

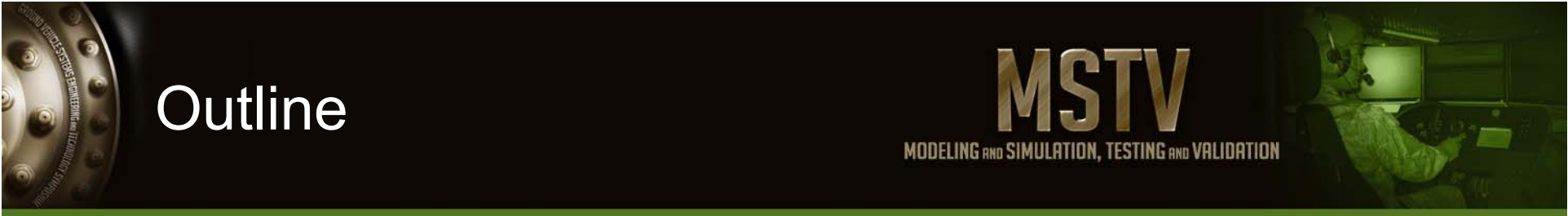


PREDICTION OF VEHICLE MOBILITY ON LARGE-SCALE SOFT-SOIL TERRAIN MAPS USING PHYSICS-BASED SIMULATION

Tamer M. Wasfy, Paramsothy Jayakumar,
Dave Mechergui, Srinivas Sanikommu

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Outline

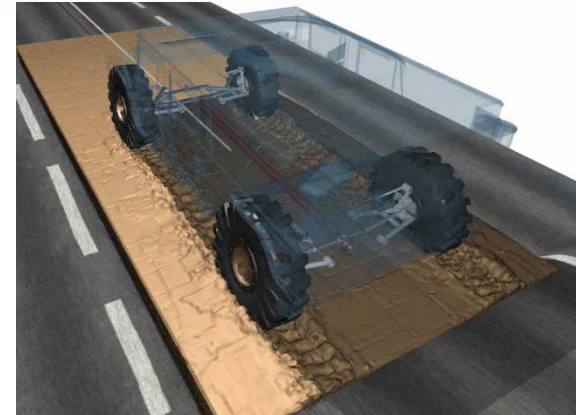
- Motivation: NRMM
- Objectives
- Soft Soils
- Review of Physics-Based Soil Models
- MBD/DEM Modeling Formulation
 - Joint & Contact Constraints
 - DEM Cohesive Soil Model
- Cone Penetrometer Experiment
- Vehicle-Soil Model
- Vehicle Mobility DOE Procedure
- Simulation Results
- Concluding Remarks

Motivation/NRMM

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- Mobility measures include:
 - Speed-made-good.
 - Fuel consumption.
 - Vibration power transmitted to occupants/payloads.
- Currently Army uses NRMM (developed in 1970's) to predict speed-made-good maps.
- NRMM is based on empirical relations and considers the following terrain variables:
 - Soil cone index (CI); surface cover (normal, water or snow); grade (uphill, downhill, and side); surface roughness; mound/trench obstacle size and spacing; tree/vegetation stem size and spacing; visibility.
- Empirical relations tuned using 1960's to 1980's military vehicles.
- NRMM may not be accurate for new military vehicles: oversized wheels/tracks; small robotic vehicles; airless tires; belt-type tracks; vehicles with independent suspension or control technologies such as ABS, TCS, ESC, etc..
- Tuning the empirical relations is very expensive and time consuming.

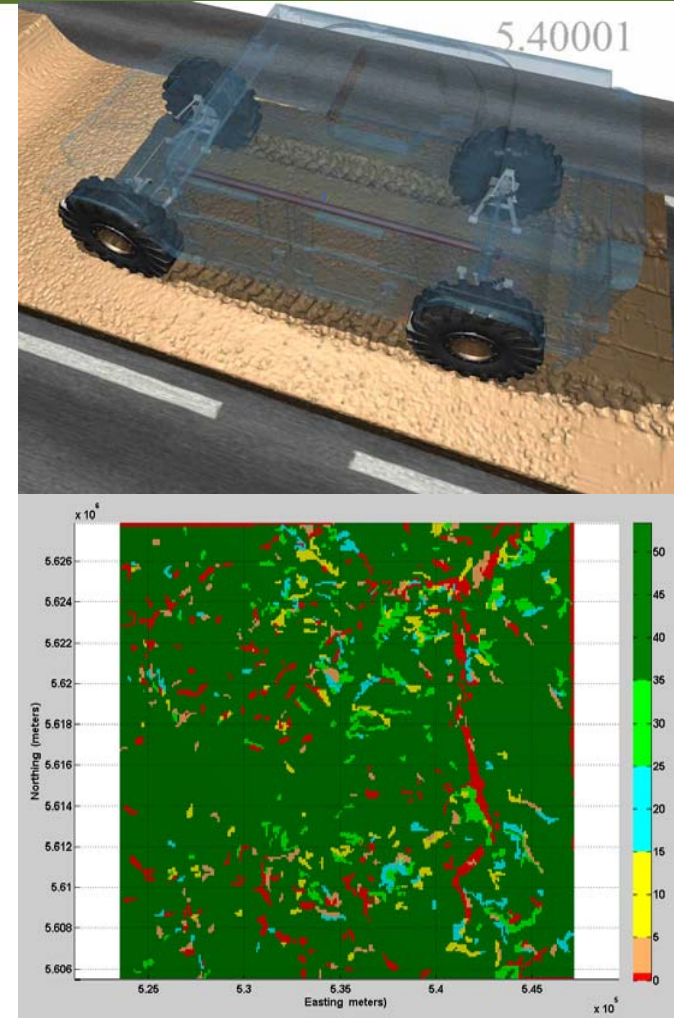


Objectives

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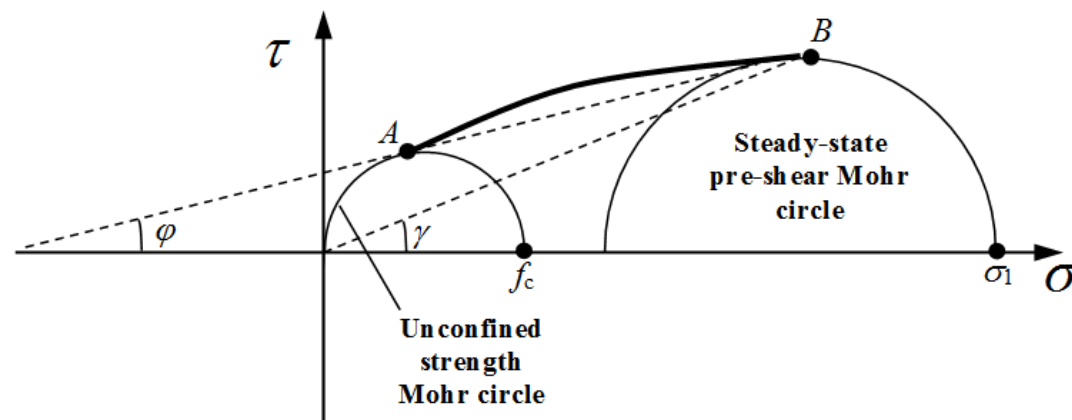
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- Develop a **high-fidelity physics-based** technique to accurately and reliably predict vehicle mobility maps over large-scale off-road terrain maps.
- The focus of the paper is on only two terrain variables:
 - Soil shear strength measured by the Cone Index (CI).
 - Terrain uphill grade.
- Rest of the terrain parameters will be considered in future work.



Terrain map (22 km x 22 km) colored by speed-made-good in mph

- Soft soils can be divided into: cohesive and non-cohesive.
- This paper focuses on cohesive soils.
- Cohesive soils modeling challenges:
 - Bulk density & shear strength increase with normal compressive stress.
 - Bulk density & shear strength values are maintained after removal of the normal compressive stress (consolidation/memory effect).
 - Bulk density & shear strength values decrease when the soil is subjected to normal tensile stress (relaxation effect).
 - Nonlinear elastic, damping, viscous, and friction response.





Physics-Based Soil Models

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Physics-based models for soil include:

- Height-field models.
- Finite Element models.
- Particle-based models.
 - Smoothed Particle Hydrodynamics (SPH)
 - Material Point Method (MPM)
 - Discrete Element Method (DEM)

Physics-Based Soil Models

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- Height-field models

- Calculate normal & tangential forces between a tire/track shoe and a plastically deformable soil surface based on sinkage and relative normal & tangential velocities.
- Implemented in most commercial multibody dynamics software.
- Advantages: Fast.
- Disadvantages:
 - Bias in vertical direction.
 - Difficulty with long and side sloped terrains.
 - Inability to correctly account for the state of 3D flow/deformation/stress in the soil.
 - Ruts, heaps, and soil separation/reattachment not accurately modeled.
 - Accuracy range limited to small-moderate soil deformation.

Madsen et al. 2013



Physics-Based Soil Models

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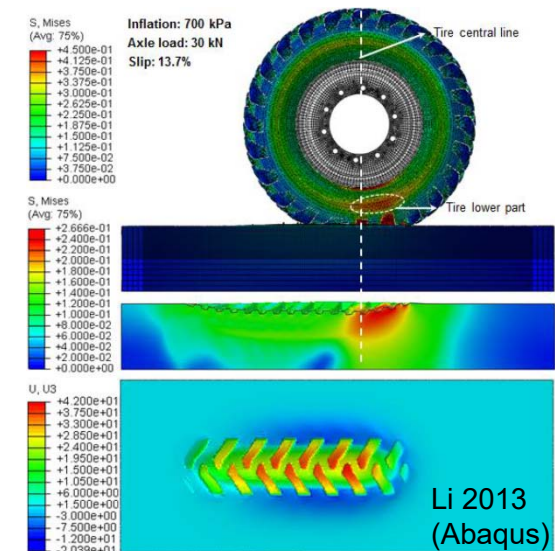
- Finite element models

- Advantages

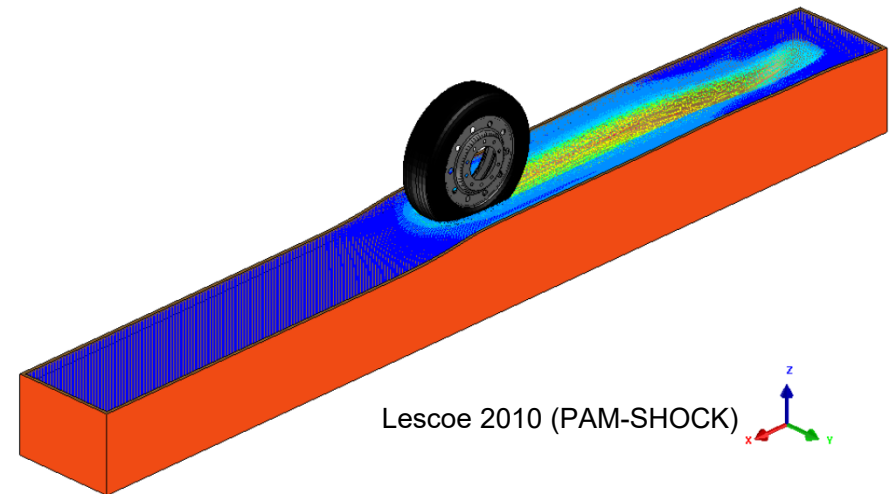
- Element size can be spatially varied.

- Disadvantages

- Soil constitutive models (eg. Drucker-Prager-Cap) cannot automatically account for flow.
 - Constitutive material model which accounts for: flow, fracture, plasticity, friction, and cohesion, and their dependence on stress/stress history is an open research problem.
 - ALE can be used to model flow. However, special treatment is needed to avoid small node mass.
 - Inability to capture soil separation/reattachment without special techniques such as VOF and level-set.
 - Difficult to capture large deformation effects (ruts & heaps) since remeshing is needed.
 - Remeshing reduces solution accuracy since the solution fields must be re-interpolated to the new mesh.
 - Remeshing is computationally expensive.

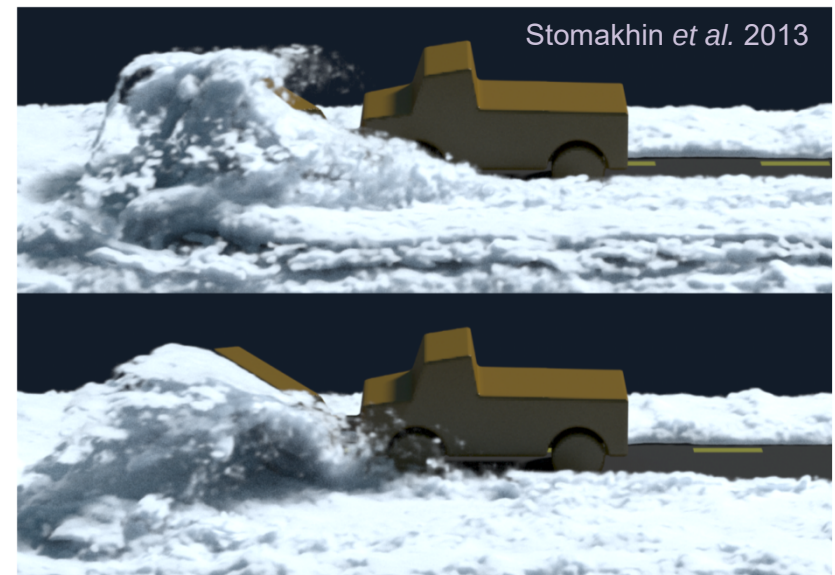


- Smooth particle hydrodynamics (SPH)
 - The continuum mechanics governing equations are discretized for each particle using a kernel smoothing function used to evaluate (interpolate) each particle properties and fluxes using neighboring particles.
 - Advantages
 - Can easily account for large material deformation, flow, and separation/reattachment.
 - Disadvantages
 - Large number of particles are needed
→ Computationally expensive.
 - Rely on a continuum mechanics formulation, and therefore, requires a continuum mechanics cohesive soil constitutive material model.



Lescoe 2010 (PAM-SHOCK)

- Material-Point-Method (MPM).
 - A Cartesian grid is used along with the particles to find neighboring particles as well as to discretize and solve the continuum mechanics governing equations.
 - Advantages
 - Can easily account for large material deformation, flow, and separation/reattachment.
 - Disadvantages
 - Large number of particles are needed
→ Computationally expensive.
 - Rely on a continuum mechanics formulation, and therefore, requires a continuum mechanics cohesive soil constitutive material model.



Physics-Based Soil Models

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- Discrete Element Method (DEM)

- Material behavior modeled using inter-particle forces which include normal (elastic, damping, and cohesive) and tangential (viscous and friction) contact forces.

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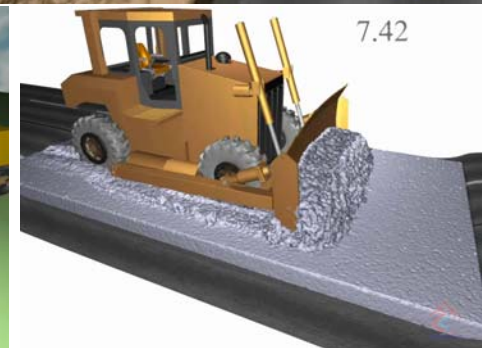
- Advantages

- Can easily account for large material deformation, flow, & separation/reattachment.
- Closer the physics of actual soil particles.
→ easier to develop inter-particle force models.

- Disadvantages

- Large number of particles are needed
→ Computationally expensive.

- ***Chosen for modeling soft soil in this study.***



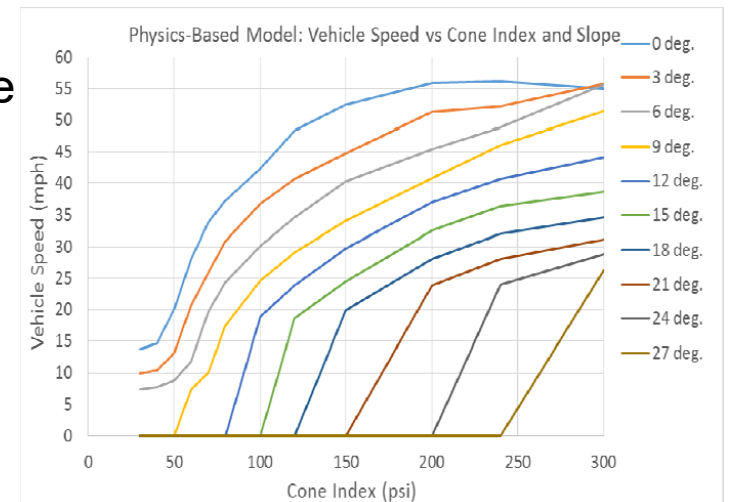
Current Approach

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- **One-solver approach:** DEM and multibody dynamics are seamlessly integrated into one explicit time-integration solver.
 - **General cohesive soil material DEM model.**
 - **High-fidelity multibody dynamics model** of a typical 4x4 military vehicle.
 - The cone index is calibrated to the DEM soil model using a **simulation of a cone penetrometer experiment.**
 - To enable predicting high vehicle speeds (up to 60 mph), a **moving soil patch strategy** is used.
- **An HPC-based DOE procedure** is used to generate the terrain mobility maps, considering two terrain variables: Cone index and up-hill slope.



MBD/DEM Formulation

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- Semi-discrete translational and rotational equations of motion:

$$M_K \ddot{x}_{Ki}^t = F_{s_{Ki}}^t + F_{a_{Ki}}^t \quad I_{Kij} \ddot{\theta}_{Kj}^t = T_{s_{Ki}}^t + T_{a_{Ki}}^t - \left(\dot{\theta}_{Ki}^t \times (I_{Kij} \dot{\theta}_{Kj}^t) \right)_{Ki}$$

- Lumped mass and inertia matrices are used.
- Rotational equations of motion written in a body (material) frame.
- The equations of motion are integrated using a semi-explicit parallel solution procedure that uses the trapezoidal-integration rule.

$$\begin{aligned} \dot{x}_{Kj}^t &= \dot{x}_{Kj}^{t-\Delta t} + 0.5 \Delta t (\ddot{x}_{Kj}^t + \ddot{x}_{Kj}^{t-\Delta t}) & \dot{\theta}_{Kj}^t &= \dot{\theta}_{Kj}^{t-\Delta t} + 0.5 \Delta t (\ddot{\theta}_{Kj}^t + \ddot{\theta}_{Kj}^{t-\Delta t}) \\ x_{Kj}^t &= x_{Kj}^{t-\Delta t} + 0.5 \Delta t (\dot{x}_{Kj}^t + \dot{x}_{Kj}^{t-\Delta t}) & \Delta \theta_{Kj}^t &= 0.5 \Delta t (\dot{\theta}_{Kj}^t + \dot{\theta}_{Kj}^{t-\Delta t}) \end{aligned}$$

- The incremental rotations are added to the total body rotation matrix.

$$R_K^t = R_K^{t-\Delta t} R(\Delta \theta_{Ki}^t)$$

- Translational DOFs referenced to the global inertial reference frame.
- Rigid-body rotations referenced to a body-fixed frame.

Joints

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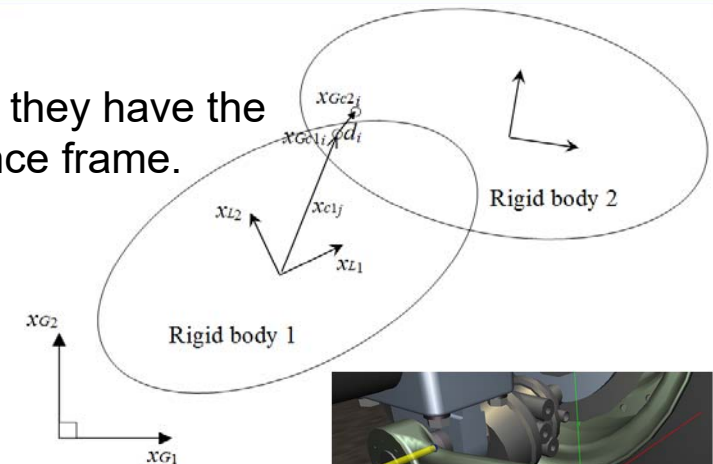
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- **Penalty formulation is used for all joints.**
- **Spherical Joint:** Constrains 2 points on 2 bodies such that they have the same translational coordinates relative to the global reference frame.

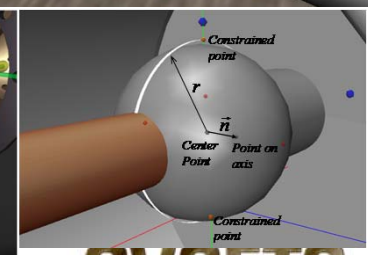
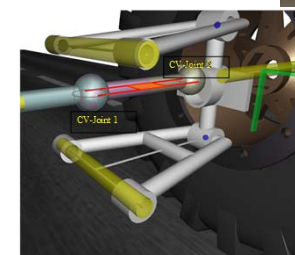
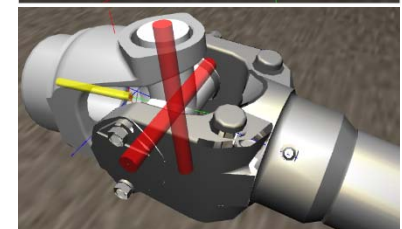
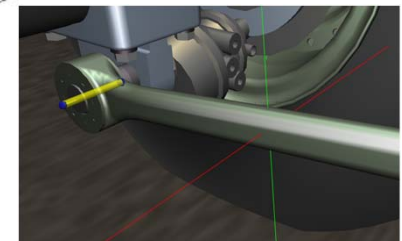
$$F_p = k_p d + c_p d_i \dot{d}_i / d$$

$$d_i = X_{c1i}^t - X_{c2i}^t \quad \dot{d}_i = \dot{X}_{c1i}^t - \dot{X}_{c2i}^t$$

$$d = \sqrt{d_1^2 + d_2^2 + d_3^2} \quad F_{p_i} = F_p d_i / d$$

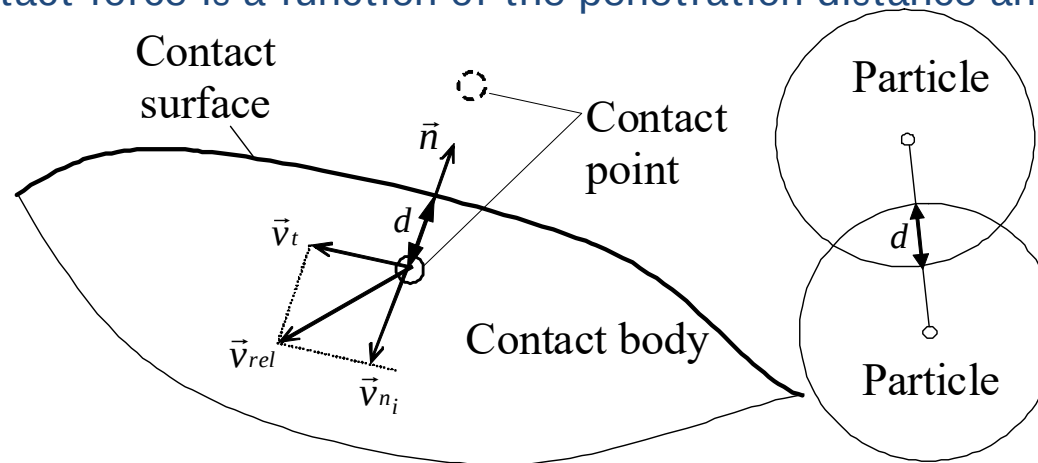


- **Revolute joint** 2 spherical joints along a line
- **Universal joint** 2 perpendicular revolute joints
- **Bracket joint** 4 non-coincident spherical joints
- **Cylindrical Joint** 2 points restricted to move on a line
- **Prismatic joint** 2 parallel cylindrical joints
- **CV joint** 2 perpendicular cylindrical circular-path joints with 2 points restricted to move along each path



Penalty Contact Model

- The normal contact force is a function of the penetration distance and penetration velocity.



$$F_{c_i} = F_{n_i} + F_{t_i}$$

$$F_{n_i} = n_i |F_n|$$

$$|F_n| = F_{adhesion} + F_{repulsion} + F_{damping}$$

$$F_{repulsion} = f(d) = k_n d$$

$$F_{damping} = g(d, \dot{d}) = \begin{cases} c_n \dot{d} & \dot{d} \geq 0 \\ s_n c_n \dot{d} & \dot{d} < 0 \end{cases}$$

$$F_{t_i} = t_i |F_t|$$

$$|F_t| = F_{viscous} + F_{friction}$$

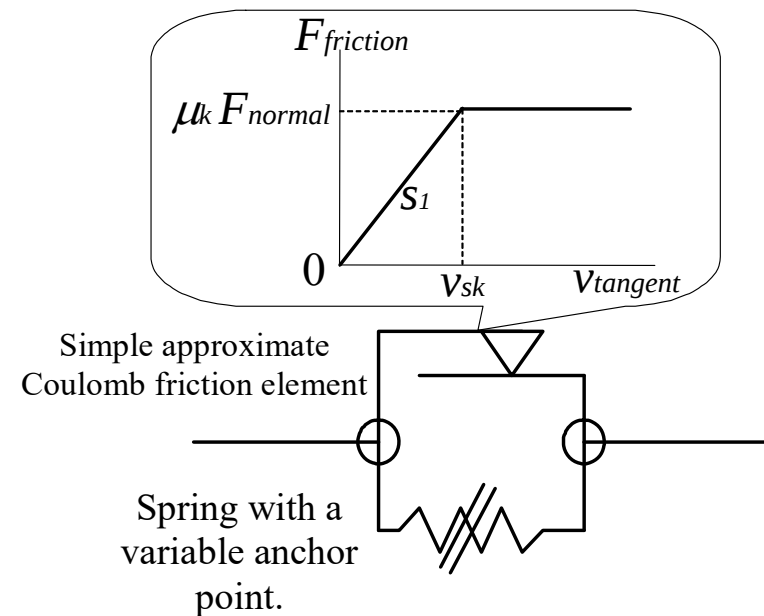
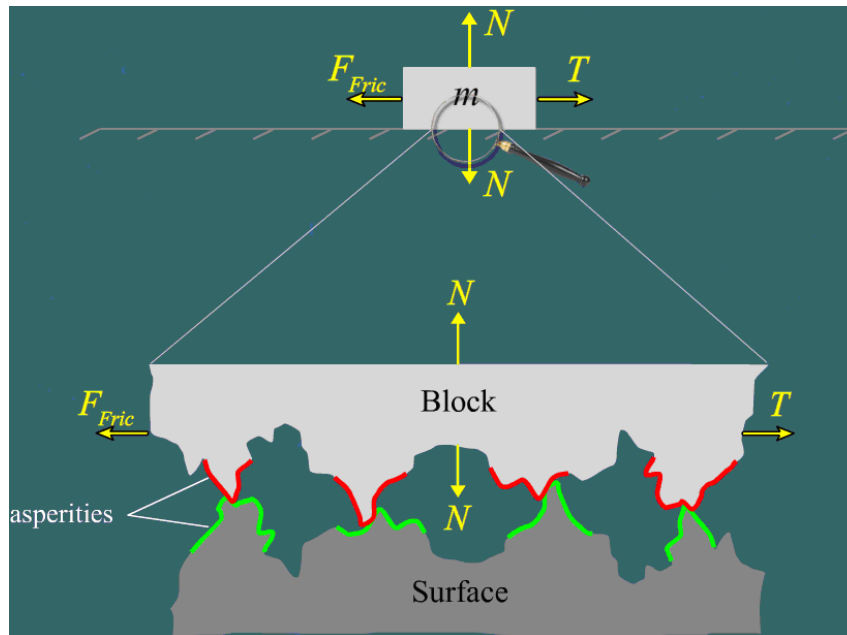
$$F_{viscous} = c_t |v_t|$$

Friction Force Model

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$$|F_t| = F_{viscous} + F_{friction}$$

- Asperity friction model (approximate Coulomb friction model).



DEM Cohesive Soil Model (1/2)

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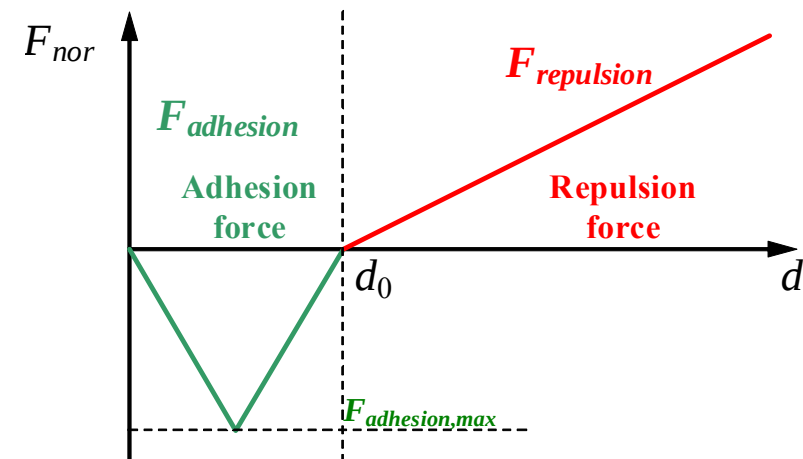
- Spherical point particles (no rotational DOFs).
- The contact force model includes:

- **Normal adhesion and repulsion forces** as a function of penetration (d).

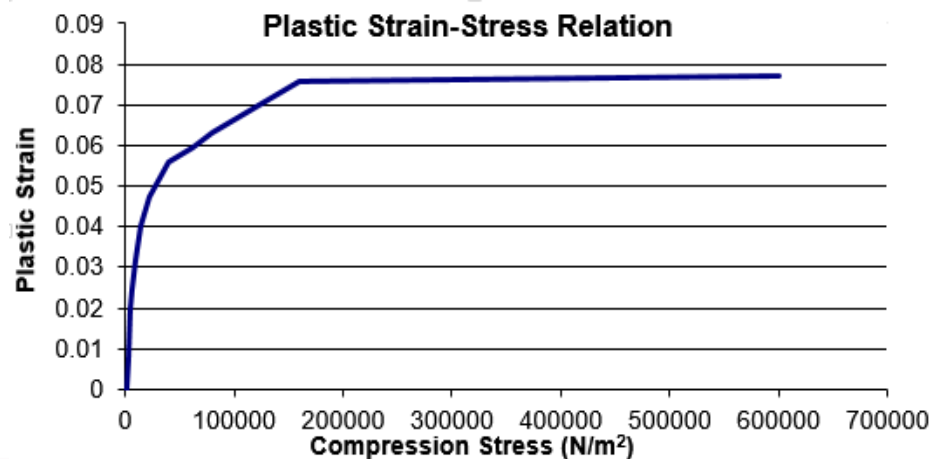
$$|F_n| = F_{adhesion} + F_{repulsion} + F_{damping}$$

- **Tangential forces:**

$$|F_t| = F_{viscous} + F_{friction}$$



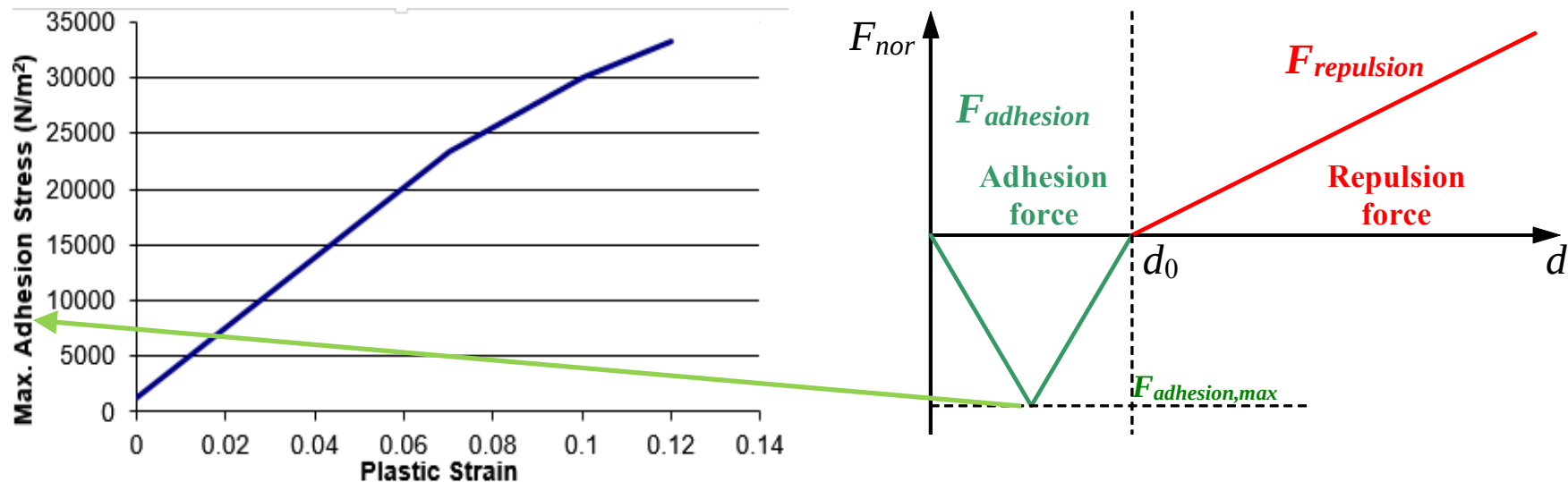
- **Plastic deformation specified as a function of repulsion (compression) force.**



DEM Cohesive Soil Model (2/2)

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- Maximum adhesion force is a function of plastic deformation.



Cohesion factor f used to scale the above graph.

- Time relaxation:** accounts for reduction of soil cohesive strength and soil bulk density when soil is in subjected to tension.

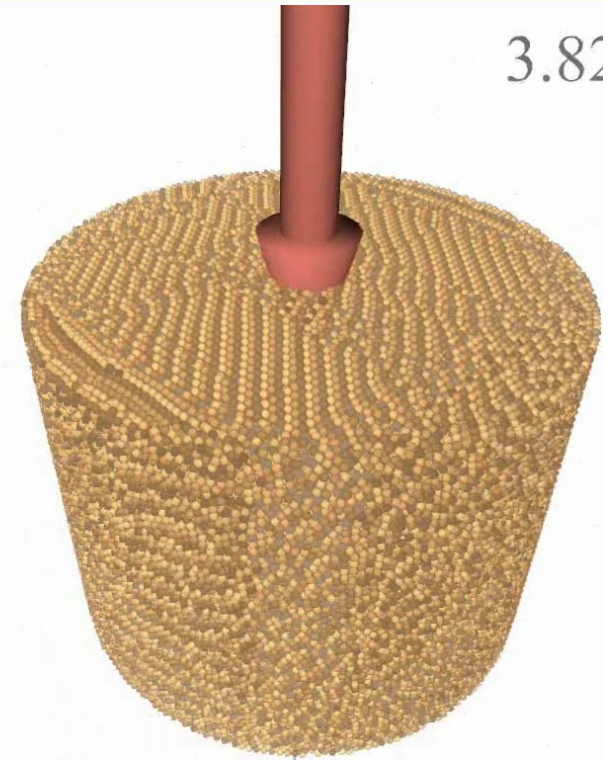
$$\delta_{plastic} = \delta_{plastic} - \begin{cases} 0 & F_{repulsion, max} \geq F_{adhesion, max} \\ V_{relax} \times \Delta t & F_{repulsion, max} < F_{adhesion, max} \end{cases}$$

Cone Penetrometer Experiment (1/2)

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- MBD/FE model of standard cone penetrometer used to calibrate the cone index (CI) used in NRMM with the parameters of the DEM soil material model.
- The CI is tuned by varying two DEM parameters:
 - Cohesion factor: f
 - Friction coefficient: μ



Unstressed (unconsolidated) particle diameter	0.03 m
Particle mass density	1800 kg/m ³
Inter-particle friction coefficient	0.1
Particle to tire/cone penetrometer friction coefficient	0.5
Inter-particle viscosity	0
Inter-particle damping per unit area	2.1×10^4 N/m ³ /s
Particle stiffness (slope of repulsion stress versus penetration strain in Figure 7)	4.42×10^7 N/m ²
Plastic strain versus compressive stress	Slide Figure
Nominal maximum adhesion stress versus plastic strain curve	Slide Figure
Plastic relaxation speed	0.045 m/s
Total number of DEM particles	300,000

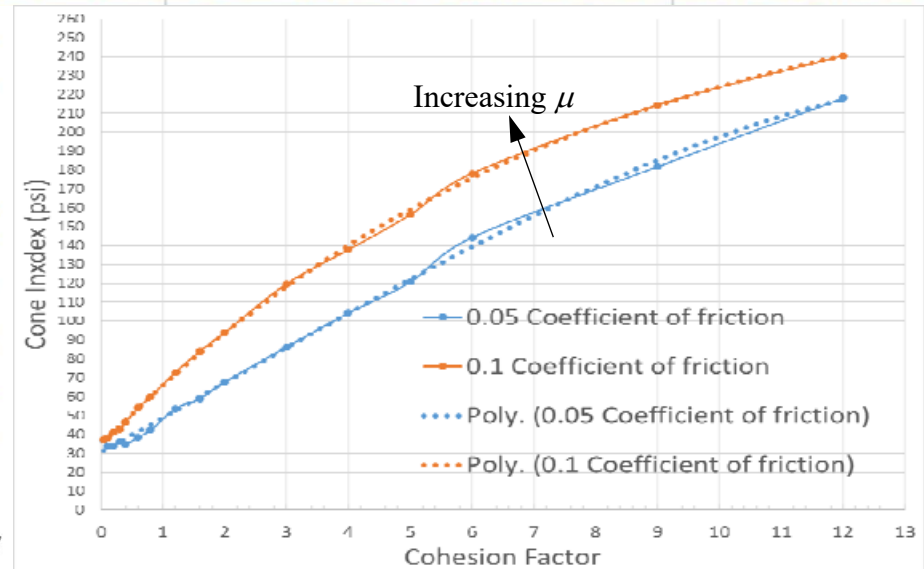
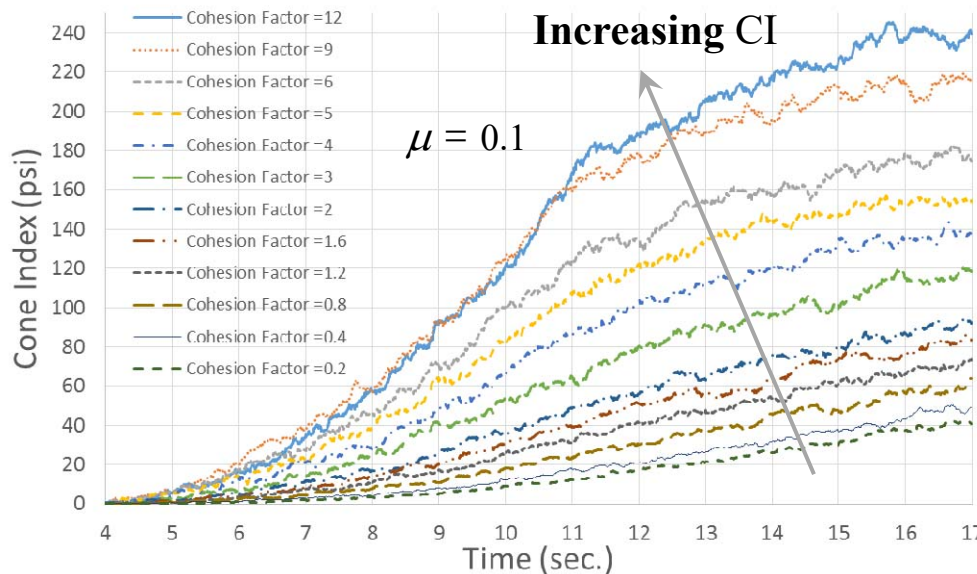
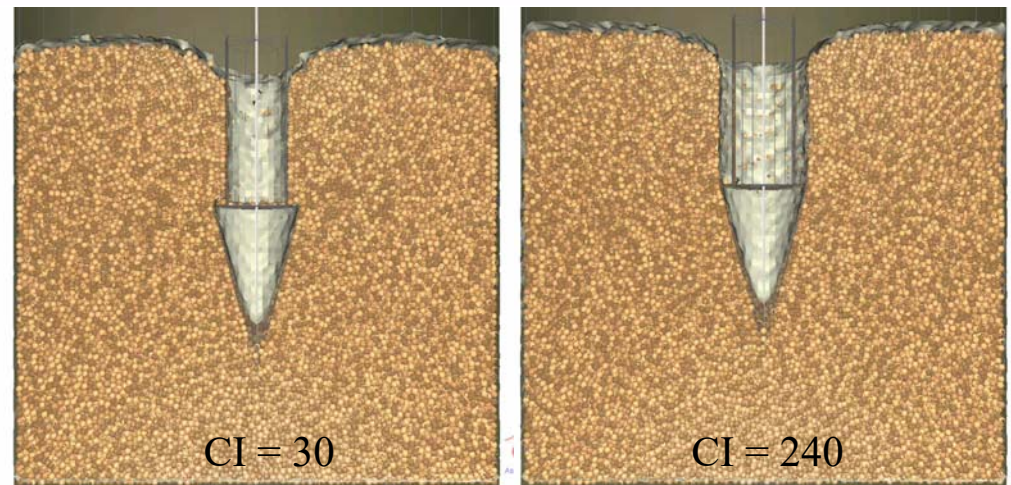
Cylindrical container diameter	2 m
Consolidating lid pressure	33.3 kPa
Cone penetrometer base diameter	0.375 m
Cone penetrometer length	0.7 m
Cone penetrometer cone angle	30°
Penetrometer speed	0.1 m/s
Δt	1.5×10^{-5} s

Cone Penetrometer Experiment (2/2)

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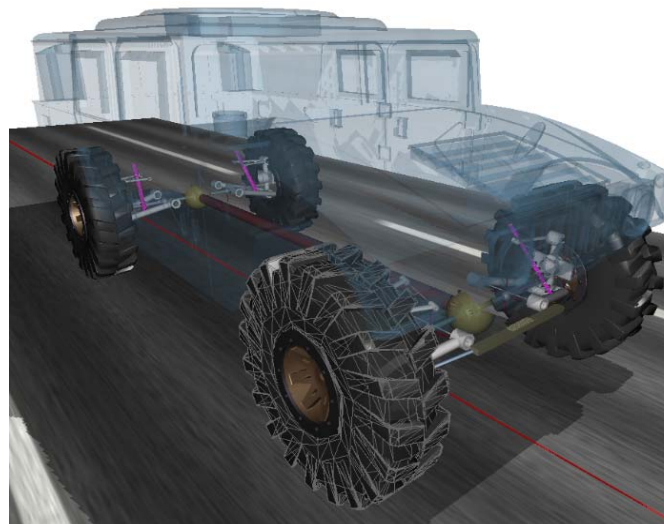
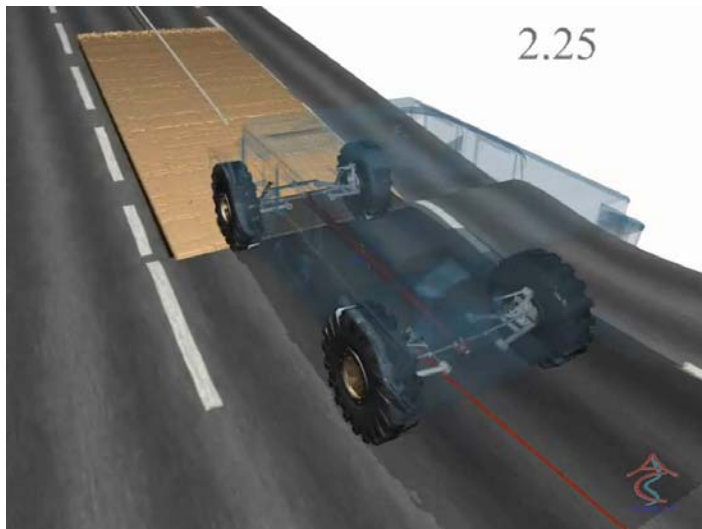
- Fix μ at 0.1 and vary f between 0.2 to 12 to tune to the value of CI.
- 3rd order polynomial used to map f to CI.



Vehicle-Soil Model (1/3)

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- HMMWV driving over a soft cohesive soil.
 - Two soil parameters: CI and positive long grade.
- Vehicle model
 - Rotational actuator for modeling the engine (torque limited by engine characteristics).
 - Total sprung mass = 4430 kg.
 - Wheel mass = 50 kg.
 - Contact between the tires – ground: polygonal tire contact surface (6662 triangles).

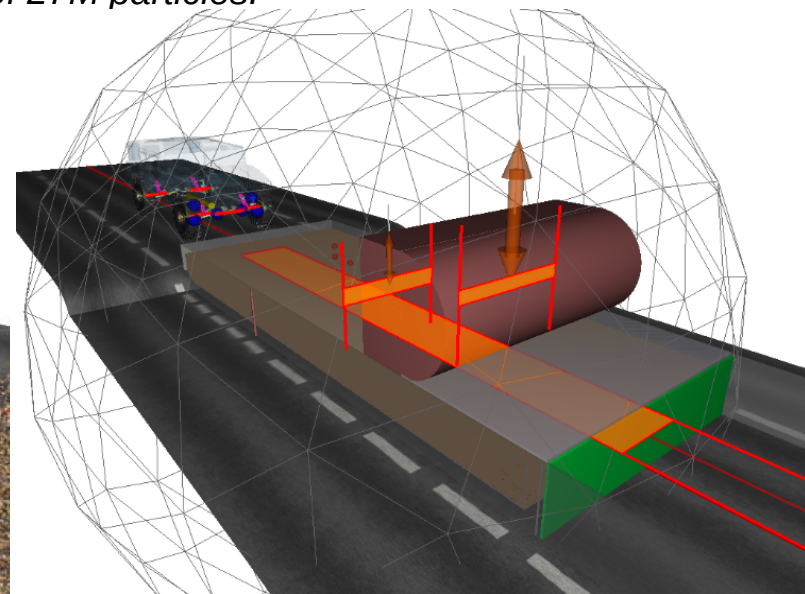
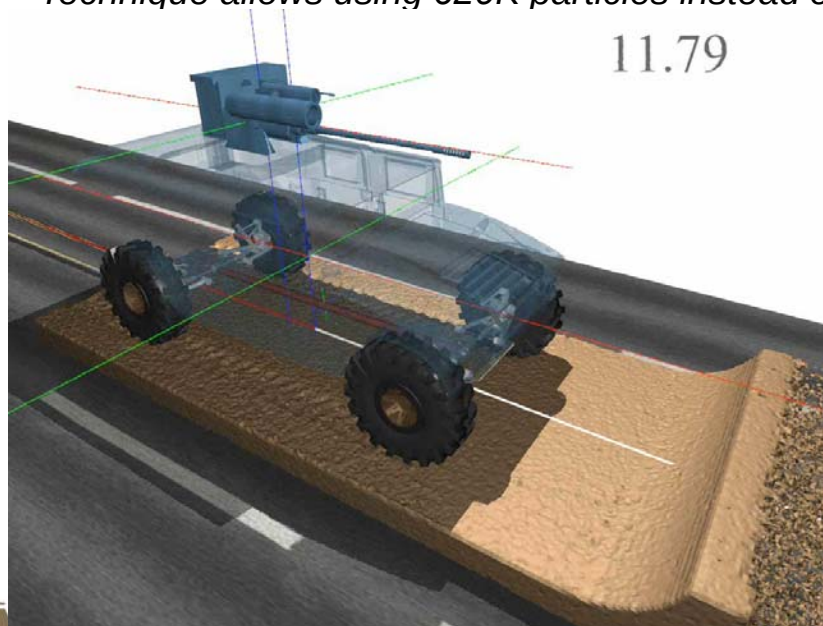


Vehicle-Soil Model (2/3)

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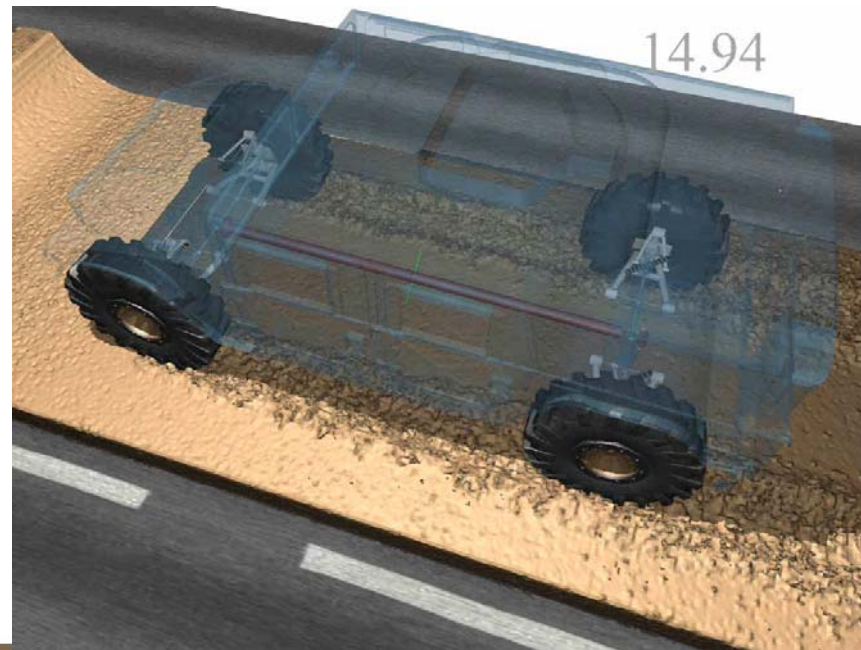
- 620,000 DEM particles.
- Undeformed particle diameter = 3 cm.
- Soil particles inside bounding box: 9.3 m long, 3.5 m wide, 0.9 m high.
- Soil is compressed using a flat lid. Pressure = 33.3 kPa.
- Lid is removed after consolidated soil settles to a height ≈ 0.4 m.
- Moving soil patch technique:
 - **Components:** Rectangular particle emitter, leveling cylinder/plate, and bounding sphere.
 - X-coordinate of center of bounding sphere is moved with the X-coordinate of center of vehicle.
 - When a particle goes outside the bounding sphere, it is deactivated and then reemitted.
 - *Technique allows using 620K particles instead of 27M particles.*



Vehicle-Soil Model (3/3)

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- Terrain and soil patch are set to the desired grade.
- Simulation starts by leveling and consolidating the soil using the flat lid.
- Leveling cylinder and plate are lowered to the initial height of the soil (about 0.4 m).
- Vehicle is commanded to accelerate at 1 m/s^2 from rest to a maximum speed of 25 m/s (56 mph) in 25 sec.
- Soil and grade resistances cause the vehicle speed to level off below the commanded maximum speed, at which point the engine is applying the maximum available torque.
- Total simulation time = 40 sec; Time step = $1.5 \times 10^{-5} \text{ s}$
- Steady-state maximum vehicle speed is the “speed-made-good.”



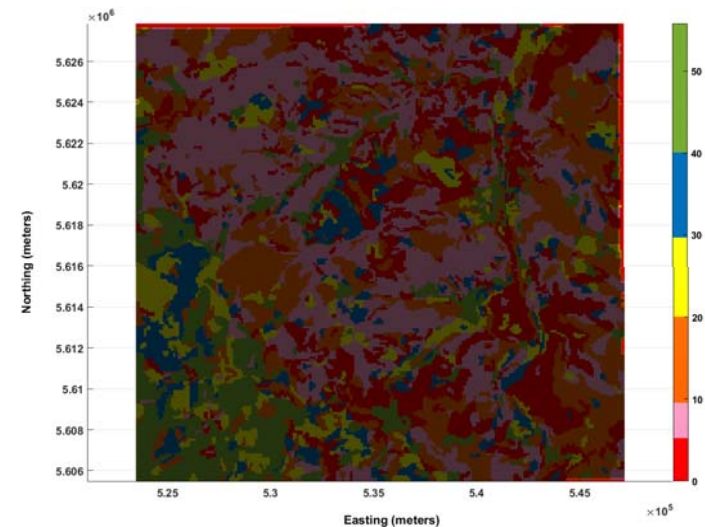
Vehicle Mobility DOE Procedure

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- Terrain map (22 x 22 km) is divided into grid cells of the same size as the vehicle (20×20 m).
- For each grid cell **slope** and **CI** are found.
- Range of slopes and CIs for the entire terrain map are found.
- Positive slope range of the terrain map is discretized into a certain number of values (G). The CI range is discretized into a certain number of values (C).
- A vehicle mobility simulation is performed for each of the $G \times C$ combination of slope and CIs. All the combinations are run in parallel on individual HPC nodes.
- For each combination, steady-state vehicle mobility measures are calculated.
- The mobility measure values for each terrain grid cell are interpolated from the calculated values.
- A map of the mobility measure over the entire terrain map is generated by coloring each grid cell using the mobility measure (such as the speed-made-good).



Simulation Results (1/4)

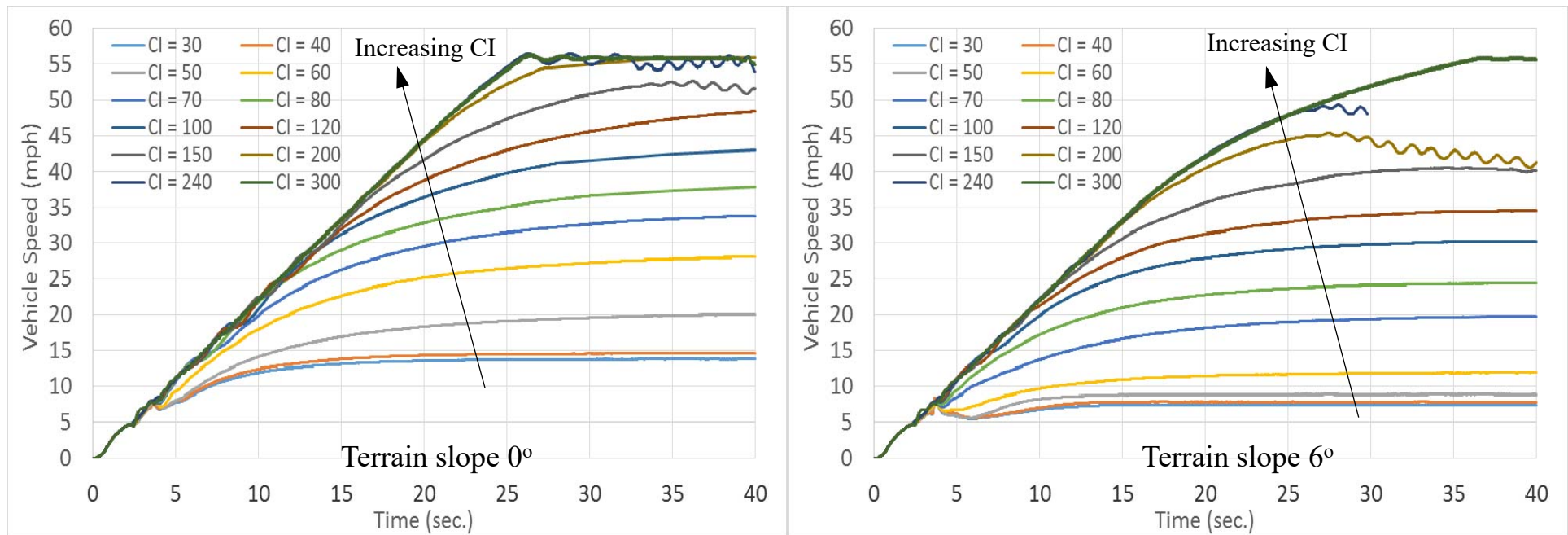
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Simulation Results (2/4)

- Time-history of vehicle speed for different soil CI and terrain slopes.



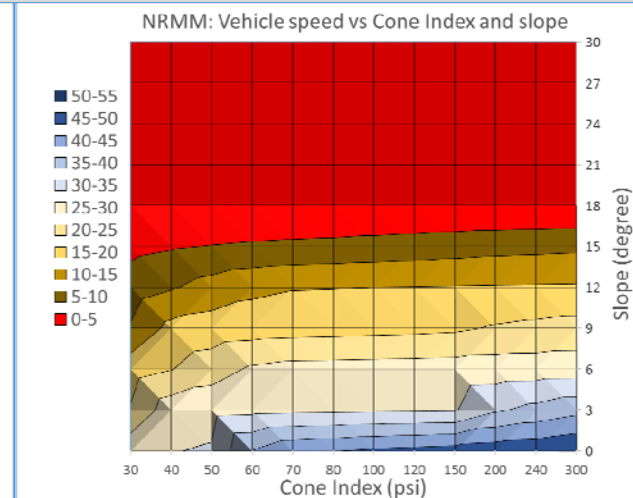
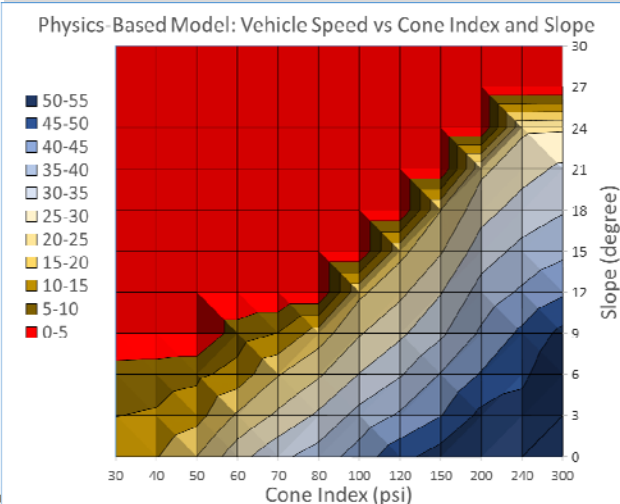
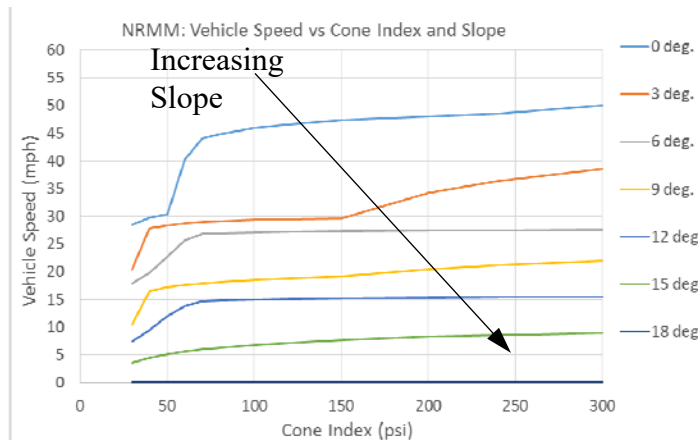
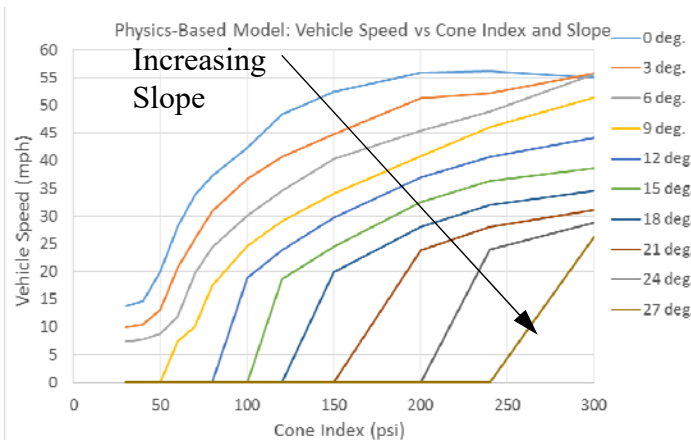
- As cone-index increases vehicle speed increases for all slopes.
- As slope increases vehicle speed decreases.

Simulation Results (3/4)

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- Vehicle speed-made-good as a function of CI and terrain slope.
 - For the current physics-based model, as expected: vehicle speed is proportional to CI and inversely proportional to slope.
- The results of the current model and NRMM are different.

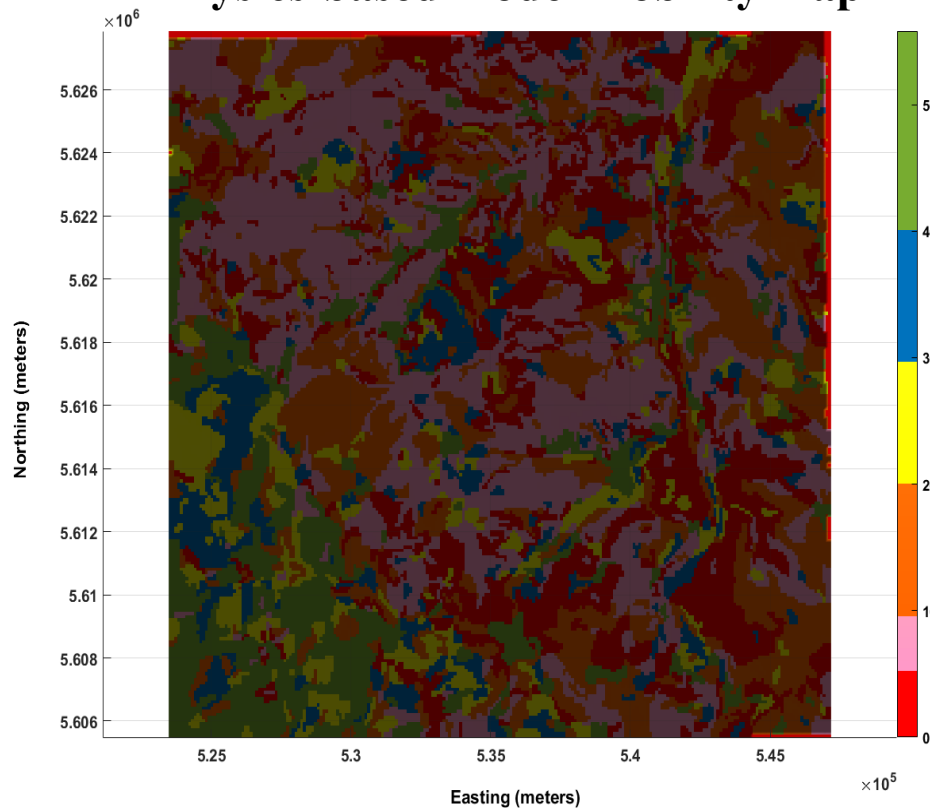


Simulation Results (4/4)

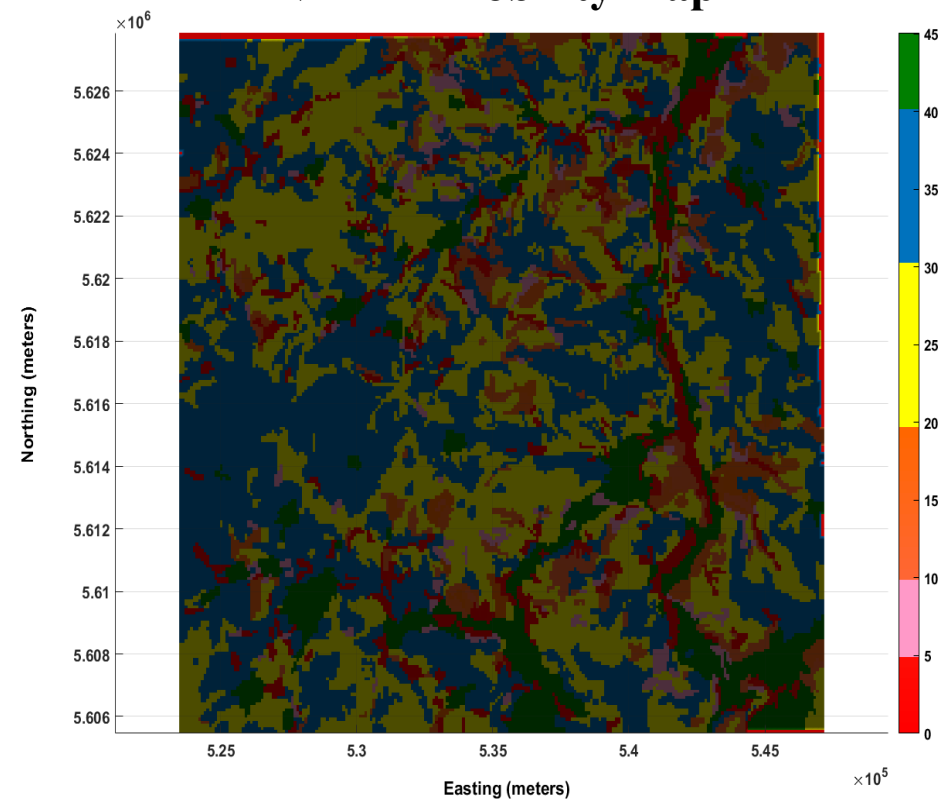
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- Comparison of mobility maps generated by the current physics-based model and NRMM

Physics-based model mobility map



NRMM mobility map





Concluding Remarks

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- For the first time, a high-fidelity physics-based simulation to predict vehicle mobility measures over large terrain maps was presented. Modeling approach based on:
 - Seamless integration of MBD for modeling the vehicle and DEM for modeling cohesive soils into one solver.
 - An HPC DOE procedure.
 - A moving terrain patch strategy.
- This general approach is proposed to replace the current practice of NRMM.
- Future work will focus on:
 - Expanding the DOE procedure to include additional terrain and soil properties.
 - Experimental calibration and validation for the physics-based model.