Annex G – THRUST 3 - COMPLEX TERRAMECHANICS MODEL AND DATA

Note: This Annex appears in its original format.

AVT-308 Cooperative Demonstration of Technology on Next-Generation NATO Reference Mobility Model Development

Houghton, Michigan, USA

September 25-27, 2018

Thrust Area 3: Complex Terramechanics

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September 25, 2018

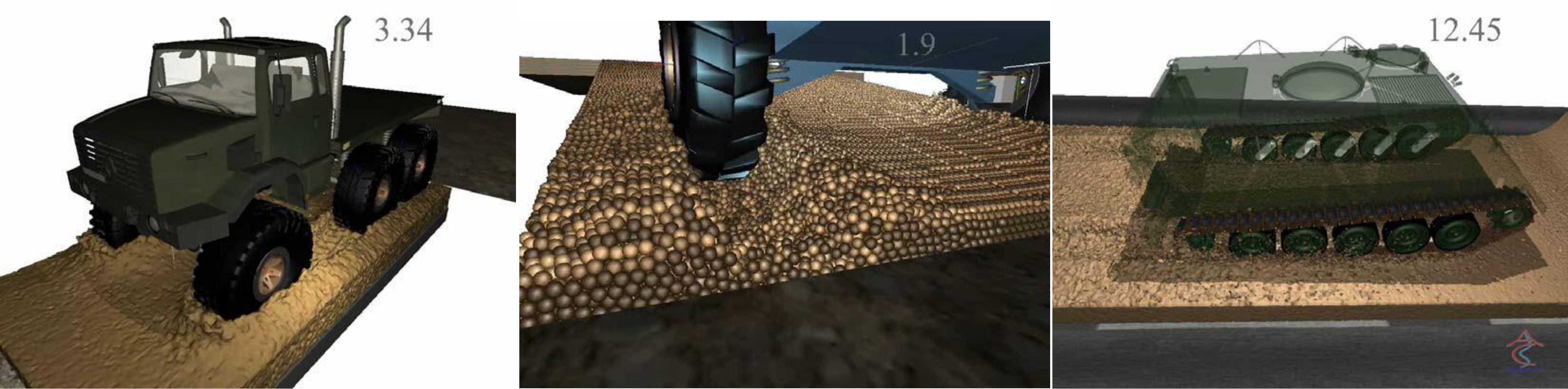
Outline

- Definition of **Complex Terramechanics (CT)**
- Classification of terramechanics model types by scale
- Review of CT modeling techniques
- Motivation
- Objectives
- CT software tools requirements
- CT state of technology
- CT future developments

Definition of Complex Terramechanics

NG-NRMM CT models are those that given any **3D soil loading condition** by a vehicle surface can accurately predict the **3D soil flow/deformation** including both elastic & plastic deformation.

- Rut depth/width/shape
- Rut side wall height
- Soil bulldozing
- Soil separation/reattachment

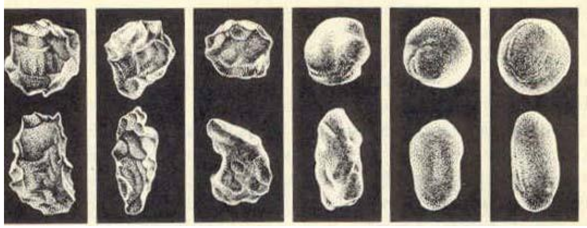


Complex Terramechanics

Micro-Scale Soil Properties

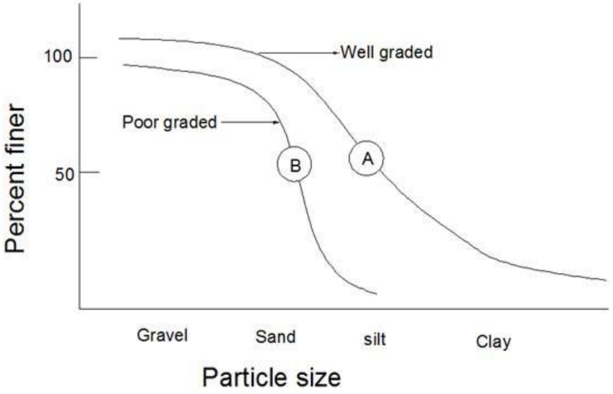
Chemical Composition: Mineral, organic

Particle Shape: Angular to rounded
Particle Surface Roughness

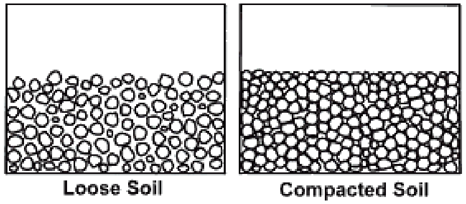


Particle mechanical properties: Young's modulus, Poisson's ratio, damping, fracture strength.

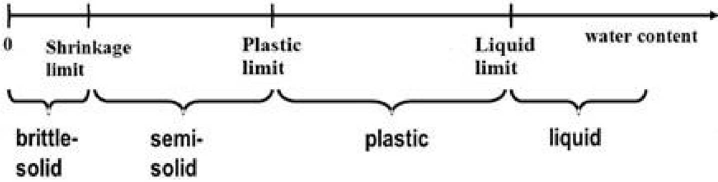
Particle size distribution: 0.1 to 10^{-6} m



Compaction State



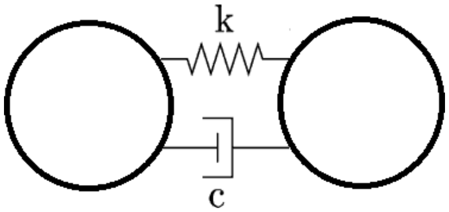
Moisture Content (Atterberg limits)



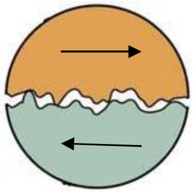
Temperature

Micro-Scale Soil Forces

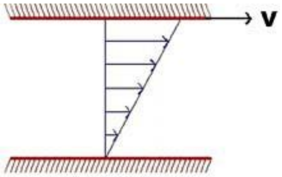
Normal contact forces: elastic and damping



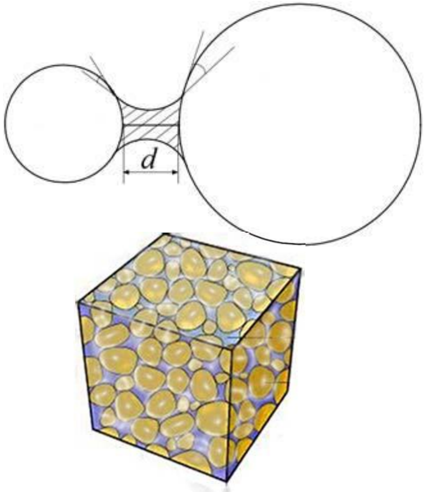
Friction Force



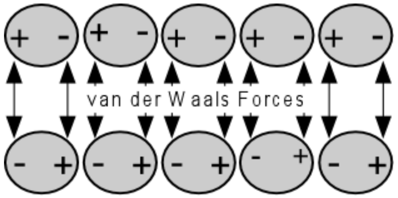
Viscous Force



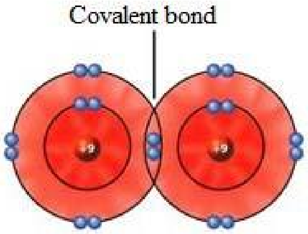
Capillary forces



Van der Waals forces



Chemical bonding forces



Challenges of a Micro-Scale Soil Model for Vehicle Mobility

- Prohibitive computational time: months – years of HPC time
  - Large number of soil particles: $10^{12} – 10^{15}$
  - Small time step → inversely proportional to particle size
- Large number of soil particle properties which are not easy to measure
- Large number of soil chemical components
- Poorly understood micro-scale forces
- Soil particle fracture not well understood

Classification of Terramechanics Models by Scale

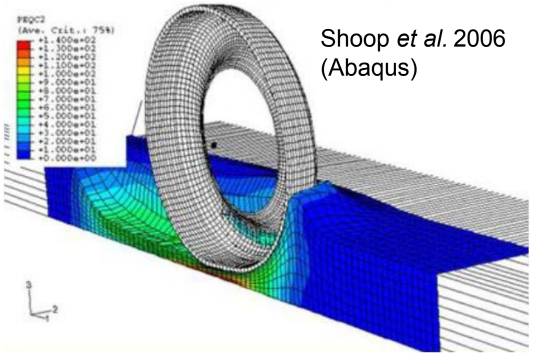
	Quantum Mechanics	**Molecular Dynamics**	**Micro-scale Model** **Complex Terramechanics**	**Macro-Scale Model** **Complex Terramechanics**	**Height Field Model** **Simple Terramechanics**	**Height Model** **Simple Terramechanics**	**Empirical Steady-State model**
Fidelity	Very high						Very low
Physics-based	Fully physics based						Fully empirical
Description	Sub-atomic to atomic scale models	Molecular scale model	Soil particles are individually modeled	Soil particles are lumped to form a virtual particle or a finite element (e.g. DEM or FEM)	Terrain is divided into vertical cells. For each cell height and state of stress is stored. A Bekker-Wong type pressure-sinkage-traction-sli[model is used for each cell.	Pressure and slip are used to calculate sinkage and tractive force using a Bekker-Wong model.	NRMM / NRMM-II
Number of Soil DOFs for vehicle mobility applications	$>10^{20}$	10^{18}	$10^{14} – 10^{11}$	$10^{7} – 10^{6}$	$10^{4} – 10^{3}$	1	0
Current Computational Cost	Prohibitive	Prohibitive	Months-Years of HPC time.	A few hours to 1 week HPC time	Minutes/ real time	Faster than real time	Faster than real time
Our current state of knowledge	Unknown how to take the model to the micro-scale	Taking the model to the micro-scale requires research because soil consists of many materials	More research is needed to understand the micro-mechanical interaction forces	More research is needed to improve, calibrate, and validate the soil models	More research is needed to improve, calibrate, and validate the soil models	More research is needed to improve, calibrate, and validate the soil models	Implemented in NRMM/NRMM-II

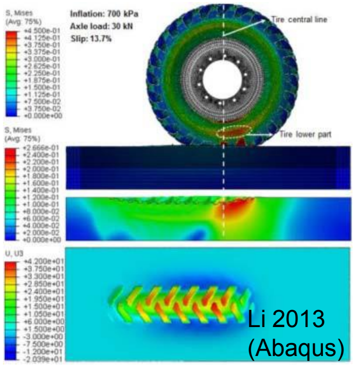
Complex Terramechanics Macro-Scale Models

- **Finite element models**
  - Lagrangian/ALE formulation
  - Eulerian formulation
- **Mesh-free/particle based models.** There are over 30 types of particle methods. Main methods used to model granular material –body interactions are:
  - Discrete element method (DEM)
  - Smoothed particle hydrodynamics (SPH)
  - Material point method (MPM)
  - Particle finite element method (PFEM)

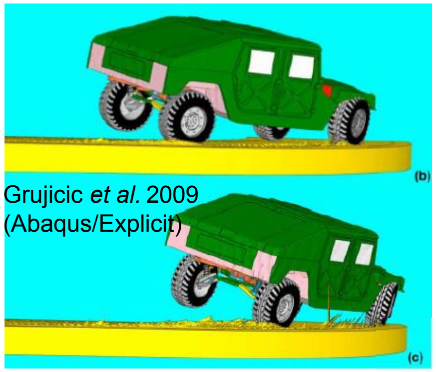
Macro-scale soil models: Finite Element Lagrangian/ALE models

- Soil deformation modeled using the motion of FE nodes/mesh along with an elasto-visco-plastic constitutive material model such as Drucker–Prager-Cap model for the soil.
- ALE used to model the free surface.
- Remeshing can be used to accommodate large soil deformation.

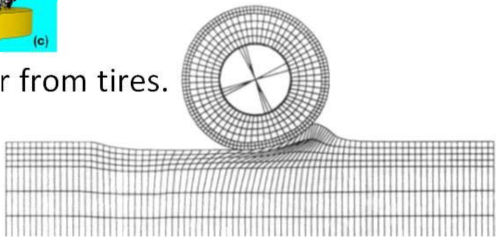

Shoop *et al.* 2006 (Abaqus)



Li 2013 (Abaqus)

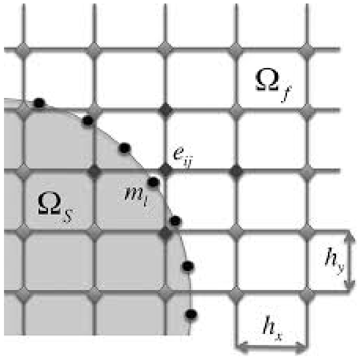


Grujicic *et al.* 2009 (Abaqus/Explicit)



- **Advantage.**
  - ➢ Element size can be adapted: small elements are used in areas near tires and large element are used far r from tires.
- **Disadvantages.**
  - ➢ Large soil deformation requires re-meshing → computationally expensive and reduces accuracy.
  - ➢ Soil separation and reattachment are difficult to capture.
  - ➢ Lagrangian or ALE FE formulations are not capable of modeling material flow between elements.
  - ➢ FEM relies on a continuum mechanics formulation. Currently, there is no constitutive material model which accounts for the combined effects of large strain/flow, plasticity, shear failure, friction, compressibility, and cohesion.
  - ➢ Mesh generation is difficult in case of irregular terrains.

Macro-scale soil models: Finite Element Eulerian models



- A fixed CFD-type mesh (typically Cartesian mesh) is used through which soil can flow.
- Cut-cell BCs used to model solid surfaces.
- Free surface of soil modeled using the volume-of-fluid (VOF) or level-set methods.
- Method has been rarely used to model granular material, but is routinely used to model fluids in fluid-structure interaction problems.
- **Advantages:**
  - Element size can be adapted: small elements are used in areas near tires and large element are used far from tires.
  - Can be used for large soil deformation including soil flow and separation/reattachment.
- **Disadvantages**
  - Relies on a continuum mechanics formulation. Currently, there is no general constitutive material model can account for all mechanical soil effects (especially using an Eulerian formulation).
  - Difficult to maintain mass conservation with solid boundaries moving at high-speed (such as tires and tracks) using the cut-cell BCs.
  - Difficult to accurately account for friction and viscous forces at solid boundaries using the cut-cell BCs.

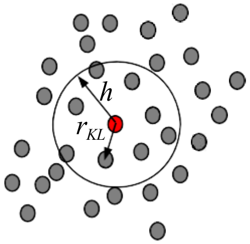
Macro-scale soil models: Particle Methods: DEM

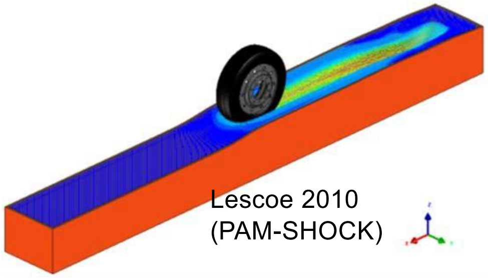
- Material behavior is modeled using inter-particle forces which include: normal contact forces, attraction forces, friction forces, viscous forces, and distance dependent forces (gravity, electrostatic, and magnetic forces).
- DEM particles can be point particles or rigid body particles.

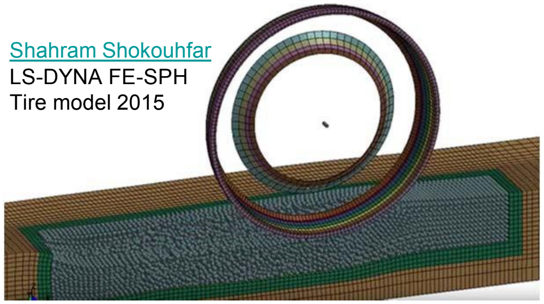
- **Advantages:**
  - Can be used for large soil deformation including soil flow, separation/reattachment, and adhesion with vehicle components.
  - An inter-particle force model which can account for the combined effects of plasticity, elasticity, damping, viscosity, fracture, friction, compressibility, and cohesion has been developed by many groups and used in many practical applications.
- **Disadvantages**
  - Large number of particles because the smallest needed particle size must be used for all particles since he particles can flow.
  - Particle size/shape affects the soil model parameters because mechanical properties such as friction, cohesion, and plasticity scale differently with particle size.

Macro-scale soil models: Particle Methods: SPH

- Particles are used as interpolation points for solving the continuum mechanics governing equations.
- The continuum equations are discretized for each particle using a kernel smoothing function used to evaluate each particle's properties and the acting fluxes/forces using neighboring particles.




Lescoe 2010
(PAM-SHOCK)

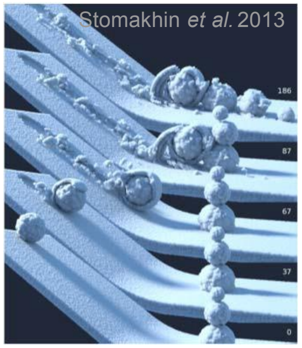

Shahram Shokouhfar
LS-DYNA FE-SPH
Tire model 2015

- **Advantages:**
  - Can be used for large soil deformation including soil flow, separation/reattachment, and adhesion with vehicle components.
- **Disadvantages:**
  - Large number of particles.
  - Computationally slower than DEM since a particle does not only interact with its immediate neighbors but with all the particles within the kernel radius.
  - Relies on a continuum mechanics formulation. Currently, there is no general constitutive material model can account for all mechanical soil effects.

Macro-scale soil models: Particle Methods: MPM

- A Cartesian grid is used along with the particles to discretize and solve the continuum mechanics governing equations.


Stomakhin *et al.* 2013

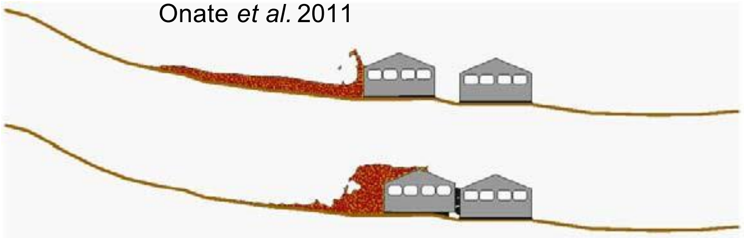

Stomakhin *et al.* 2013

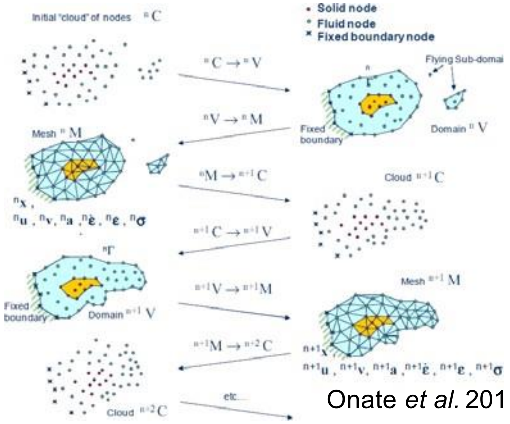
Al-Kafaji 2013


- **Advantages:**
  - Can be used for large soil deformation including soil flow, separation/reattachment, and adhesion with vehicle components.
- **Disadvantages:**
  - Large number of particles.
  - Relies on a continuum mechanics formulation. Currently, there is no general constitutive material model can account for all mechanical soil effects.

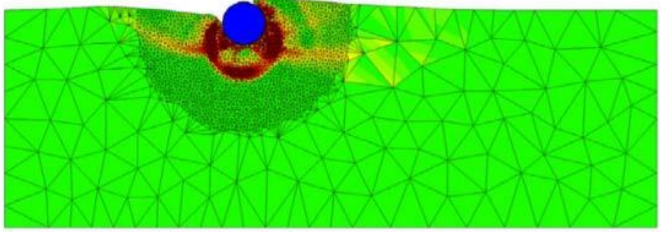
Macro-scale soil models: Particle Methods: PFEM

- The particles are used to generate a polyhedral finite element mesh every time step using an extended Delaunay tessellation. The solution of the continuum mechanics governing equations is then carried using that mesh.


Onate *et al.* 2011



Onate *et al.* 2011

Zhang et al. 2013


- **Advantages:**
  - Can be used for large soil deformation including soil flow, separation/reattachment, and adhesion with vehicle components.
- **Disadvantages:**
  - Large number of particles.
  - More computationally intensive in 3D than other particle methods due to the Delaunay tessellation step.
  - Relies on a continuum mechanics formulation. Currently, there is no general constitutive material model can account for all mechanical soil effects.

Complex Terramechanics Model Technology Readiness

Measure	Lagrangian/ALE FEM	Eulerian FEM	DEM	SPH	MPM	PFEM
Accuracy/generality of soil material models	5	3	8	6	6	6
Range of soil deformation	4	9	9	9	9	9
Ability to include embedded obstacles	3	7	9	9	9	9
Fidelity of the soil-vehicle interface	5	7	8	8	8	5
Computational speed	5	7	6	5	6	2
Experimental Validation	4	4	6	5	4	2
Current use in vehicle mobility	5	4	8	6	5	2
Total	**31**	**41**	**54**	**48**	**47**	**35**

Motivation for Complex Terramechanics

Enable accurate (higher accuracy that ST or NRMM) prediction of vehicle mobility for:

- Operational analysis/mission planning (generating mobility maps using GIS).
  - CT models can be used along with response surface/machine learning surrogate models to provide fast vehicle mobility prediction.
- Improve vehicle design for off-road mobility.
- Allow more accurate and faster evaluation of alternative vehicle systems/designs during acquisition.
- Accident reconstruction.
- Virtual rehearsing of physical tests.

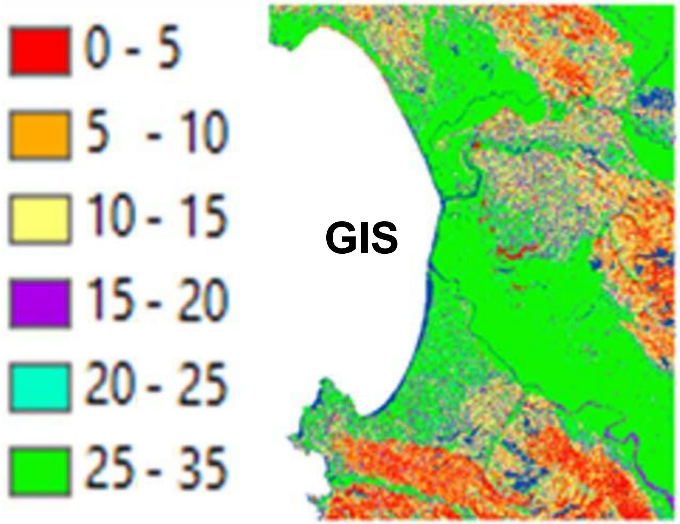
Objectives of the Complex Terramechanics Thrust Area

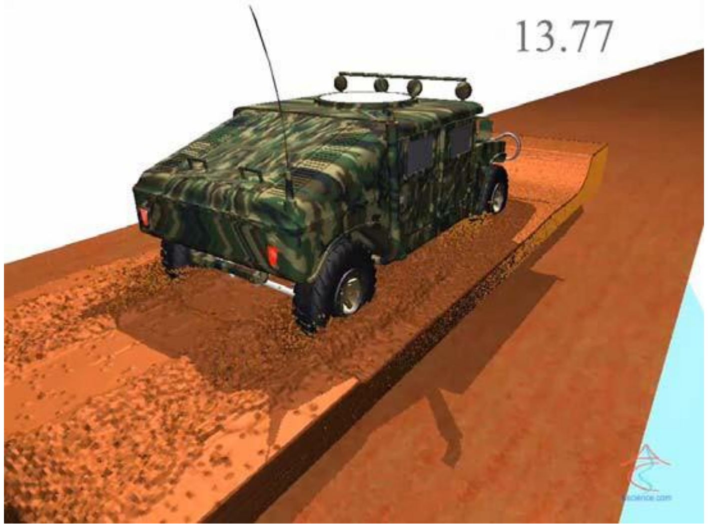
- Provide a set of CT requirements which will guide development of CT software tools and associated calibration and validation experiments for the NG-NRMM. Those requirements will be documented in a NATO STANREC.
- Create CT prototypes which attempt to satisfy the requirements. CT prototypes can be used:
  - As examples for other CT software tools
  - To demonstrate that the requirements are achievable in a relatively short term.

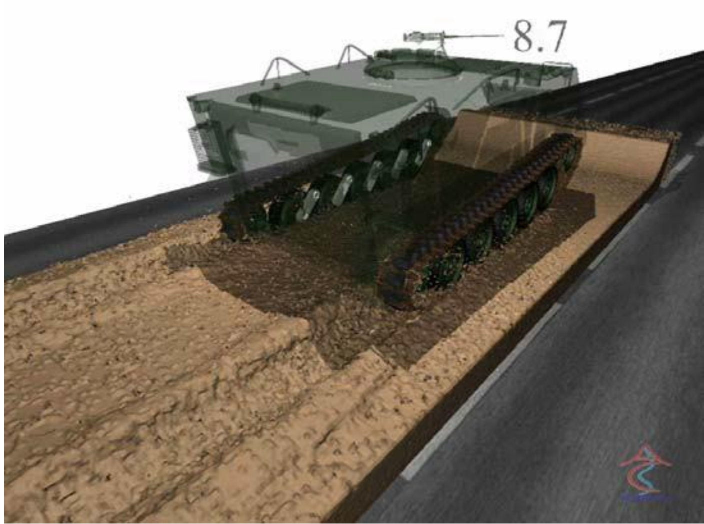
CT Requirements: Ability to predict vehicle mobility measures

GO/NOGO	Speed	Fuel/energy consumption	Engine torque/power
Engine RPM	Sinkage	Slip	Tire deflection
Suspension deflection	Drawbar pull	Absorbed vibration power	Components stresses/forces
Acceleration	Braking distance	Rollover	Loss of traction
Loss of directional control	Vehicle control activity	Factors limiting performance	

Direction
Omni value
Down-hill value
Up-hill value
Side-hill value
Along a specified direction
Along the traverse direction

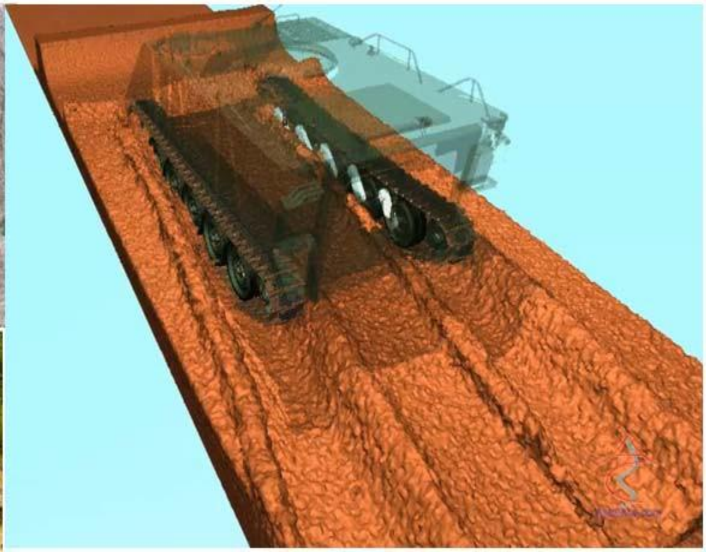


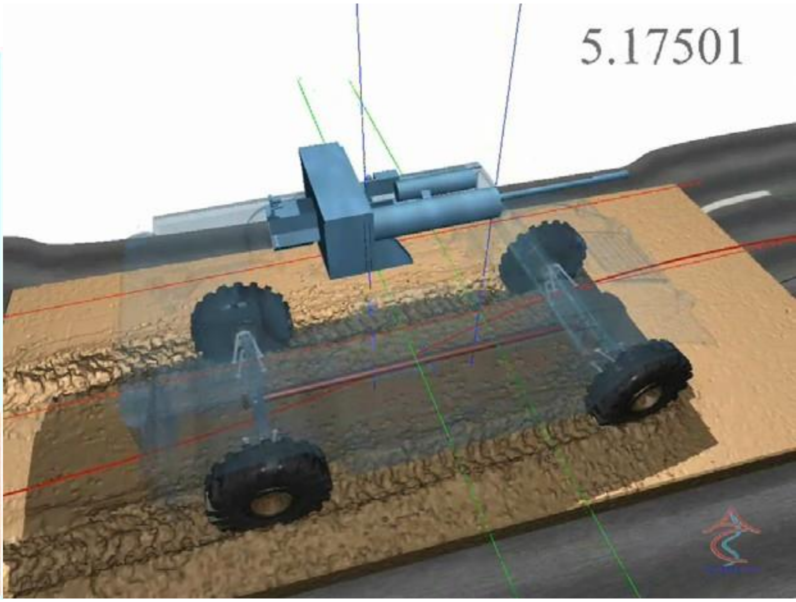




CT Requirements: Ability to predict terrain vehicle mobility measures

Rut depth	Rut width	Rut shape	Rut side wall height	Road damage



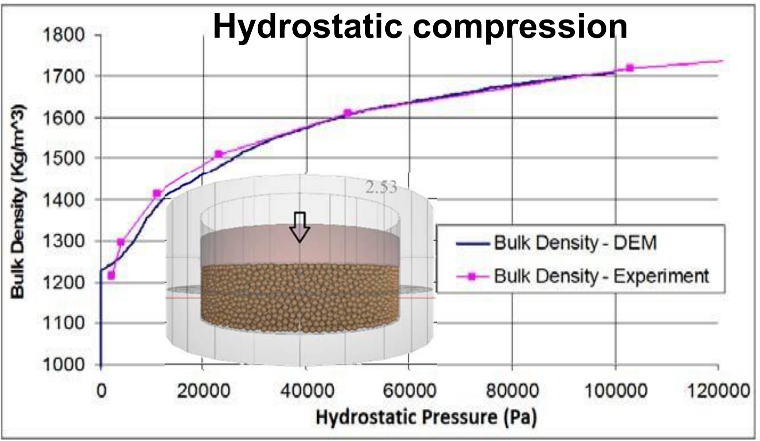


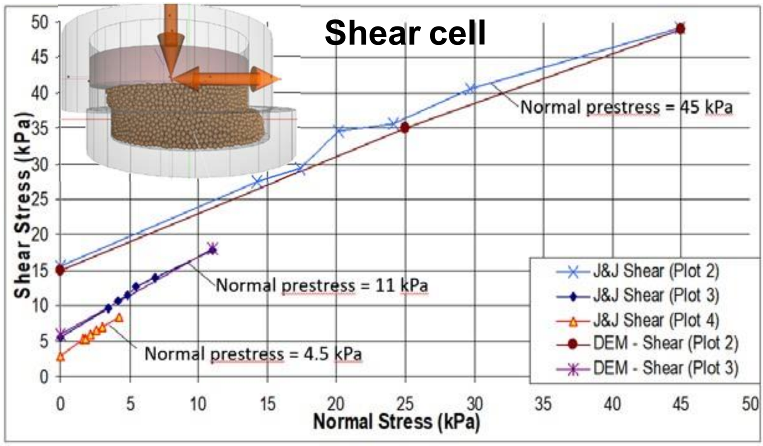
CT Requirements: Reproduce the mechanical response of worldwide soils/terrains

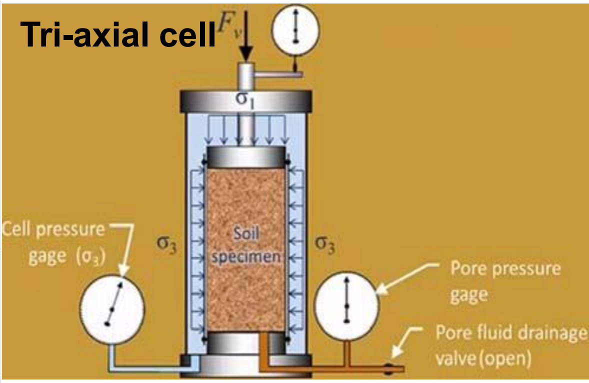
- **Main effects that CT must be able to account for:**
  - Traction of the vehicle running gear:
    - Friction between terrain and running gear
    - Soil shear strength: internal soil friction & cohesion.
  - Change in soil bulk density as a function of compaction.
  - Change in soil shear strength as a function of compaction.
  - Velocity dependent soil forces: damping and viscous forces.
  - Soil dilation.
  - Adhesion of the soil to the vehicle surfaces.
- **CT models must be able to reproduce those effects for:**
  - World-wide soils - all USCS (Unified Soil Classification System) soil types.
  - Range of moisture: dry to saturated.
  - Soil compaction: loose to highly compacted.
  - Temperature: below freezing to > 40º

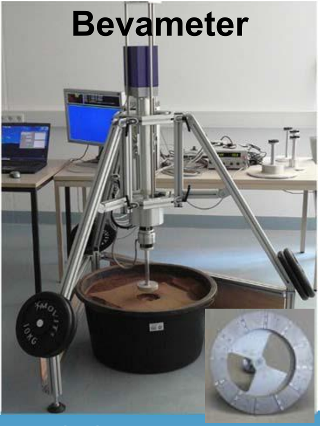
CT Requirements: Predict soil response in terramechanics experiments

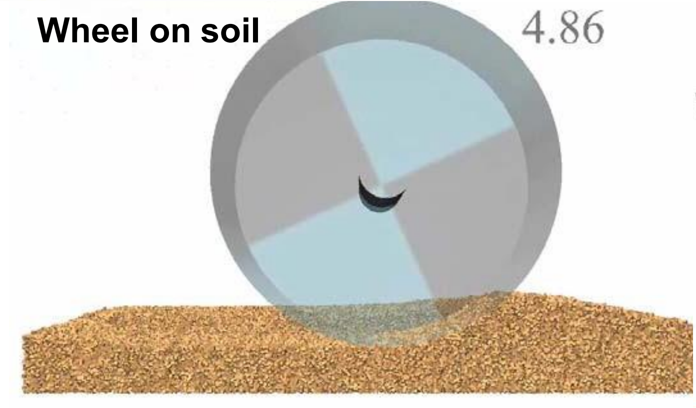
- The terramechanics experiments are used to calibrate the CT model parameters.

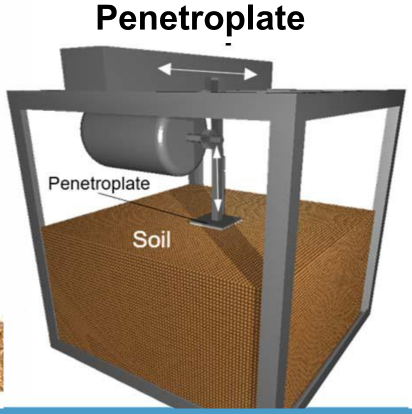

Hydrostatic compression

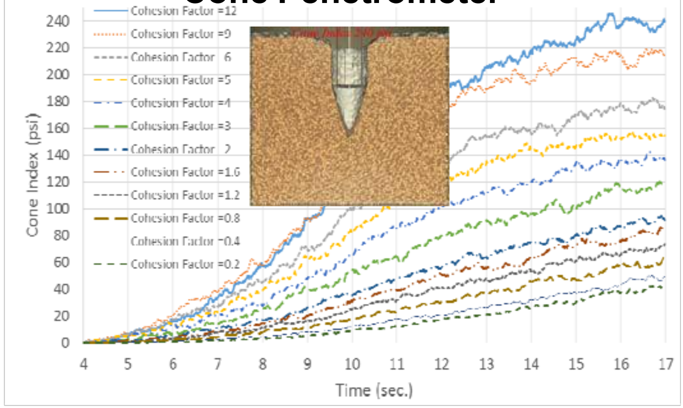

Shear cell


Tri-axial cell

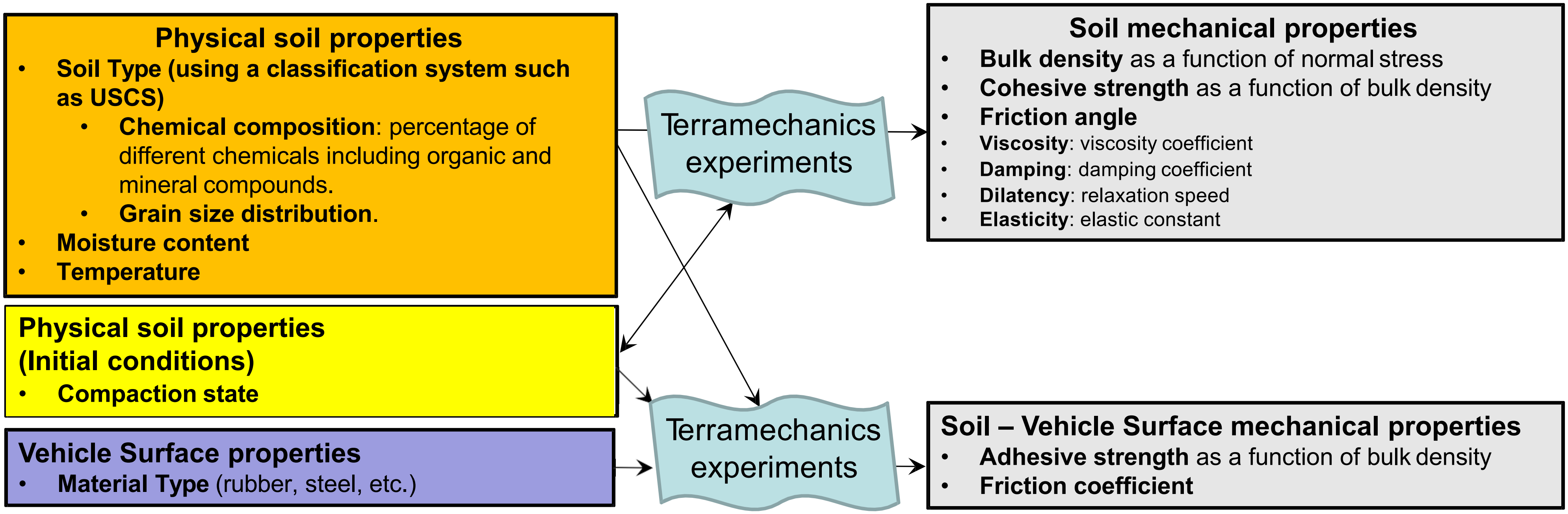

Bevameter


Wheel on soil


Penetroplate


Cone Penetrometer

CT Requirements: Mapping physical soil properties into mechanical soil properties



Physical soil properties

- **Soil Type (using a classification system such as USCS)**
    - **Chemical composition**: percentage of different chemicals including organic and mineral compounds.
    - **Grain size distribution.**
- **Moisture content**
- **Temperature**

Physical soil properties (Initial conditions)

- **Compaction state**

Vehicle Surface properties

- **Material Type** (rubber, steel, etc.)

Soil mechanical properties

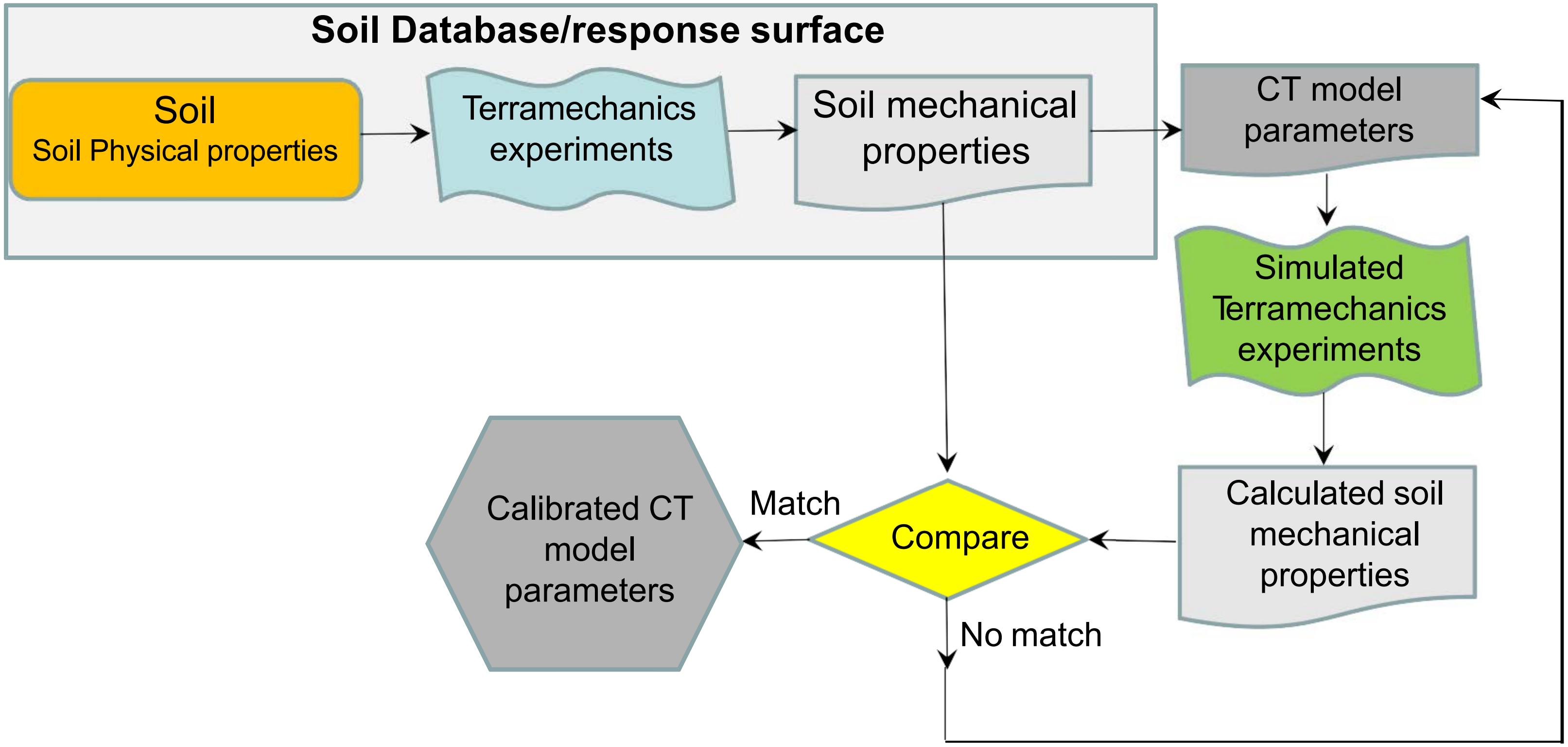
- **Bulk density** as a function of normal stress
- **Cohesive strength** as a function of bulk density
- **Friction angle**
- **Viscosity**: viscosity coefficient
- **Damping**: damping coefficient
- **Dilatency**: relaxation speed
- **Elasticity**: elastic constant

Soil – Vehicle Surface mechanical properties

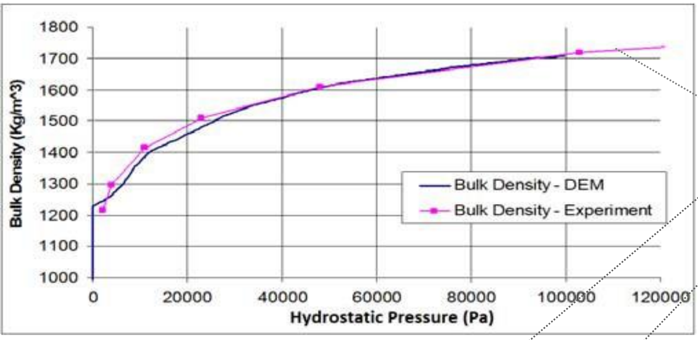
- **Adhesive strength** as a function of bulk density
- **Friction coefficient**

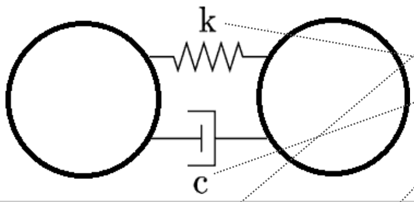
- A **soil database/response surfaces** can be created to produce for any **physical soil properties** the corresponding **soil mechanical properties**.
- ~700 terramechanics experiments (20 soil types × 7 moisture content × 5 temp.) needed to develop database.
- A micro-mechanical soil model can be developed to help reduce the number of experiments.

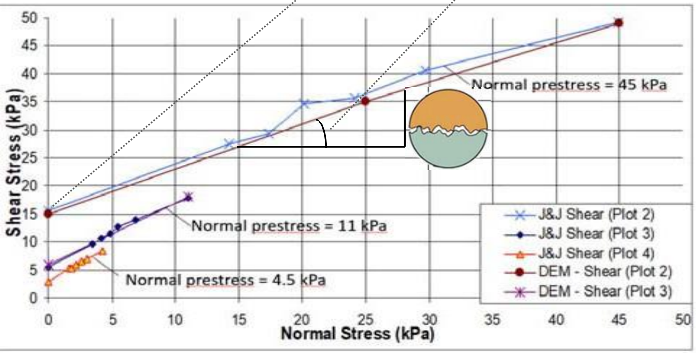
CT Requirements: Mapping mechanical soil properties into CT model parameters



Complex Terramechanics Prototype Soil DEM Model







Soil DEM model parameters

Particle mass

Bulk density/plastic strain vs normal stress

Max adhesion stress (cohesive strength) vs plastic strain.

Friction angle

Viscosity

Damping

Dilatency

Elasticity (repulsion force)

Particle Shape

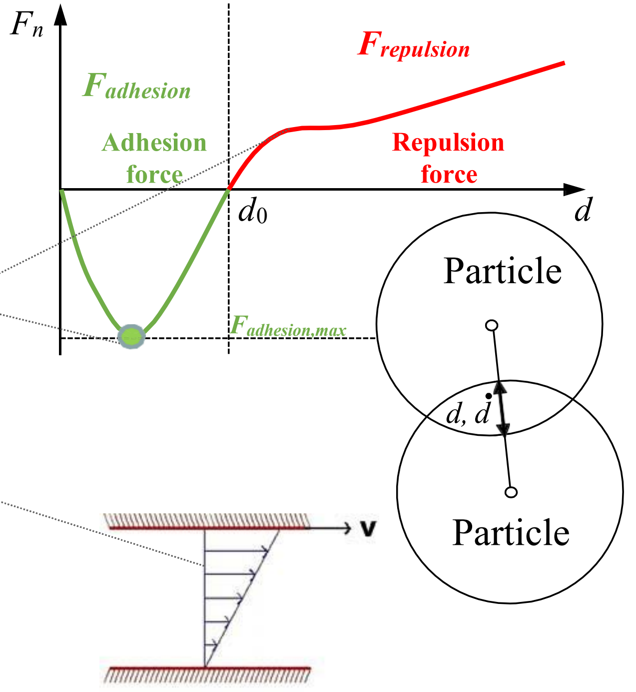
Soil – Vehicle Surface mechanical properties

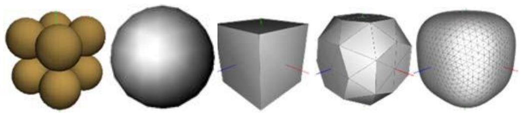
Max adhesive stress as a function of plastic strain

Friction coefficient

Damping

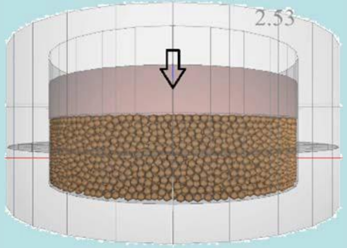
Viscosity





ASA DEM Soil Model Calibration for the CDT

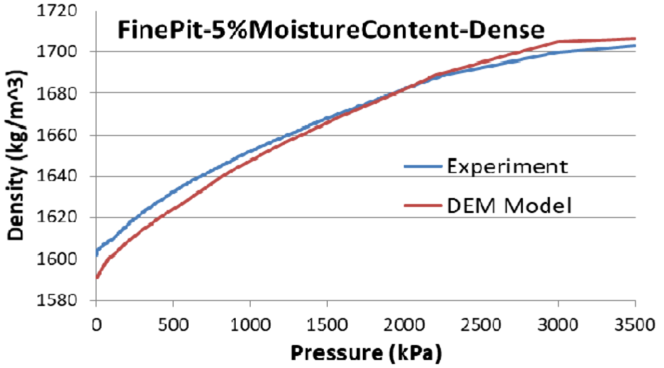
1. Hydrostatic compression test



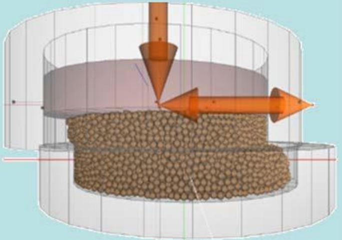
Experiment: Bulk density vs Pressure

↓

DEM Model: Plastic strain vs Compression stress



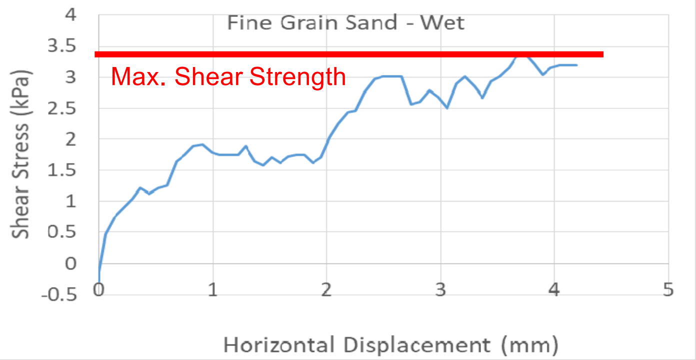
2. Shear cell



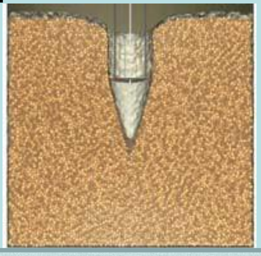
Experiment: Shear strength under 0 normal load after 60 s consolidation under 148.6 kPa

↓

DEM inter-particle adhesion stress as a function of plastic strain (cohesion)



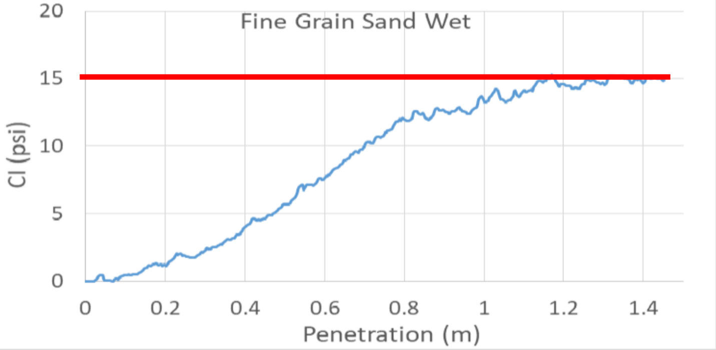
3. Cone penetrometer (in situ)



Experiment:
Cone Index: Max normal stress in psi

↓

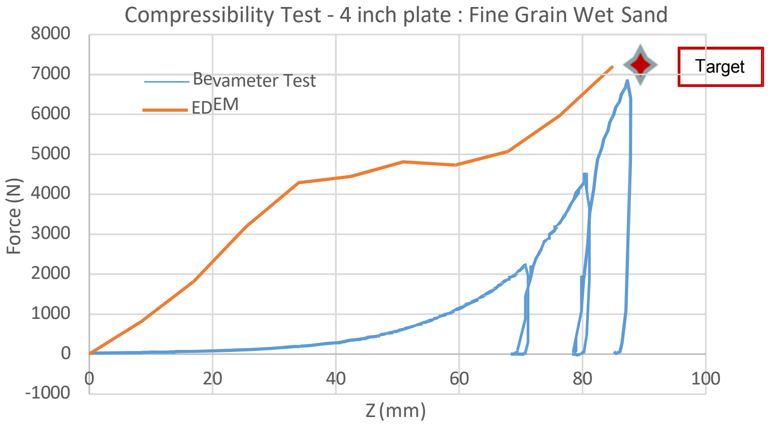
DEM inter-particle friction coefficient



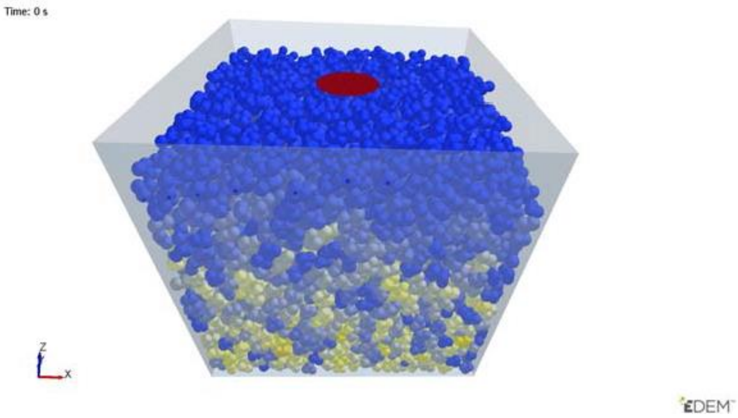
MSC/EDEM DEM Soil Model Calibration for the CDT - Pressure-Sinkage

- For pressure–sinkage tests, circular plates of 4” diameter used.
- Sinkage values from test were used as inputs to DEM model.
- Reaction forces from the DEM model were compared to pressure loading in the test.

Physical test @ KRC



Virtual EDEM Simulation



Challenges:
- Mismatch between test scale and vehicle scale
- No process to maintain properties with changing particle size
- Large particles relative to test add noise to simulation
- Limited Time for calibration due to project schedule.

Calibration Target: Roughly appropriate soil behavior

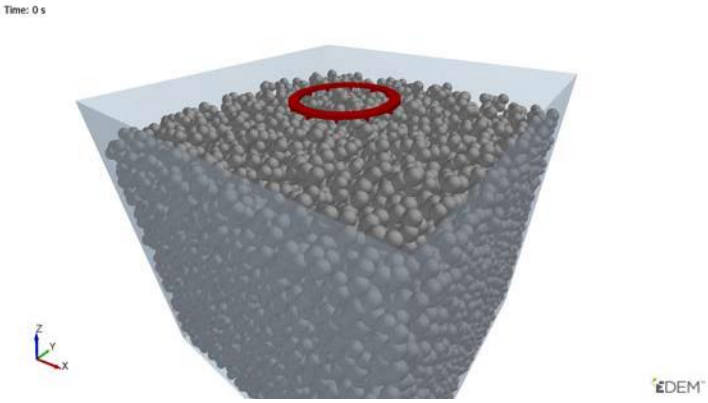
Improvements possible with added iterations on particle properties

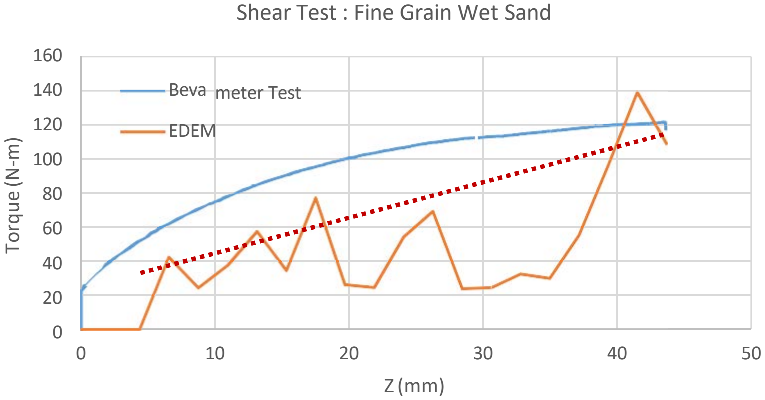
MSC/EDEM DEM Soil Model Calibration for the CDT - Shear Test

- For Shear tests , Steel grouser with diameter 13.3” inches were used.
- Sinkage values and grouser rotation angle from test were used as inputs to DEM model.
- Reaction torque from the DEM model were compared to torque values from test

Physical test @ KRC

Virtual EDEM Simulation





The particles participating in contact with the grouser have high variability, due to their large size. The resulting grouser torque contains significant noise.

Curve trend indicates rough agreement with test

- **Calibrated Properties associated to material**
  - ν-Poisson’s ratio – 0.25
  - G-Shear modulus [Pa] - 1.5E+8 Pa → Shear Test
  - μs-Coefficient of static friction - 0.5
  - μr-Coefficient of rolling friction - 0.2
  - e-Coefficient of restitution - 0.7

Sinkage Test

CDT , Aug 31, 2018

CT Requirements: Terrain conditions: Heterogeneous terrain

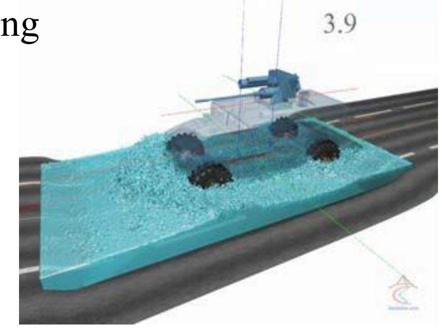
Heterogeneous terrains are multi-component terrains, including:

- Terrains with discrete patches of different soil types
- Terrains with embedded boulders, rocks, stones, and/or gravel.

The discrete terrain component can be specified by its size, shape, and spacing distributions as well as its mechanical properties.

CT Requirements: Terrain conditions: Water covered terrain

Fording



Swimming

Main effects that CT must be able to account for:

1. Water resistance to vehicle motion.
2. Soil entrainment/suspension.
3. Air bubble entrainment.
4. Soft soil water bottom.
5. Water currents.
6. Water waves.
7. Multiple solid bodies moving in the fluid.
8. Liquid free surface.
9. Propellers and water jets.
10. Transition of the vehicle from solid terrain to flooded terrain and vice versa.
11. Different types of water bodies including swamps, rivers/streams, lakes, and seas/oceans.

Water is modeled using SPH in the CT prototype

CT Requirements: Terrain conditions: Multi-layer terrain

Tilled soil

Organic muskeg soil

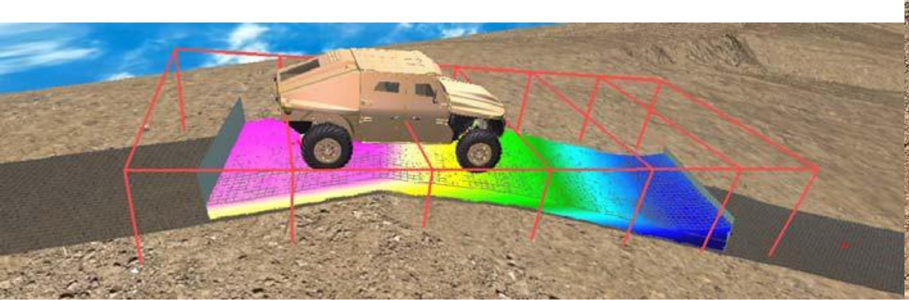
Snow

- A layer is defined by its thickness and the soil mechanical properties.
- CT tools should support at least 2 soil layers.

CT Requirements: Terrain conditions: Complex topography terrain

Complex terrain topography includes:

1. Turns
2. Ditches
3. Bumps
4. Long +ve/-ve Slopes
5. Side Slopes
6. Roughness.



CT Requirements: Terrain conditions: Vegetation

Handle all vegetation types in the US National Vegetation Classification (USNVC)

CT Requirements: Terrain conditions: Obstacles

Obstacles include:

- Natural obstacles: Rocks/boulder
- Poles,
- Walls: brick, concrete, and sheet metal
- Fences: metal wire, metal bars, and wood.
- Bridges
- Tunnels
- Vehicles
- Debris
- Small structures.

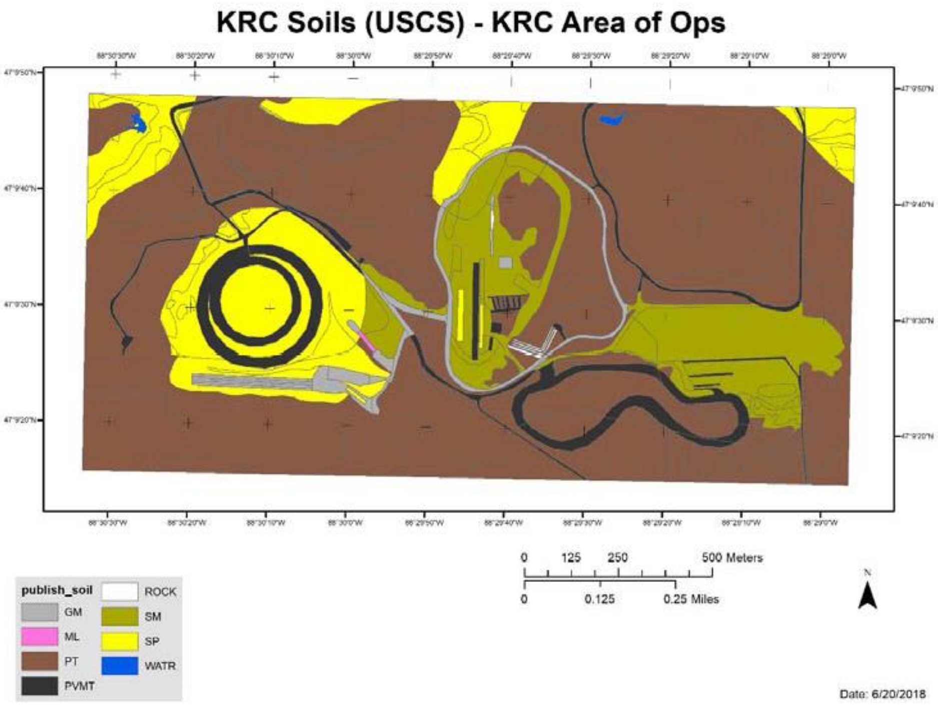
Effect the CT models should handle includes:

- Mechanical compliance and strength of the obstacle.
- Interaction of the obstacle with the soil. The obstacle can be embedded/buried in the soil.
- Obstacle parameters include: type, geometry, mechanical properties.
- Mechanical properties at the interface between the soil and the obstacle.

CT Requirements: Interface with GIS

Terrain map is rasterized into vehicle size cells. For each terrain cell, the following CT input parameters are specified:

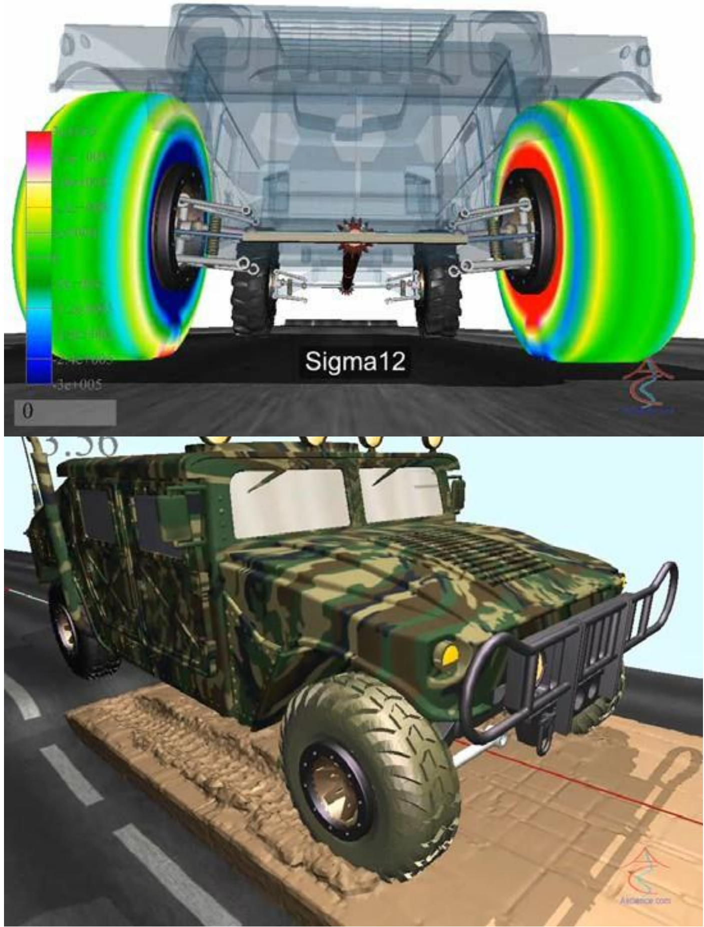
- Terrain topography parameters
  - Elevation/grade/aspect.
  - Roughness. Spectrum of wave length versus roughness/height amplitude.
  - Max. trench/pothole (negative obstacle) width, depth, and spacing.
  - Max. bump (positive obstacle) width, depth, and spacing.
- Soil: Two-Three layers each having:
  - USCS soil type.
  - Moisture.
  - Temperature.
  - Compaction.
  - Layer thickness.
- Heterogeneous terrain.
  - Embedded rocks/debris. Distributions of type, shape, size, and spacing.
- Land use.
- Vegetation
  - Vegetation type
  - Roots sizes and spacing distributions.
  - Stems sizes and spacing distributions.
- Urban obstacles: Buildings; Poles; Walls (brick, concrete, etc.); Fences; Structures; vehicles; debris.



CT Requirements: Coupling with MBD software tools for modeling the vehicle

This includes ability to model the following:

1. **Pneumatic tires**,
2. **Segmented tracks**.
3. **Continuous tracks**.
4. Other vehicle parts which can interact with the terrain:
   Underbody; **legs**; **blades**; **buckets**; **Tines**.
5. Vehicle systems necessary for mobility:
   Suspension system; **Steering system**; **drive-line**; **axles**; **engine**; **brakes**.
6. **Vehicle Controls**: ESC, ABS, and VI.
7. **Payloads**.
8. **Occupants**.
9. **Trailers**.
10. **Vehicle convoys/multiple vehicles.**
11. Ability to model the various types of **vehicle maneuvers** on any terrain in the full vehicle speed range.
12. **Stranded vehicle rescue/retrieval**.



NG-NRMM Complex Terramechanics State of Technology

Complex Terramechanics prototype currently include the following capabilities:

- General DEM soil model which can account for: bulk density, friction, cohesion, elasticity, damping, plasticity viscosity, and dilation, including dependence of those effects on soil compaction.
- CT models have been validated and calibrated for use in vehicle mobility applications during the NG-NRMM benchmarking and CDT phases.
- DEM model runs in distributed & shared parallel processing modes.
- Complex topography terrains.
- Integrated with MBD vehicle dynamics software (two-way coupling).
    - ➢ Integrated with a high-fidelity FE tire model.
- Integrated with GIS for inputting the terrain data and outputting vehicle mobility maps.
- Integrated with DOE, response surface surrogate models, and UQ tools for fast generation of vehicle mobility maps.

NG-NRMM Complex Terramechanics Future Developments

- Validate of the CT soil models for all soil types.
- Develop a database of calibrated CT soil models, including effects of moisture and temperature.
- Fundamental research of micro-scale soil models.
- Investigate/develop a soil classification system designed for vehicle mobility applications.
- Develop terramechanics experiment to measure soil damping, viscosity, and dilation.
- Improve the parallel scalability of the CT models.
- Develop models for:
  - Multi-layer terrains.
  - Water covered soft soil terrains.
  - Heterogeneous terrain.
  - Vegetation.
  - Urban obstacles.
- Validation/calibration of finite Element tire – soil models.

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