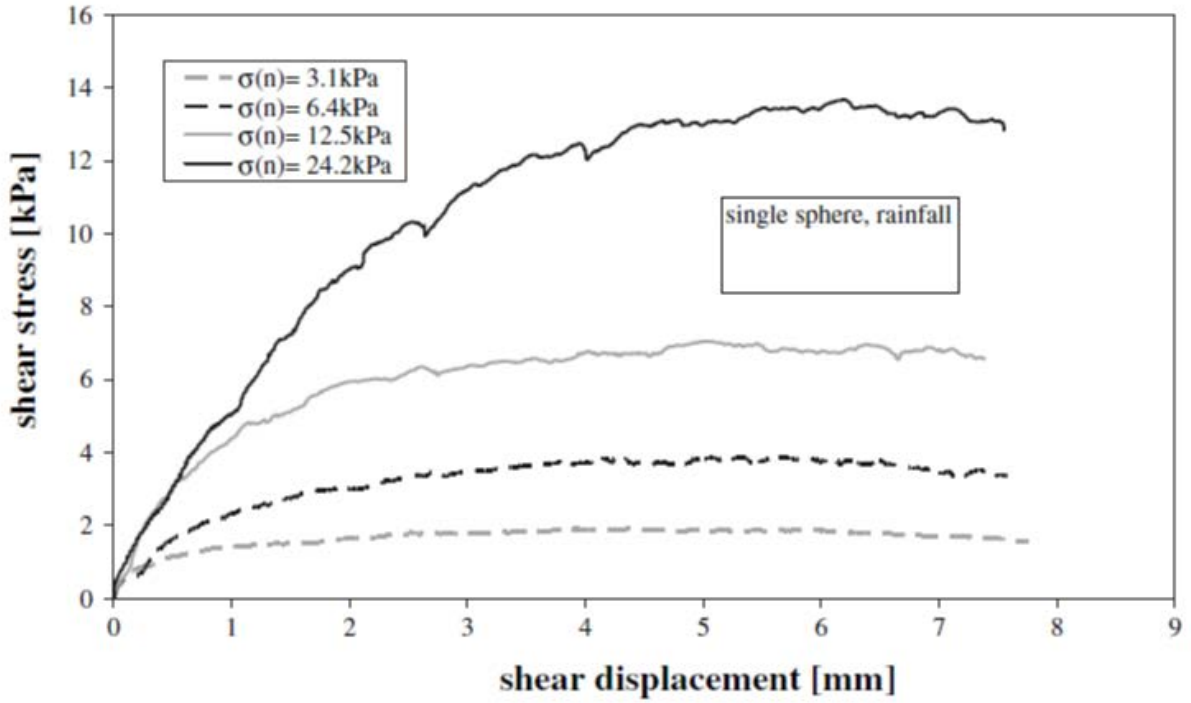




$$\tan\phi = \mu_{macro} = \frac{Shear\ Stress\ on\ Shear\ Plane}{Normal\ Stress\ on\ Shear\ Plane} = \frac{Horizontal\ Shearing\ Force}{Vertical\ Load}$$

Direct Shear validation: Uniform glass beads

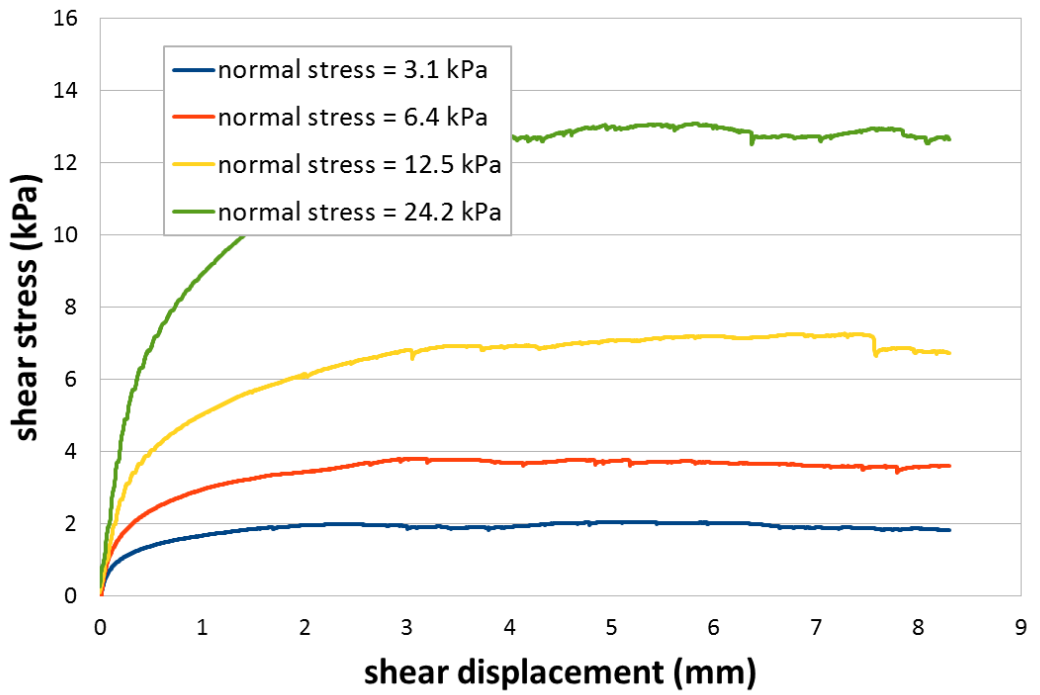
Physical Experiment: Härtl and Ooi, 2008



Void ratio e ≈ 0.7

Young's modulus E = $4(10^{10})$ Pa

Chrono: DEM-P (with tangential history)



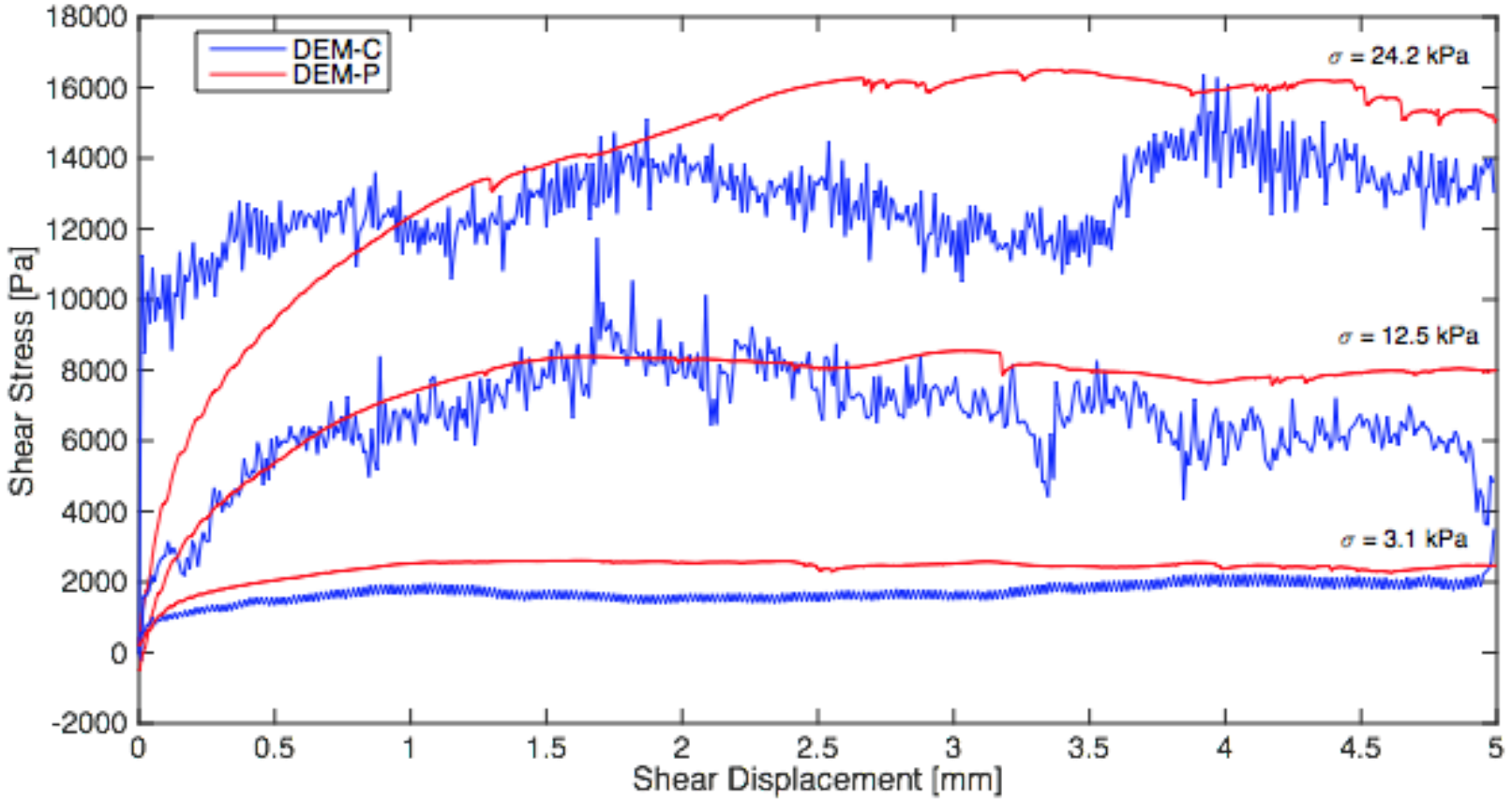
Void ratio e = 0.66, 0.65, 0.62, 0.60

Young's modulus E = $4(10^{7})$ Pa

"Experiments and Simulations of Direct Shear Tests: Porosity, Contact Friction, and Bulk Friction," J. Hartl and J.Y. Ooi, Granular Matter, 10(4), 2008.
"On the Importance of Displacement History in Soft-Body Contact Models," J. Fleischmann, R. Serban, P. Jayakumar, and D. Negrut, ASME JCND, 11(4), 2015

Simulation results

- 1000 uniform spheres randomly packed
- Particle Diameter: 6 mm
- Shear Speed: 1 mm/s
- Inter-Particle Coulomb Friction Coefficient: $\mu = 0.18$ (Glass-on-Glass)
- Void Ratio: $e \approx 0.7$ (rainfall packing)
- Simulation with Chrono::Parallel



Method comparison

Problem

- 1,000 particles
- 1 mm/s shear speed
- 10 OpenMP threads
- $r = 3 \cdot 10^{-3}$ m
- $\mu = 0.18$

Complementarity

- Step-size: 10^{-3} s
- Cost per step: 0.1615 s
  - Collision detection: 0.0036 s
  - Update: 0.0007 s
  - Solver: 0.1571 s
- Average number contacts: 4800

Penalty

- Step-size: 10^{-5} s
- Cost per step: 0.0025 s
  - Collision detection: 0.0008 s
  - Update: 0.0007 s
  - Solver: 0.001 s
- Average number contacts: 4200

Validation Studies
Cone penetrometer test

Cone penetrometer simulations

DEM-C – 60° cone

DEM-P – 30° cone

Simulation results and validation

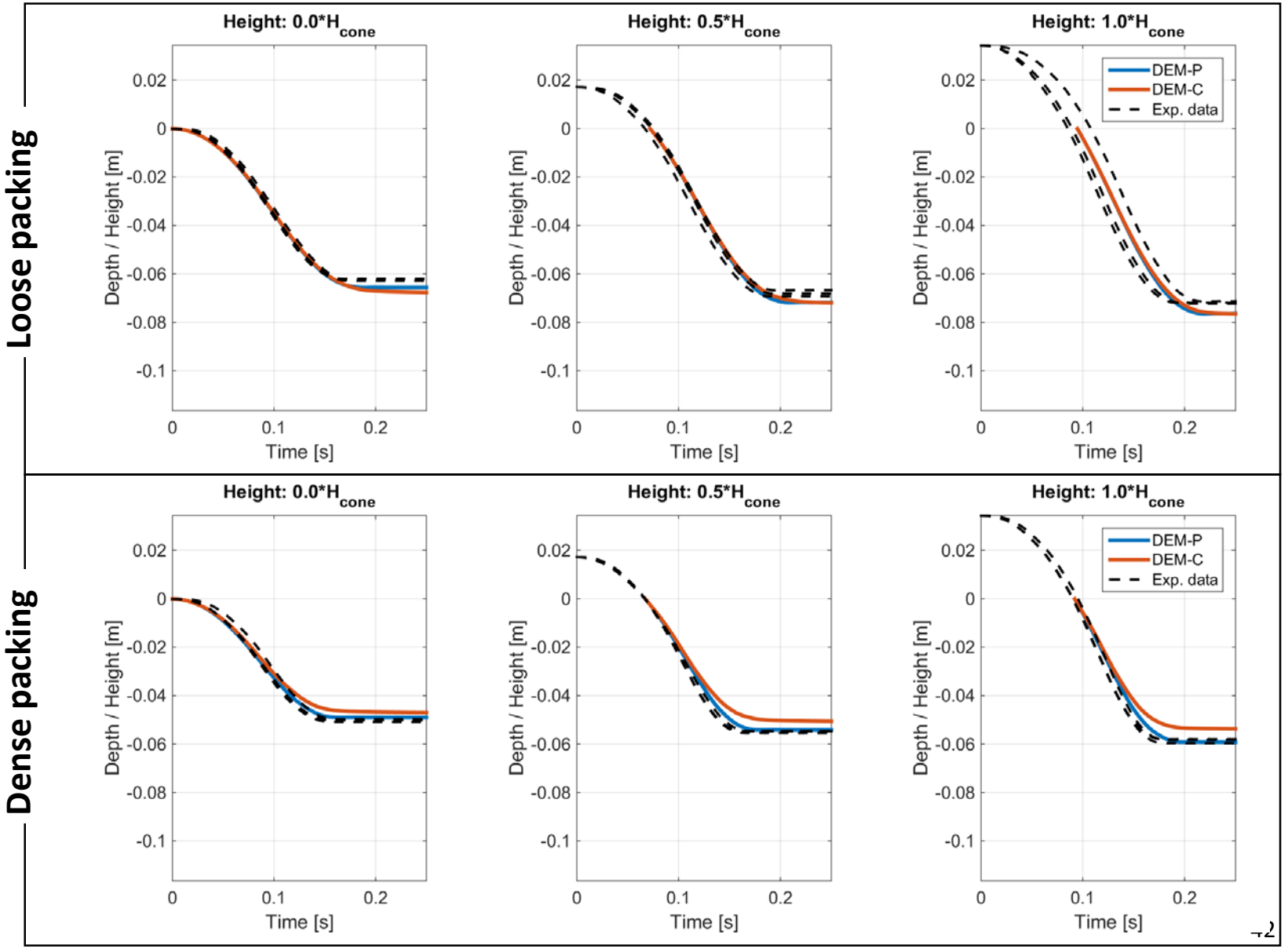
Container
- Diameter: $10.16\ cm$
- Height: $11.64\ cm$

Granular material
- Imperfect glass spheres
  $\mu = 2.84\ mm\ , \sigma^2 = 0.0834$
- Density: $2500\ \ kg/m^3$
- Friction: 0.658

Loose packing
- Density: $1504.3\ \ kg/m^3$
- Void ratio: 0.66
- Number of particles: 48864

Dense packing
- Density: $1630.3\ \ kg/m^3$
- Void ratio: 0.53
- Number of particles: 53296

Penetrometer
- Apex angle: $30°$
- Base diameter: $9.21\ mm$
- Height: $34.36\ mm$



Method comparison – settling phase

Problem

- Loose packing
- 48,865 particles
- 8 OpenMP threads

Complementarity

- Step-size: 10^{-4} s, Max. iterations/step: 50
- Cost per step: 1.803 s
  - Collision detection: 0.044 s + 0.010 s
  - Update: 0.007 s
  - Solver: 1.742 s
- Final number contacts: 164,369

Penalty

- Step-size: 10^{-5} s
- Cost per step: 0.117 s
  - Collision detection: 0.050 s + 0.010 s
  - Update: 0.012 s
  - Solver: 0.045 s
- Final number contacts: 120,300

Method comparison – dropping phase

Problem

- Loose packing
- 48,865 particles
- 8 OpenMP threads

Complementarity

- Step-size: 10^{-4} s, Max. iterations/step: 50
- Cost per step: 1.994 s
  - Collision detection: 0.045 s + 0.010 s
  - Update: 0.007 s
  - Solver: 1.930 s
- Final number contacts: 165,263

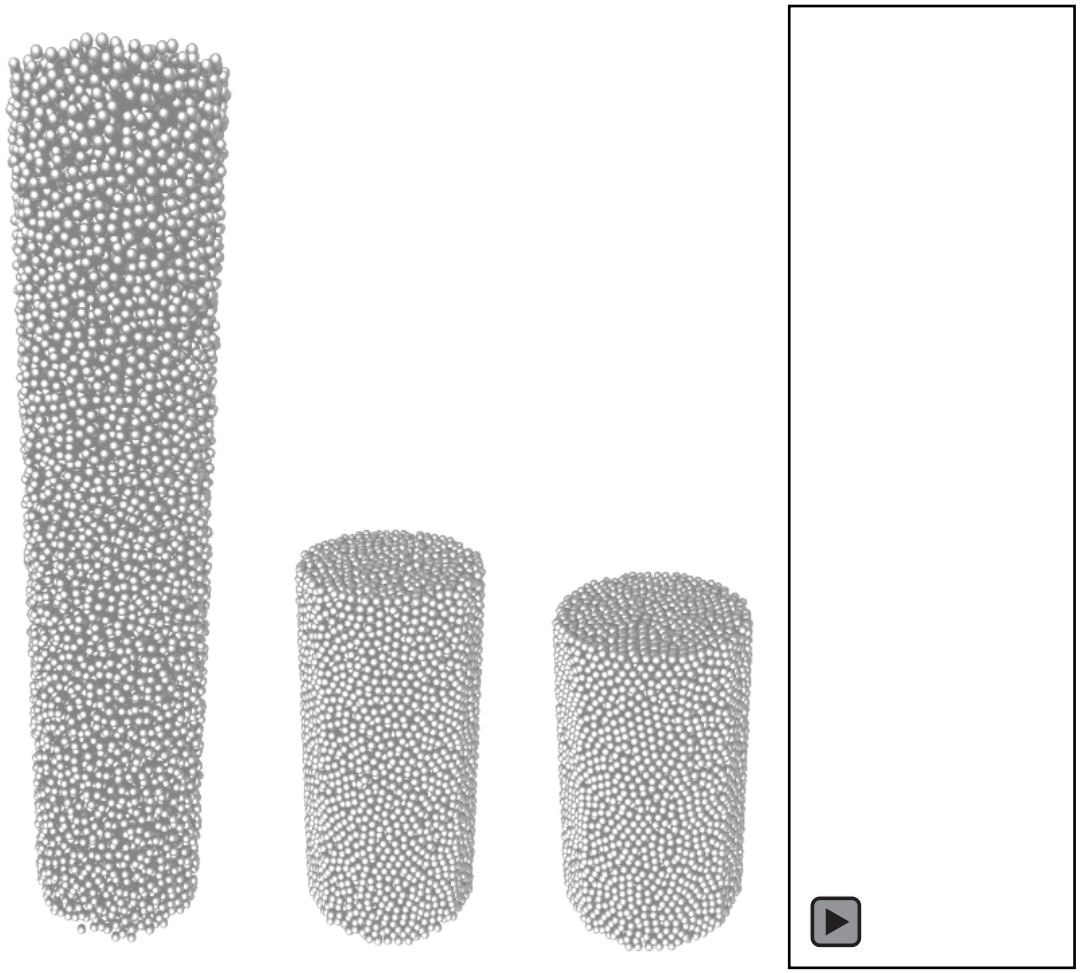
Penalty

- Step-size: 10^{-5} s
- Cost per step: 0.122 s
  - Collision detection: 0.051 s + 0.010 s
  - Update: 0.011 s
  - Solver: 0.050 s
- Final number contacts: 117,068

Validation Studies
Triaxial compression test

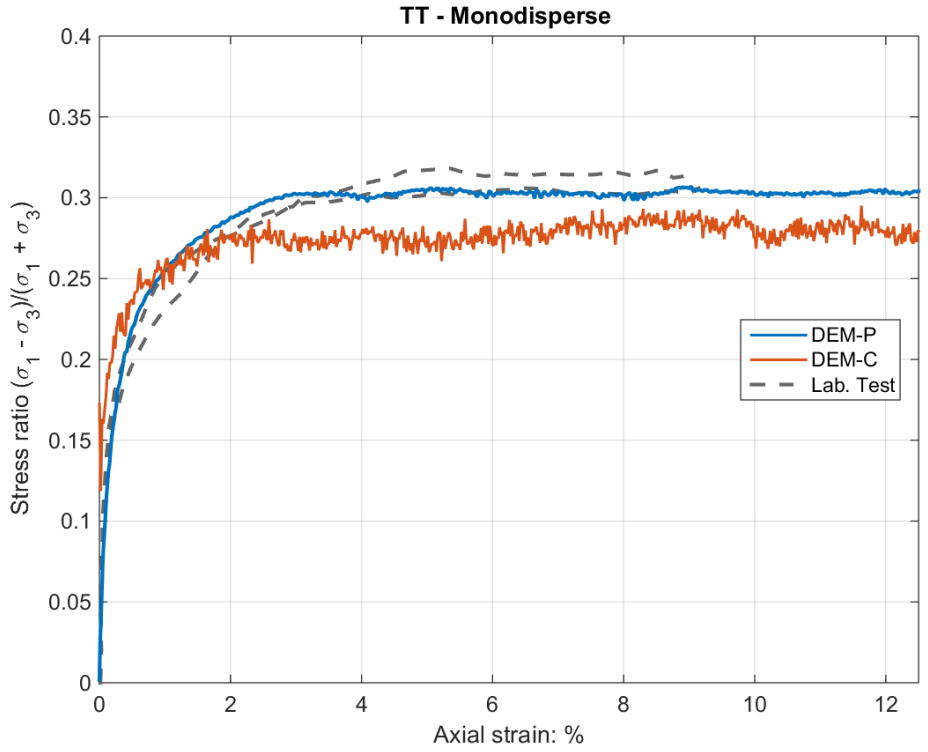
Standard triaxial test phases

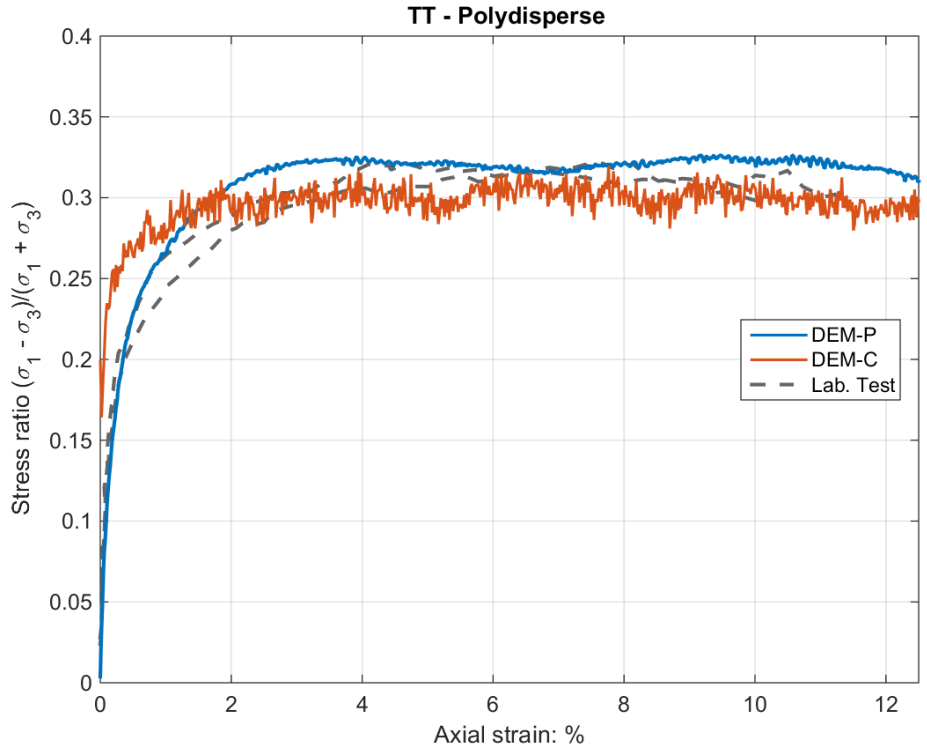
- Cylindrical Container: Φ_{cont} = 100 mm, H = 200 mm
- Granular material consists of **perfect spheres**
- Monodisperse case: φ_{beads} = 5 mm
- Polydisperse case: $\varphi_{beads} \in \{4, 5, 6\}$ mm; beads evenly distributed



Setup Settling Test

Simulation results and validation





"An analysis of the triaxial apparatus using a mixed boundary three-dimensional discrete element model," L. Cui, C. O'Sullivan, S. O'Neill, Geotechnique, 57(10), 2007

"A fundamental examination of the behaviour of granular media and its application to discrete element modelling," O'Neill, Master's thesis, University College Dublin, Ireland, 2005

Method comparison

Sim. Info		Monodisperse	Polydisperse
DEM-P	dt [s]	5.E-06	9.E-06
DEM-C	dt [s]	1.E-04	
	num. of iter	700	
	crs [m/s]	0.02	

Performance Comparison		Simulation Time [s]	Execution Time
Settling Part	DEM-P	0.5	1h 25 min
	DEM-C		9h 21min
Triaxial test	DEM-P	1.5	4h 55 min
	DEM-C		44h 14min

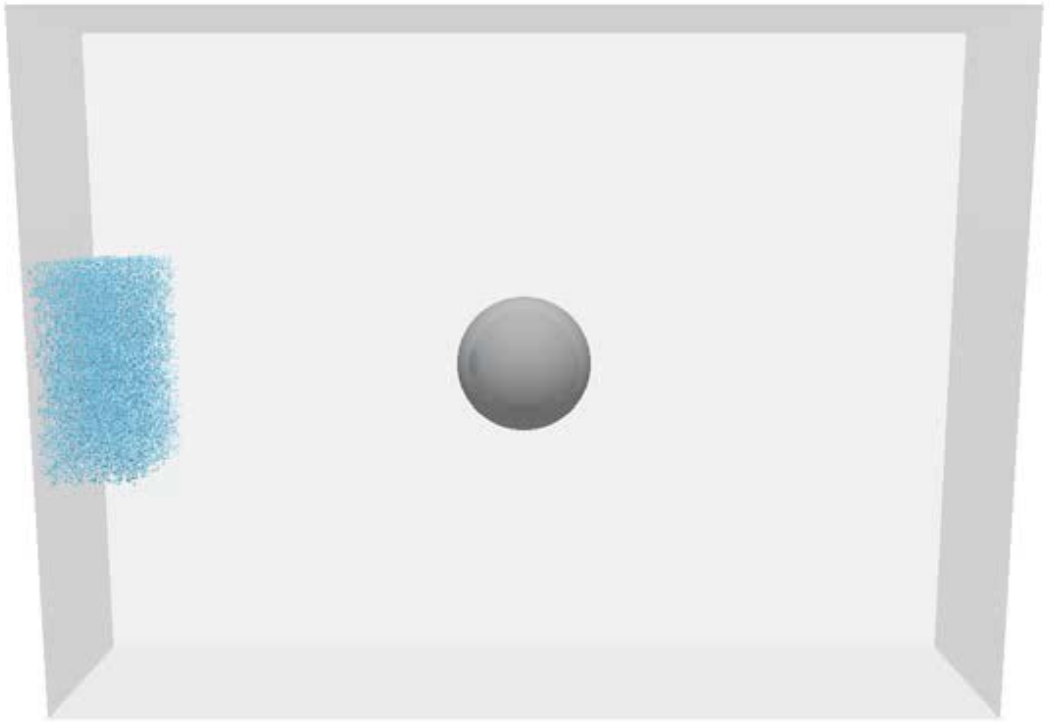
		Number of Spheres		Relative Error [%]		Void Ratio		Relative Error [%]	
Lab. Test		15382	15420			0.615	0.612		
Monodisperse	DEM-P	15918		3.485	3.230	0.641		4.266	4.777
	DEM-C					0.611		0.640	0.153
Polydisperse	DEM-P	15740		2.327	2.075	0.660		7.323	7.849
	DEM-C					0.626		1.847	2.346

Performance evolution

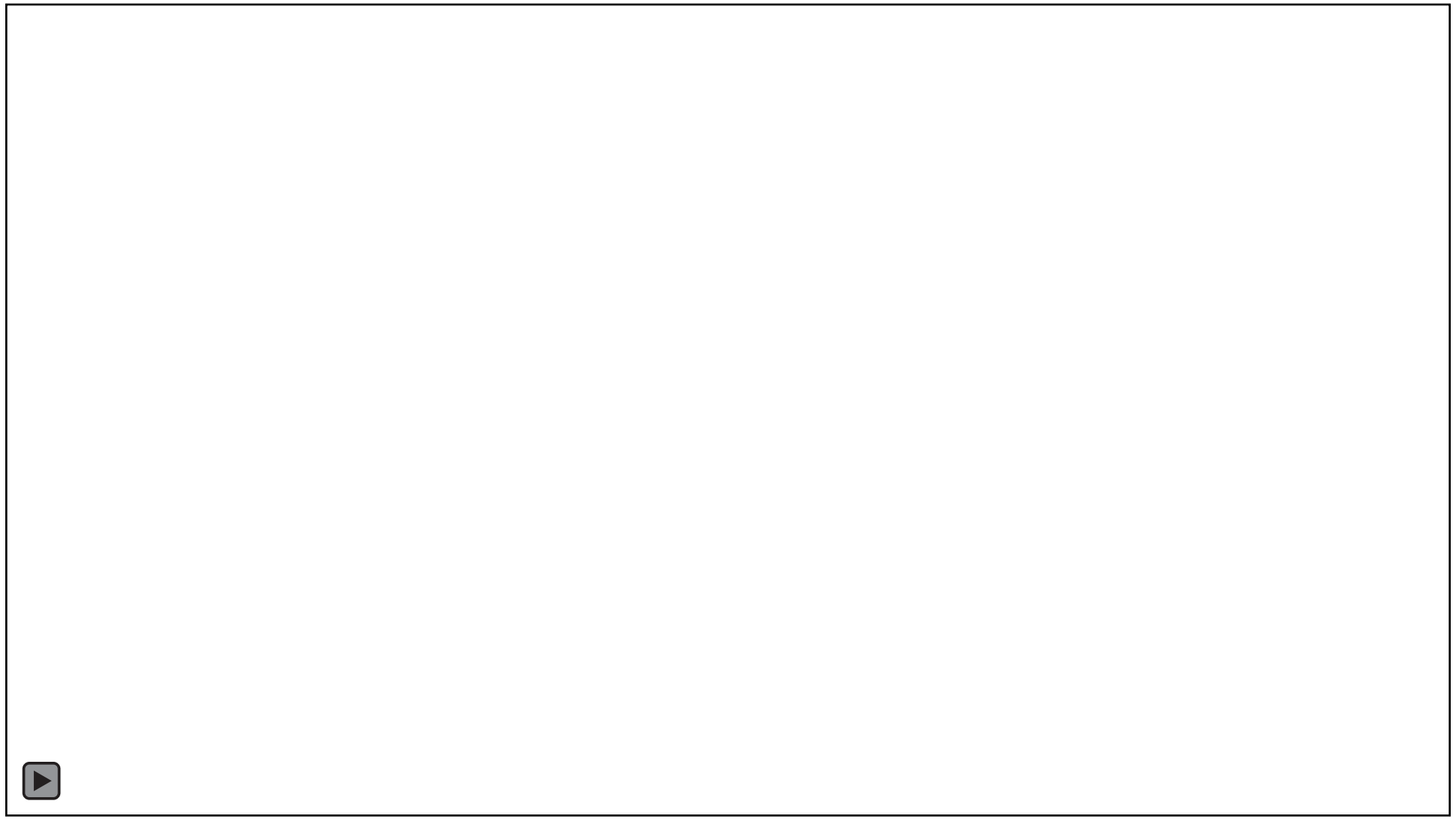
How things have evolved in the last 5 years

- Look at benchmark simulations we have been running for a while
  - Granular dynamics
  - Vehicle mobility on deformable terrain

Granular dynamics (2009)



Granular dynamics (2015)



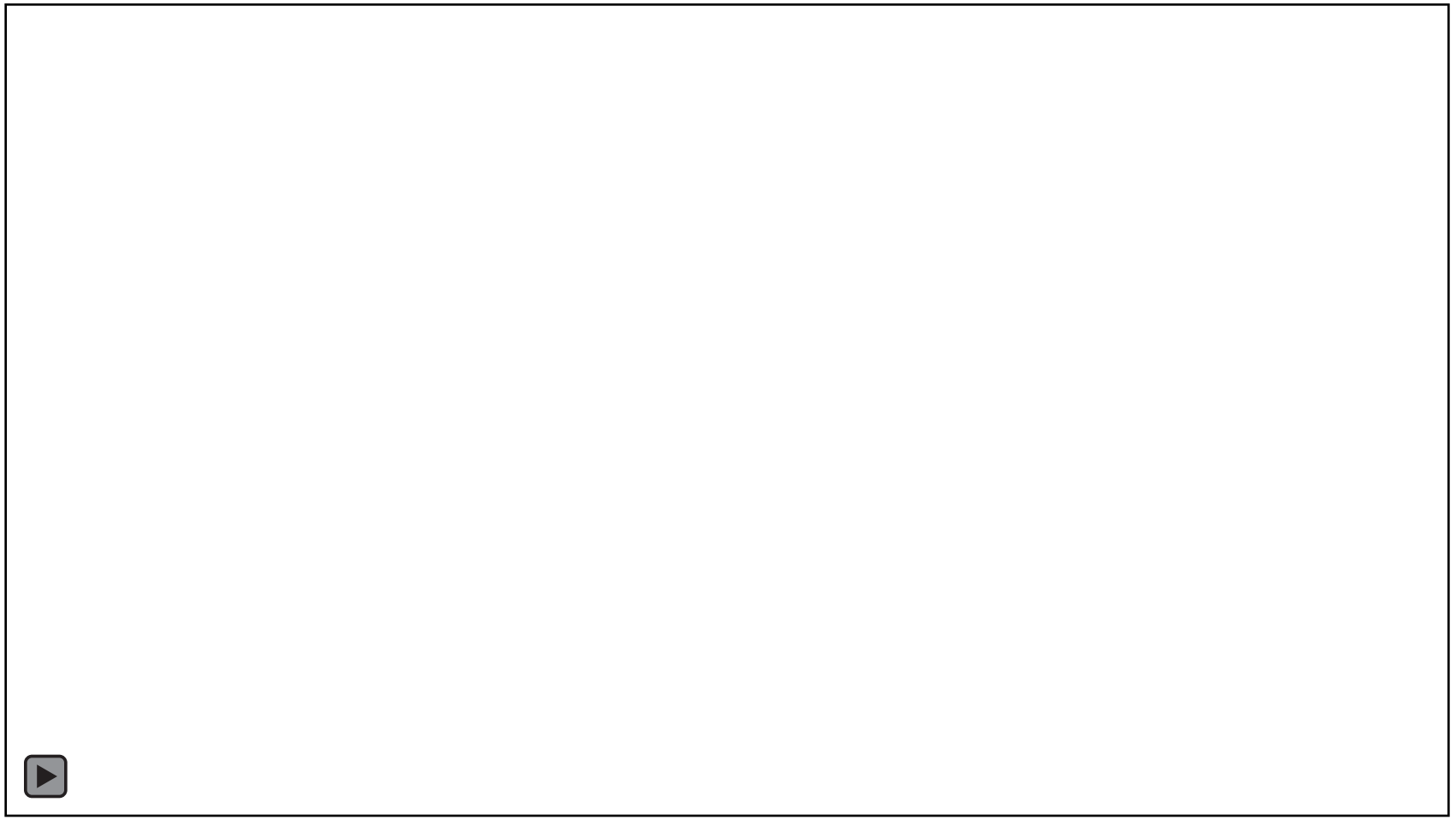
Tank wave simulation

- 2009 Implementation
  - 1 million rigid frictionless spheres
  - Integration time step: 0.01s
  - 24 sec per step
  - Hardware used: GPU
    - NVIDIA Tesla C1060
  - Velocity based complementarity
  - 20 seconds long simulation
  - Simulation Time: ~2 days

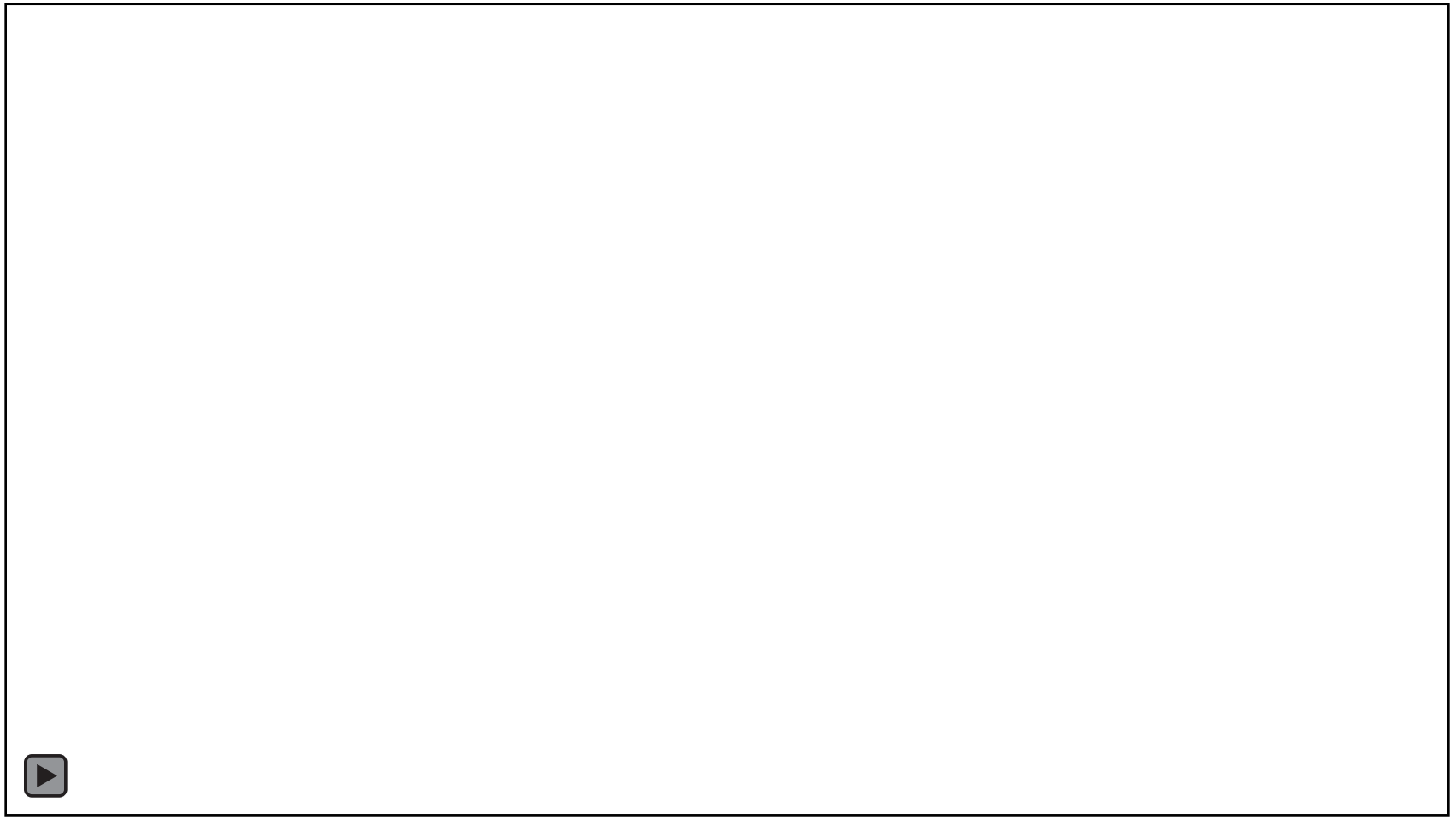
- 2015 Implementation
  - 10,648,000 rigid spheres
  - Integration time step: 0.00025s
  - 1 second per step
  - Hardware Use: GPU
    - NVIDIA Tesla K40x
  - Position based complementarity
  - 10 seconds long simulation
  - Simulation Time: 11 hours

2015 Simulation: given the number of bodies, about 20 times faster

Vehicle on granular terrain (2012)



Vehicle on granular terrain (2015)



Vehicle on granular terrain

- 2012
  - 300k rigid spheres
  - Length of simulation: 15 seconds
  - Hardware used: CPU (Intel)
    - Multicore, based on OpenMP
  - Integration time step: 0.001s
  - Velocity Based Complementarity
  - 17 seconds per time step
  - Simulation time: ~2.5 days

- 2015
  - ~1.5 million rigid spheres
  - Length of simulation: 15 seconds
  - Hardware: GPU (NVIDIA)
    - Tesla K40X
  - Integration time step: 0.0005s
  - Position Based Dynamics
  - 0.3 seconds per time step
  - Simulation time: ~2.5 hours

2015 Simulation: although 5X more bodies, runs about 25 times faster

How things have Changed in 5 years

- Look at the simulation runtimes
  - Granular dynamics: about 20 times faster
    - From two days, to about two hours
  - Vehicle mobility on deformable terrain: about 100 times faster
    - Comparing a bit apples and oranges (CPU vs. GPU)
    - Say that about 25X faster when you compensate for the CPU vs. GPU difference

- Where is this 20X speedup coming from?
  1. Improved hardware
     Moore's law – more transistors, more compute power packed inside chip
  2. Faster numerical methods and algorithms
     2013 PhD thesis led to better numerical method
     4X-5X speedup

Sample simulations

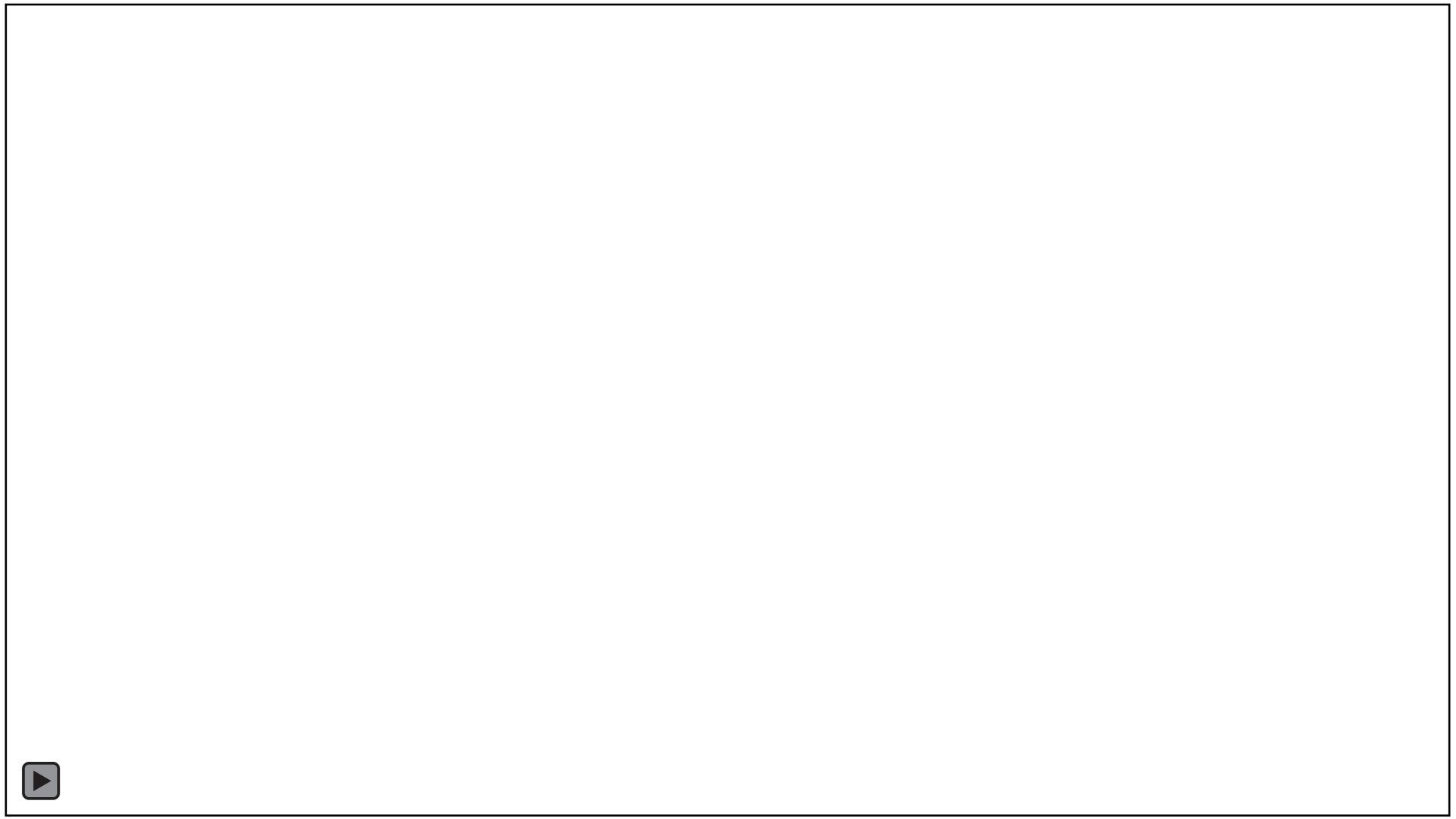
Fording simulation – frictionless granular fluid

- Fording Setup: (dimensions reduced from the original physical model)
  - Depth 8ft, Width 14ft
  - Length of bottom 15ft
- Chrono-Vehicle HMMWV Model
  - 9 Body Model, 4WD, simple drivetrain, no driver
  - Chassis/Wheels converted to convex hulls from OBJ
  - Throttle set to 1 and kept constant
- 1,051,840 rigid spheres in an HCP grid
- Integration time-step: 0.001 s, ~50 seconds per step

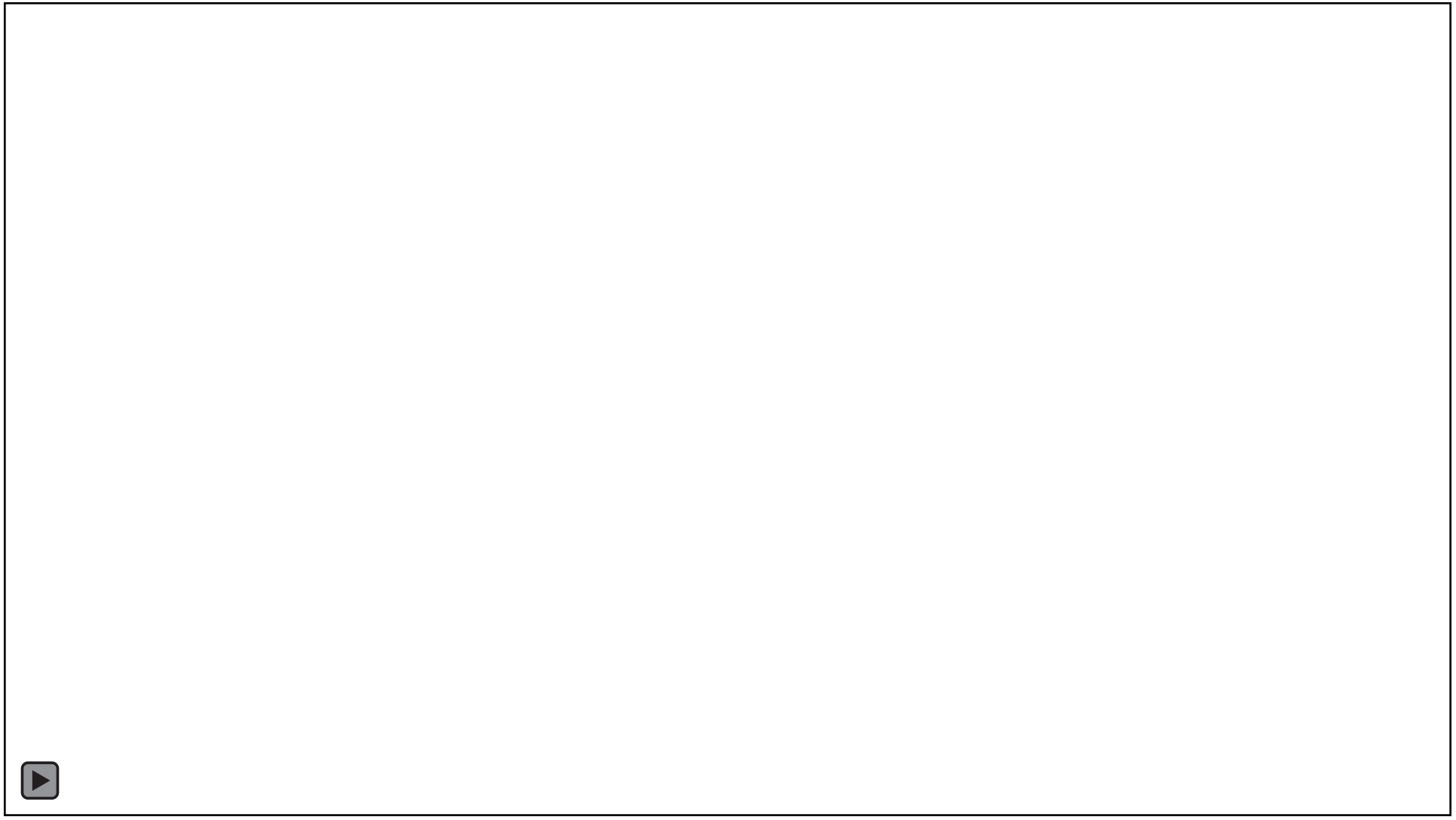
Fording simulation – constraint fluid

- 1,050,225 fluid markers in an HCP grid
- Integration time-step: 0.001 s, ~20 seconds per step

Cohesion (DEM-C)



Cohesion (DEM-C)



Mixing of granular material