FEA Based Method for Modeling Machine/Ground Interaction

Liqun Chi, Ph.D.
Machine Research – Earth Mechanics
PD & GT, Caterpillar Inc.

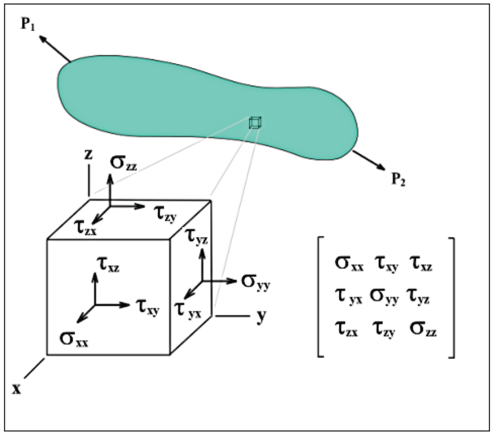
June 22, 2011

Outlines

- A Couple of Real Problems (actual videos)
- Introduction to FEA methods
- Numerical material models for earth materials
- More advanced concepts in FEA method
- Model validation
- Examples of FEA-based models
- Q & A

Equilibrium Equation: $D^T\sigma - f = 0$

$$\sigma = [\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \tau_{xy}, \tau_{yz}, \tau_{zx}]^T \qquad D = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z} \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial x} & \frac{\partial}{\partial z} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix}^T$$



Constitutive Equations: $\sigma = C\varepsilon$ ***Geometric Deformation:*** $\varepsilon = Du$

Strong Form: $D^T CDu - f = 0$

Weak Form: $\int_{\Omega_e} v^T \{D^T CD\tilde{u} - f\} d\Omega_e = 0 \qquad \int_{\Omega_e} (Dv)^T CD\tilde{u}\, d\Omega_e = \int_{\Omega_e} v^T f d\Omega_e + \int_{\Gamma_e} v^T t d\Gamma_e$

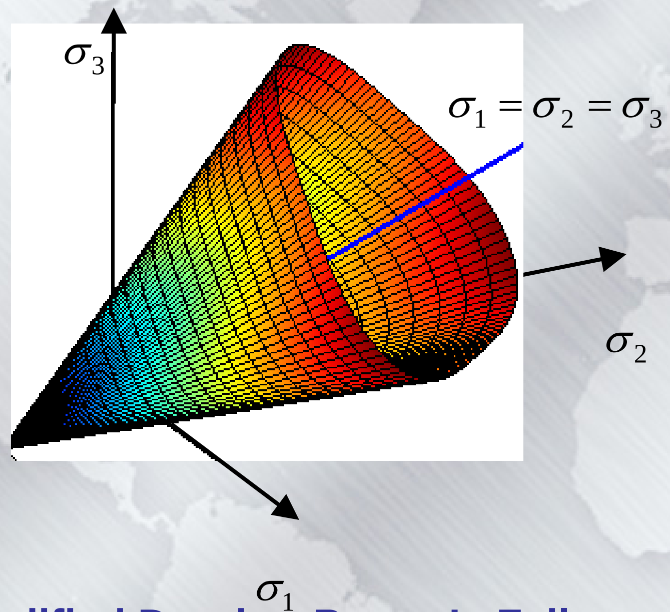
$$\tilde{u} = \Phi U^e \qquad K^e U^e = R^e \qquad K^e = \int_{\Omega_e} (D\Phi)^T CD\Phi d\Omega_e \qquad R^e = \int_{\Omega_e} \Phi^T f d\Omega_e + \int_{\Gamma_e} \Phi^T t d\Gamma_e$$

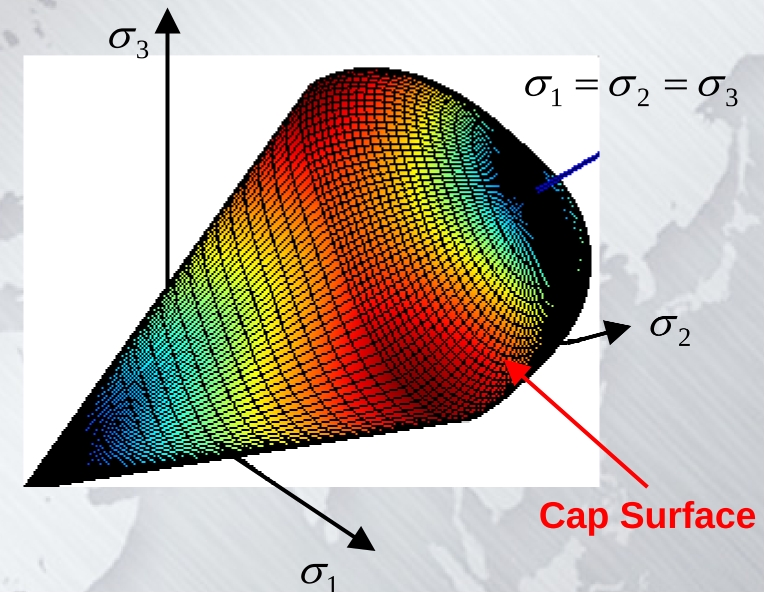
Final System Equations: $KU = R$

Yield Surfaces in Principal Stress Space

Elasto-Plastic Constitutive Model

$$\varepsilon^{ep} = \varepsilon^{e} + \varepsilon^{p}$$





Modified Drucker-Prager's Failure Surface:

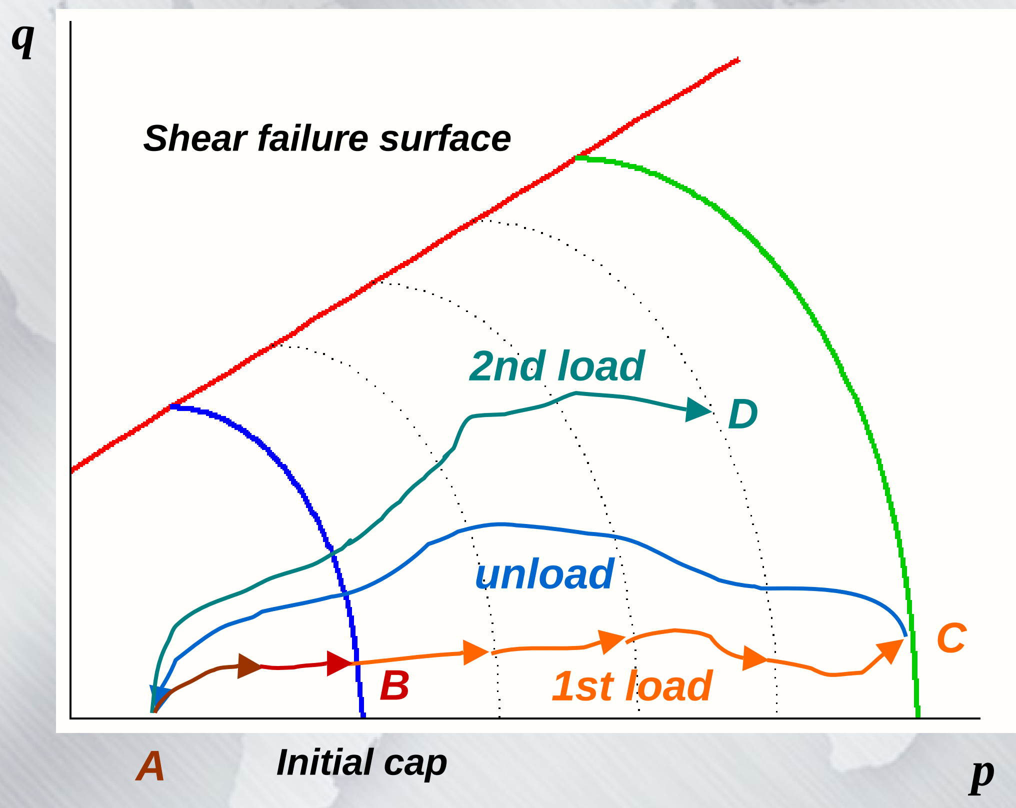
- **Shear failure - stationary surface**
- **von Mises shear stress**
- ***Stress Dependent***
- ***Inside cone - elastic region***

Capped Yield Surfaces:

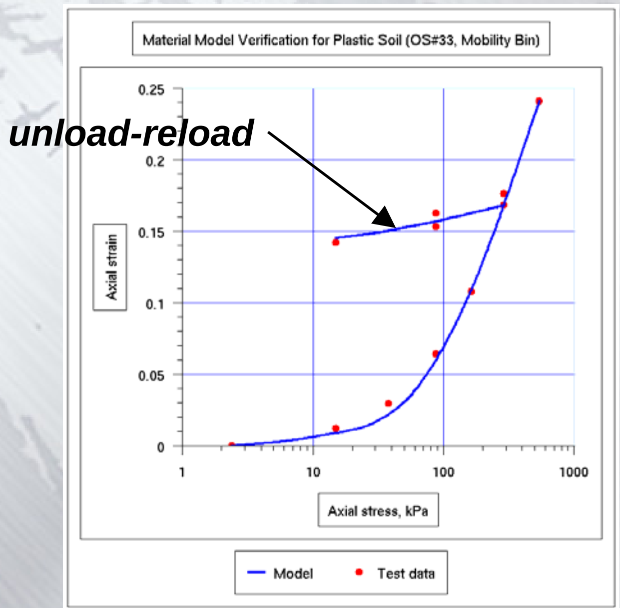
- **Closed yield surface**
- ***Series of progressive surfaces***
- ***Work hardening type***
- **Permanent compaction**

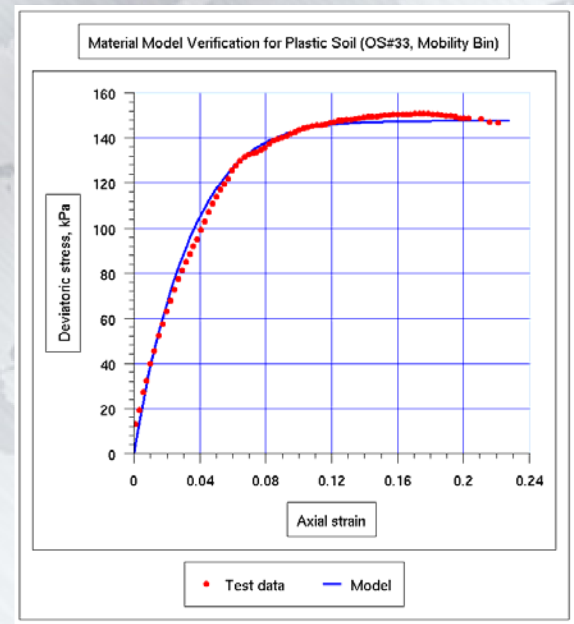
More About Cap Yield Surfaces

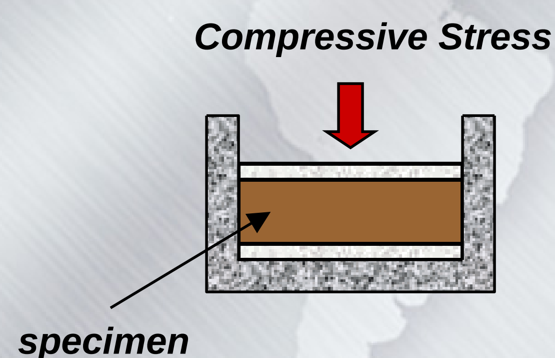
Material Model

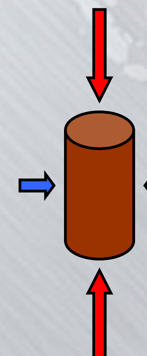


- *Space enclosed by shear failure and cap yield surfaces - elastic region*
- *Stress state reaches initial cap - developing plastic compressive volume strain*
- *Cap yield surface expands due to continuous stress increases*
- *Plastic volume strain related to cap position and size*
- *Only elastic stain during unloading*
- *History Dependent*

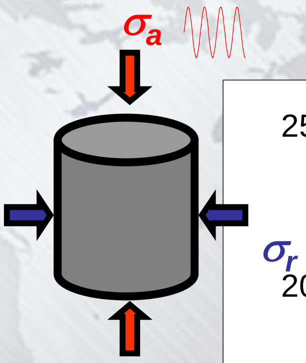

Material Model Verification for Plastic Soil (OS#33, Mobility Bin)
unload-reload
Axial strain
0.25
0.2
0.15
0.1
0.05
0
1
10
100
1000
Axial stress, kPa
Model
Test data

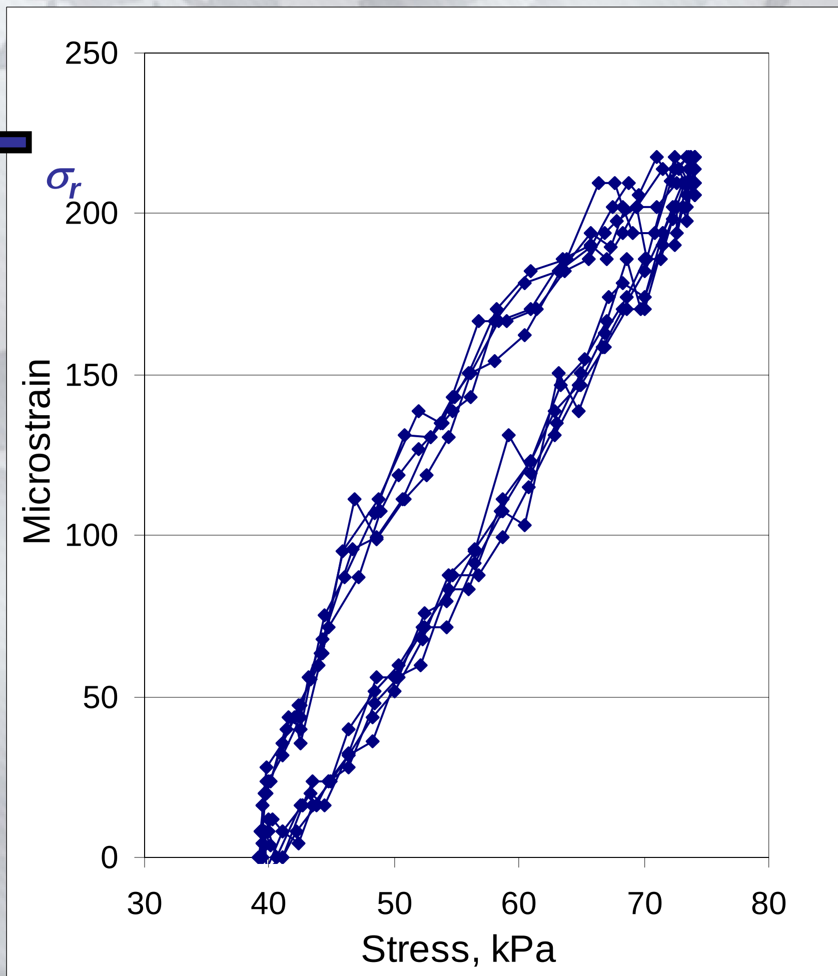

Material Model Verification for Plastic Soil (OS#33, Mobility Bin)
Deviatoric stress, kPa
160
140
120
100
80
60
40
20
0
0
0.04
0.08
0.12
0.16
0.2
0.24
Axial strain
Test data
Model

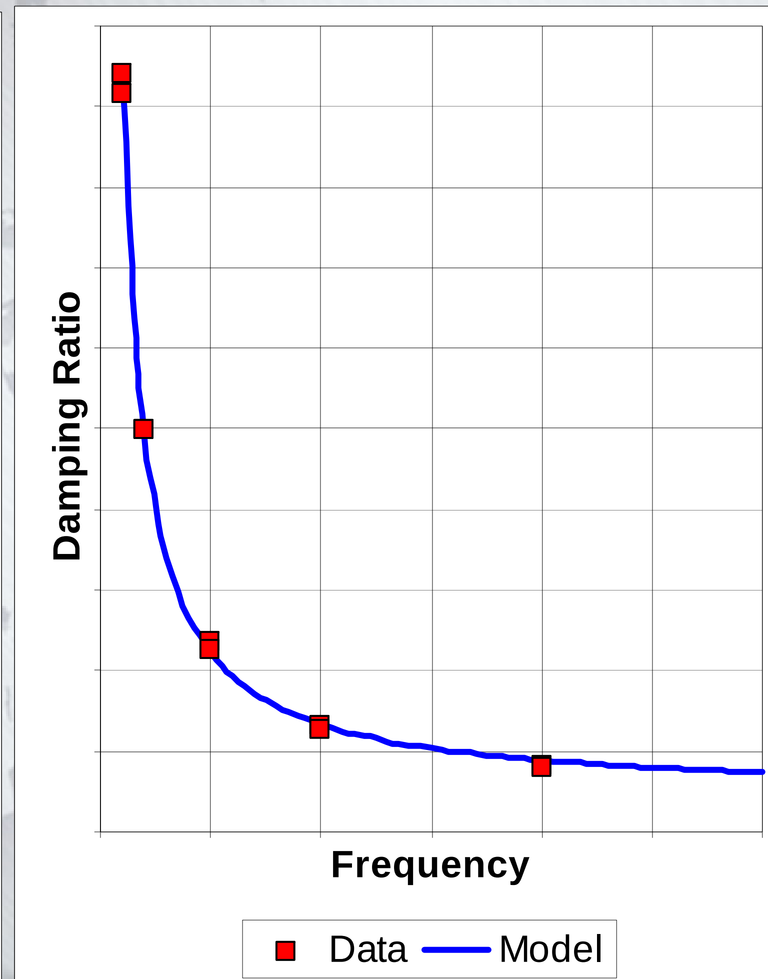

Compressive Stress
specimen



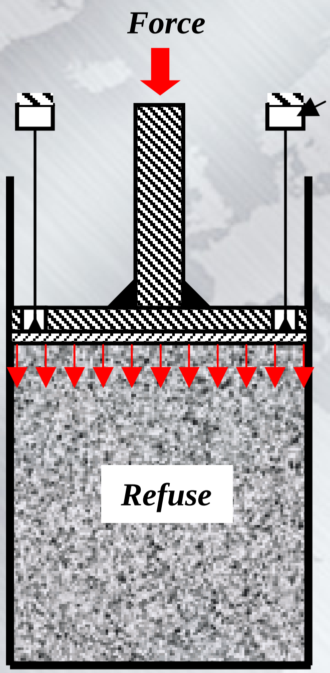
Damping Property

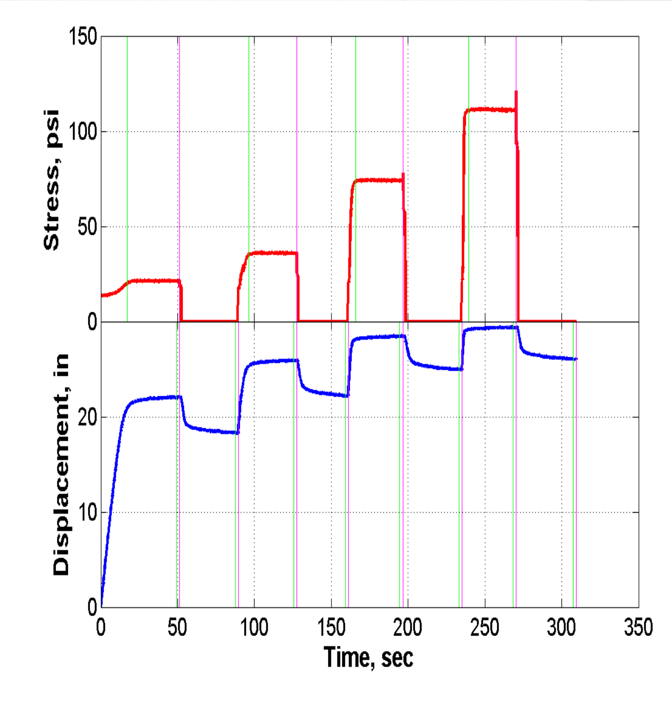






Barrel Compaction Tests





Mechanical Behavior of Waste under Applied Load

- *Elasto-Plastic behavior – reversible elastic rebound and permanent, irreversible plastic deformation*
- *Elastic rebound is stress dependent*
- *Work-hardening plastic deformation behavior – hyperbolic or exponential shape*

Explicit Method

Dynamic Equation of a System:

$$M\ddot{U} + C\dot{U} + KU = R$$

M, C and K = Mass, damping and stiffness matrices

R = Vector of external applied loads

The Central Difference Method:

$$\ddot{U}^t = \frac{1}{\Delta t^2}\left(U^{t-\Delta t} - 2U^t + U^{t+\Delta t}\right)$$

$$\dot{U}^t = \frac{1}{2\Delta t}\left(U^{t+\Delta t} - U^{t-\Delta t}\right)$$

$$M\ddot{U}^t + C\dot{U}^t + KU^t = R^t$$

The Explicit Integration Method:

$$\left(\frac{1}{\Delta t^2}M + \frac{1}{2\Delta t}C\right)U^{t+\Delta t} = R^t - \left(K - \frac{2}{\Delta t^2 M}\right)U^t - \left(\frac{1}{\Delta t^2}M - \frac{1}{2\Delta t}C\right)U^{t-\Delta t}$$

Characteristics of Explicit Method

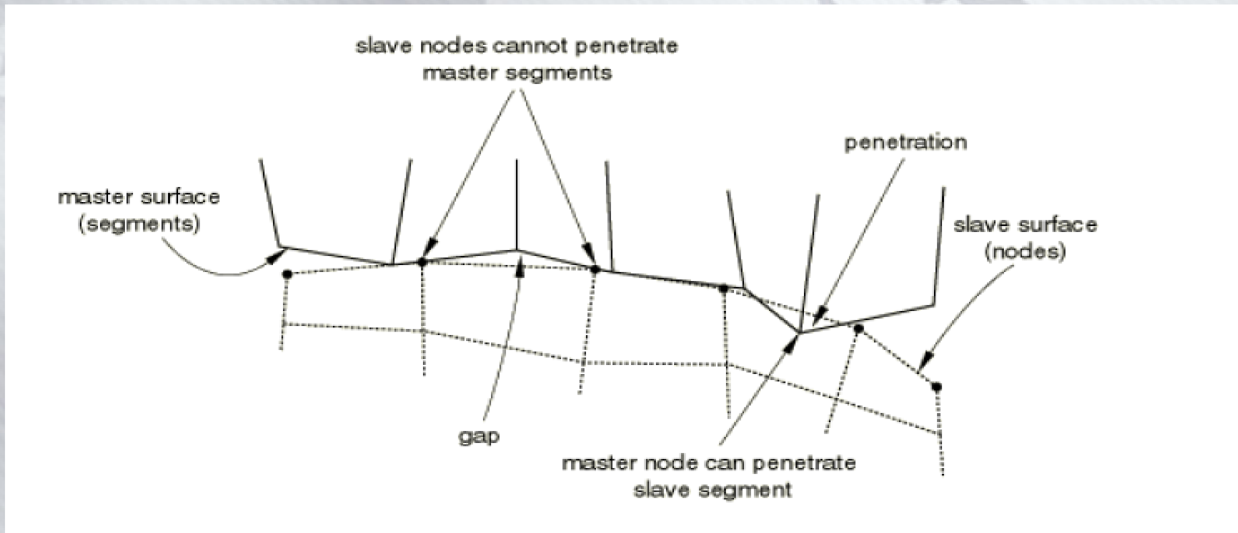
- *Lump sum mass and usually first-order, reduced integration elements*
- *Nodal related equations without matrices*
- *No iteration or convergence check needed*
- *Very general contact algorithm can be used (large sliding, self contact…)*
- *Large number of small time increments. The stable time increment is restricted by pressure wave propagation*

- *Out of balance are propagated as stress wave between neighboring elements*
- *Sophisticated engineering skills and experience needed*
- *Analysis can be terminated due to excessive element distortion*

Commercial Codes for Explicit Method: LS-DYNA   ABAQUS

Contact Algorithm

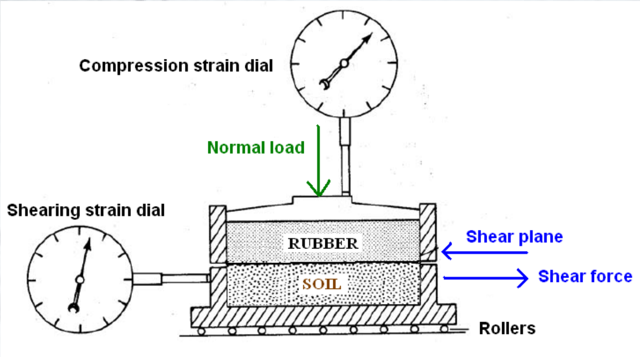
- *Treated as a special type of boundary conditions*
- *Detect the contact engagement and separation between parts of two surfaces*
- *Two type of algorithm to deal with contact engagement*
  - *Kinetic constrain method*
  - *Penalty Method*
- *Motion and force in tangential direction – friction law*



Surface Contact make problem nonlinear.

Interface Behavior

Modified Direct Shear Test at UIUC



Implement of Friction Law

Laboratory Tests

- Modified Direct shear test for interface behavior
- Different Normal Load
- Different water content

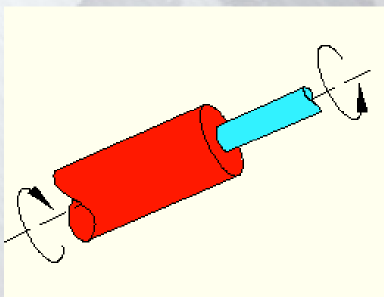
Modeling Interface Behavior

- Simple Stick-Sliding Algorithm
- Static and kinetic friction with decay curve
- Friction coefficient as a function of slip rate

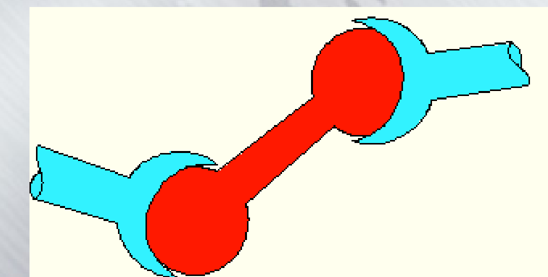
12”x12” Direct Shear Device at UIUC

Connector Elements

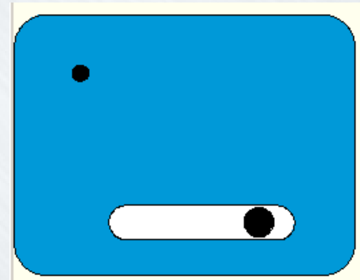
Revolute



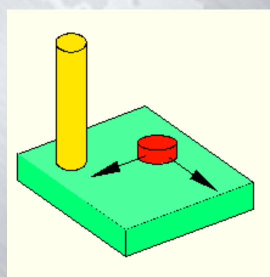
Link



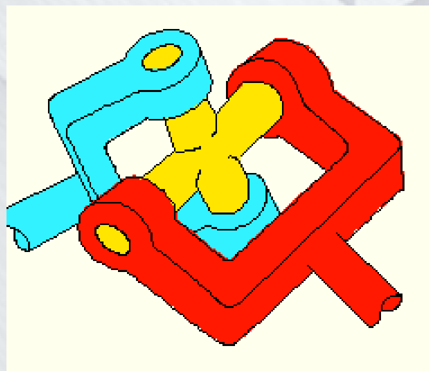
Slot



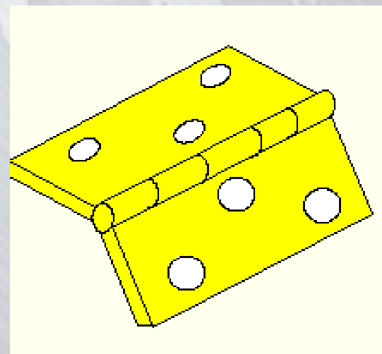
Planar



U-Joint



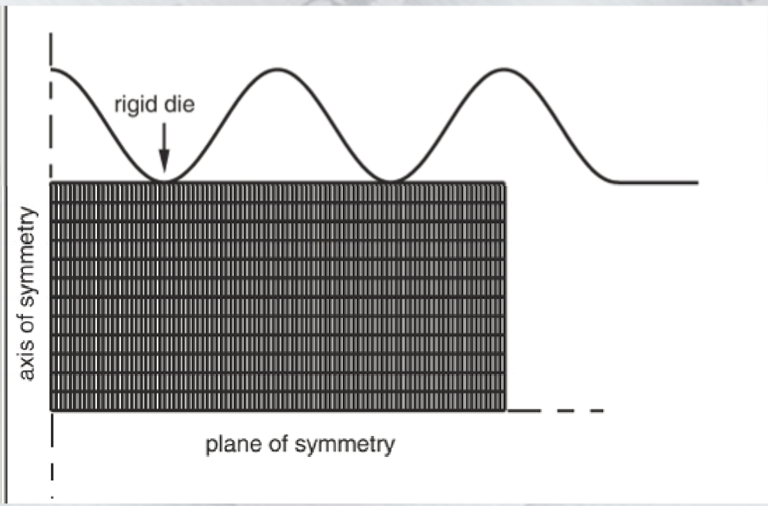
Hinge



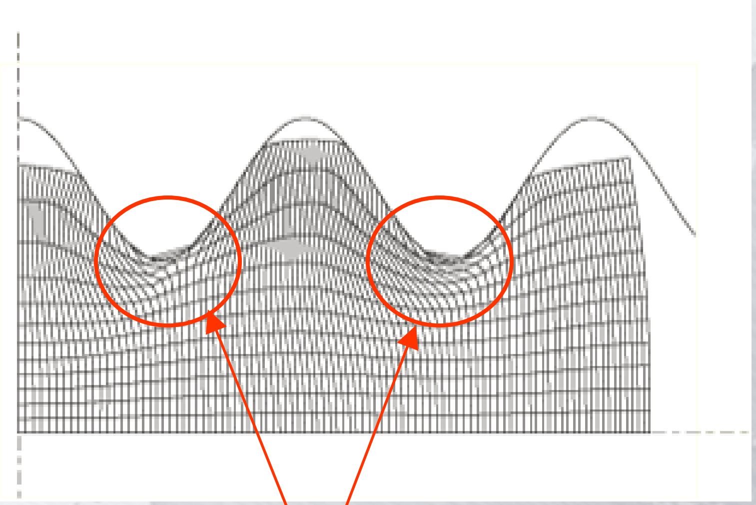
Excessive Mesh Distortion

Pure Lagrangian Formulation Example (Explicit):

Un-deformed



Deformed



Mesh follows Material

No material flows between elements

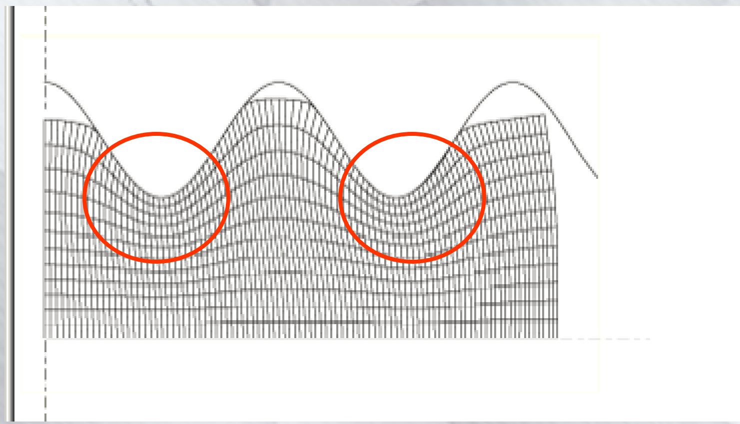
Terminated because of excessive element distortion

*** Example from ABAQUS User's Manual*

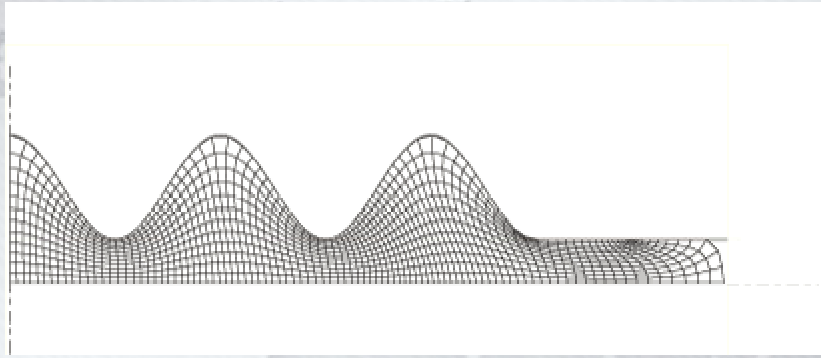
ALE Method

Arbitrary Lagrangian-Eulerian (ALE) Formulation:

Deformed - intermediate stage



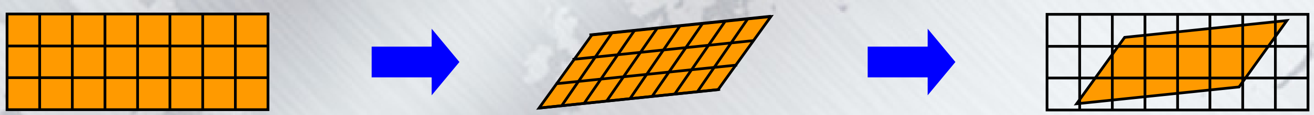
Deformed – Completed Analysis



- Adaptive remeshing
- Lagrangian mesh boundary following to material - No void or partially void elements
- No changes in # of elements and # of nodes
- Nodal coordinates changes during remeshing
- Advection of mass, momentum, and energy
- Control of remeshing frequency
- Various remeshing algorithm

*** Example from ABAQUS User's Manual*

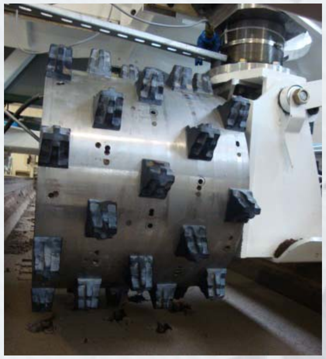
Coupled Eulerian-Lagrangian (CEL) Formulation:



Lagrangian phase ***Remeshing phase***

- The CEL method is based on an operator split of the governing equations, resulting in a traditional Lagrangian phase followed by an Eulerian, or transport, phase.
  - Lagrangian phase of the increment- nodes temporarily fixed within the material, and elements deform with the material.
  - Eulerian phase of the increment - deformation is suspended, elements with significant deformation are automatically remeshed. Mass and momentum advections between neighboring elements are computed.
- Eulerian mesh did not follow material – need to construct the surface for contact
- Void and partially void elements
- Elements filled with different materials

Model Validation — *Laboratory Soil Bin Test*



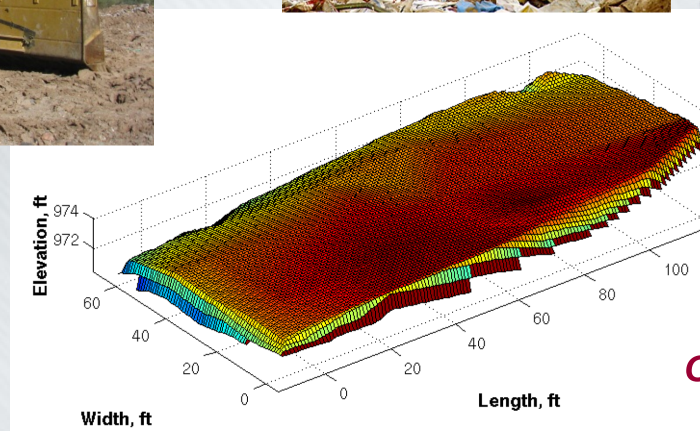
Model Validation

Field Validation Test

GPS - Measure Speed

Drive Shaft Torque and Speed

GPS Survey for Layer thickness, slopes and density



Crusher Barrel Tests

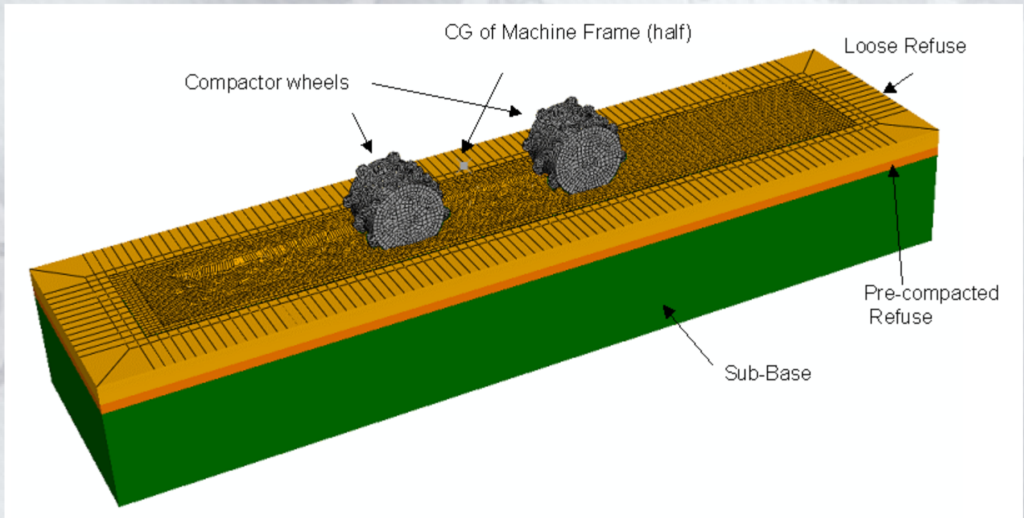
(refuse compaction behavior)

Model Examples

Landfill Compaction Model

Model Description:

- Simulate rigid wheel rolling on deformable refuse
- Friction type of contact interface between wheel and refuse
- Dynamic, explicit method (ABAQUS/Explicit)
- Loose layer and pre-compacted base



Model Input

- Wheel and tip geometry
- Total machine weight
- Weight distribution
- Material model of waste
- Friction coefficients
- Layer thickness
- Ground slope

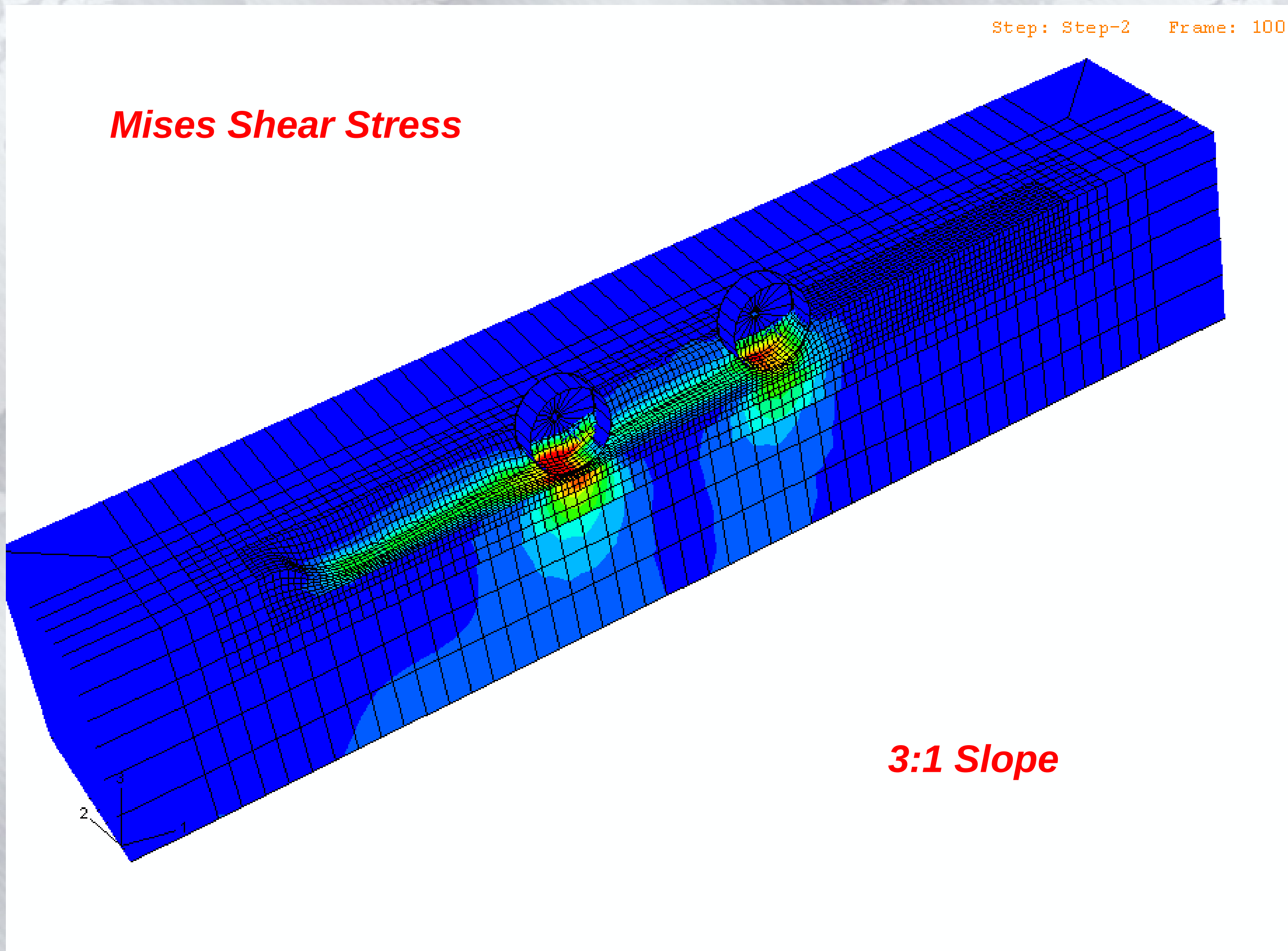
Model Prediction

Model Output

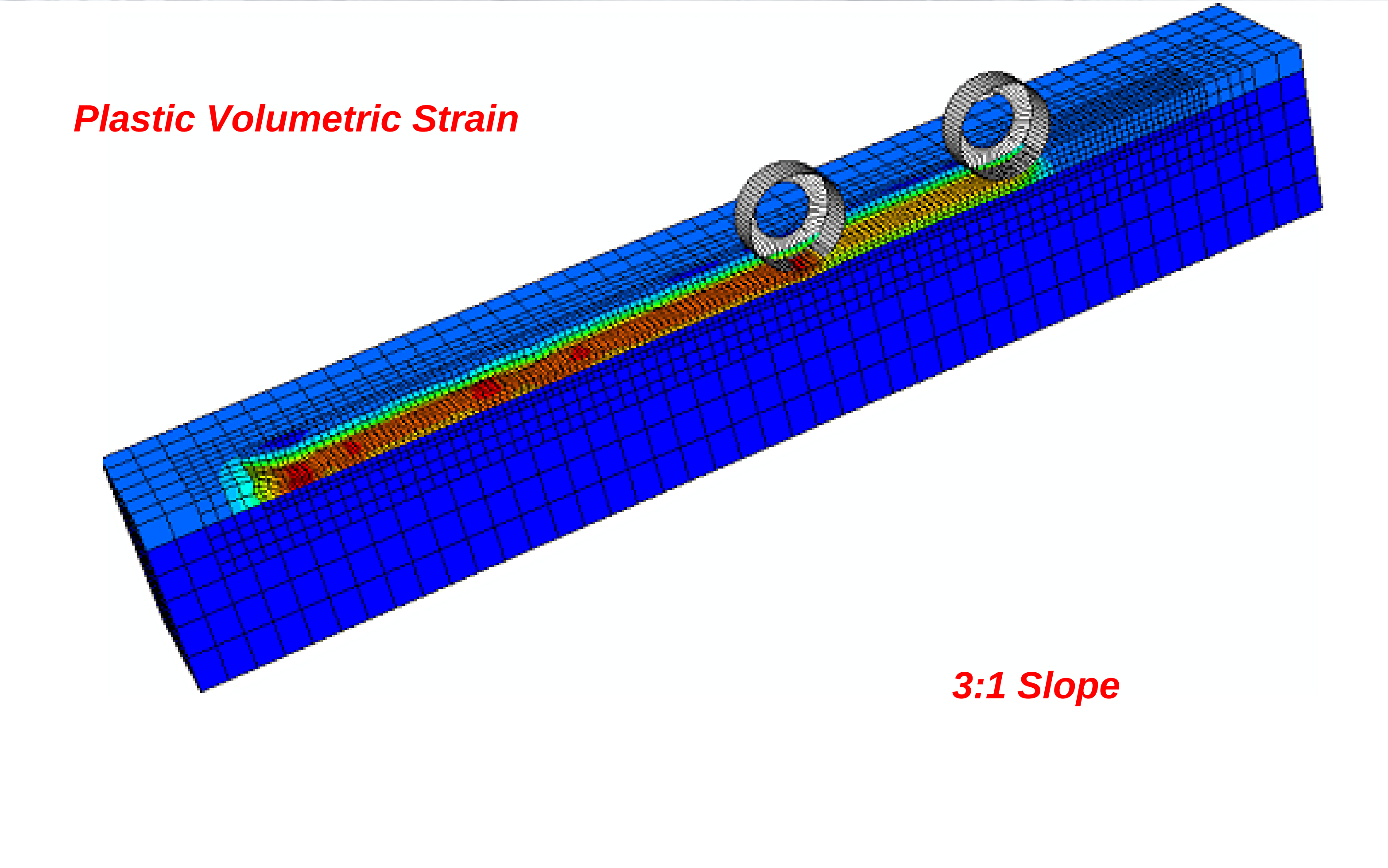
Wheel torque and power
Machine speed and travel reduction
Compaction and density
Ground clearance
Effects of layer thickness
Effects of multiple passes
Effect of slope

Model Examples

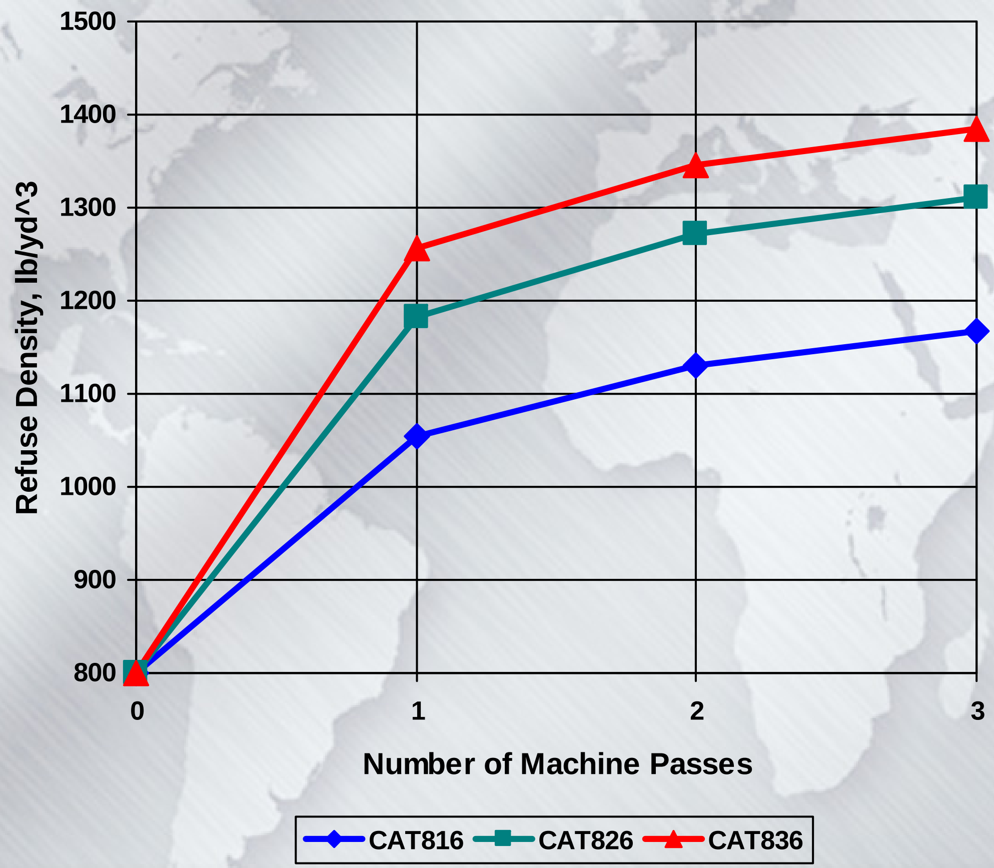
Early Model with Smooth Drum



Early Model with Smooth Drum



Early Model with Smooth Drum

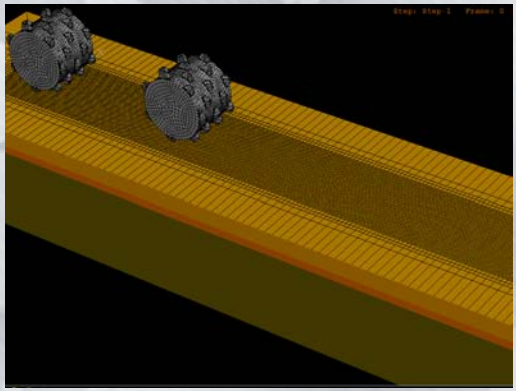


- **The effect of machine passes**
- **The effect of machine weight**
- **Determine the optimum operation procedures**

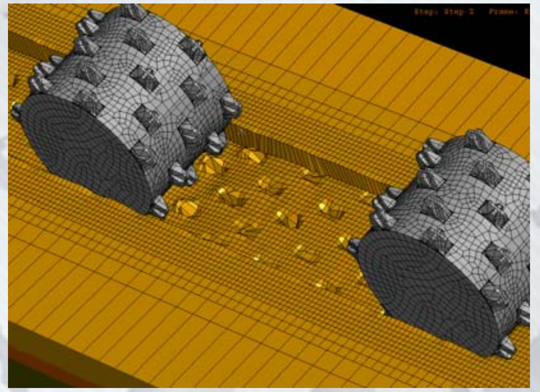
Model Examples

Compactor – Lagrangian Method

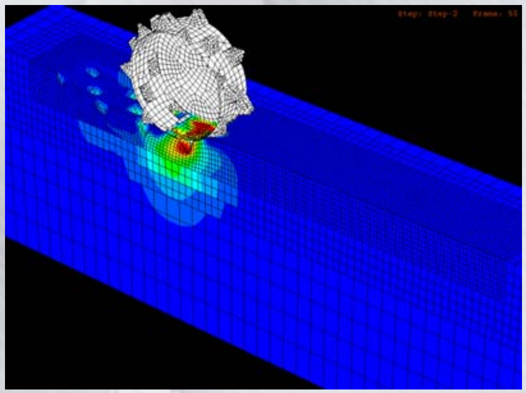
Video - Model



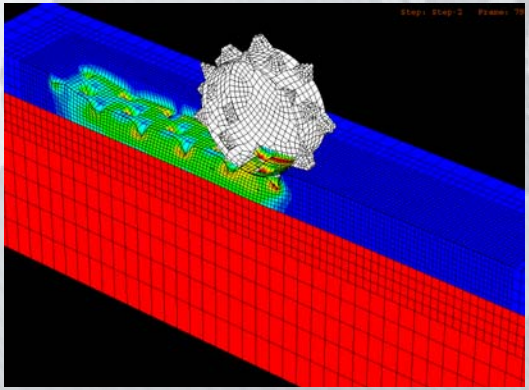
Video – Model Close-up



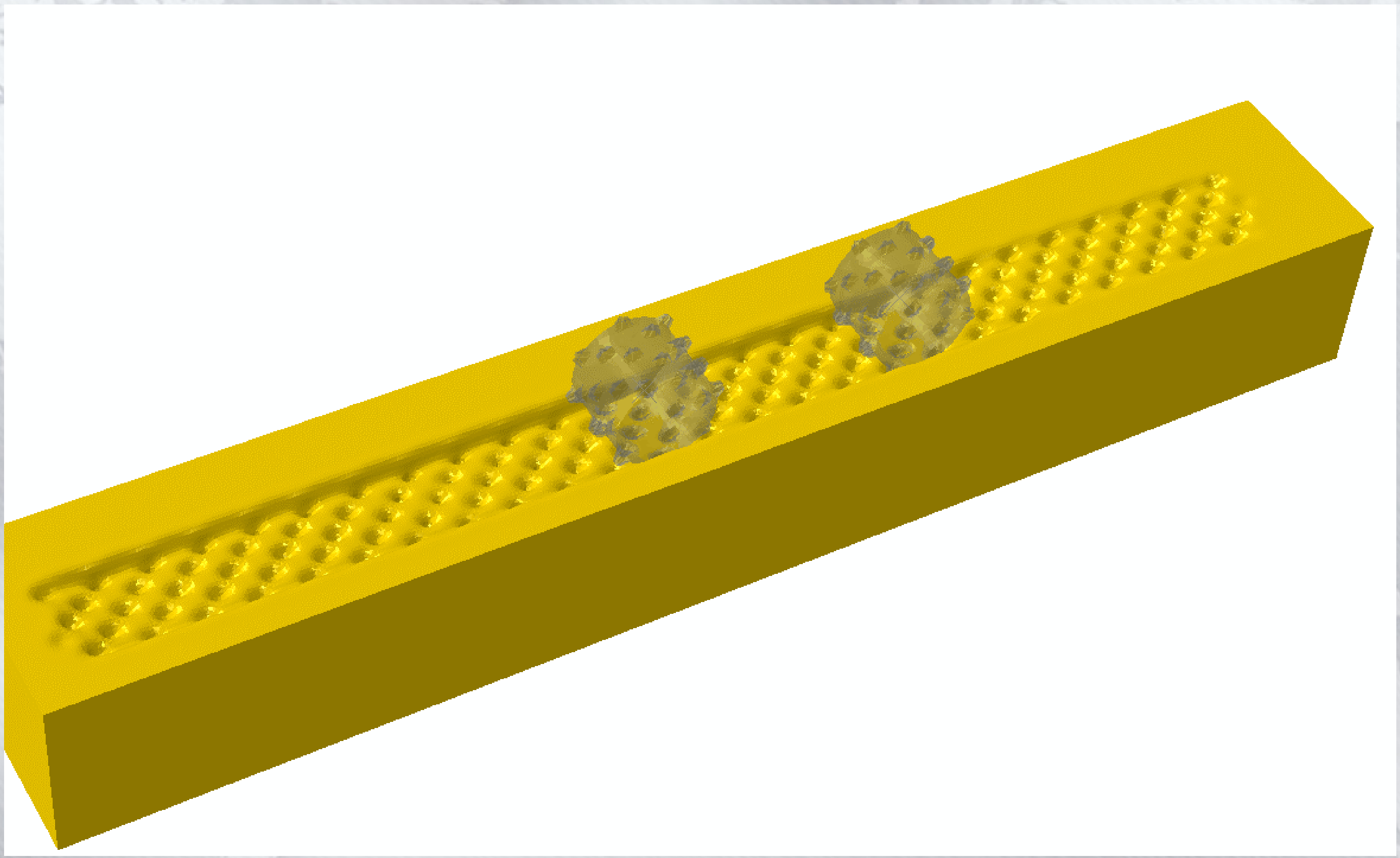
Video – Stress



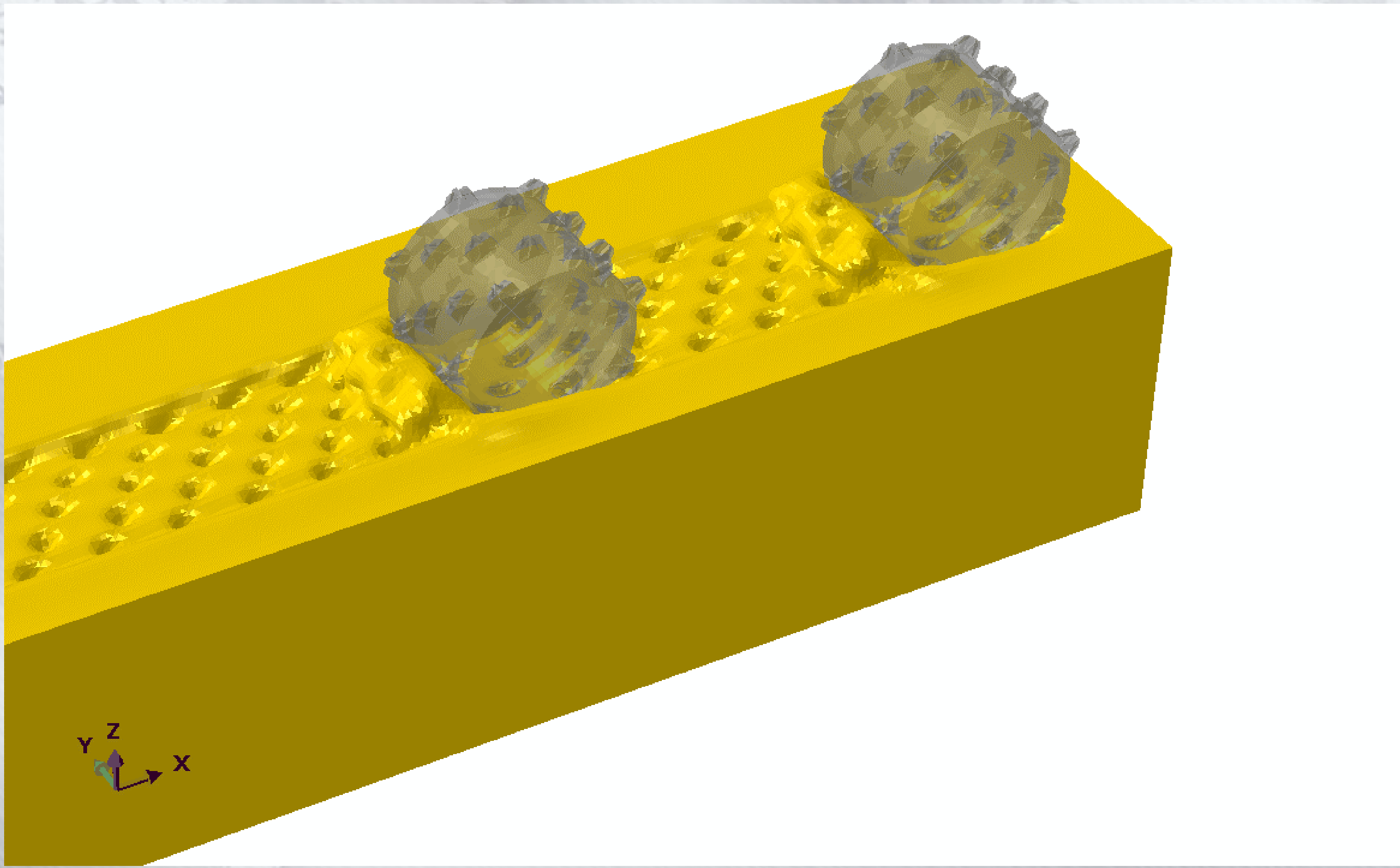
Video – Density



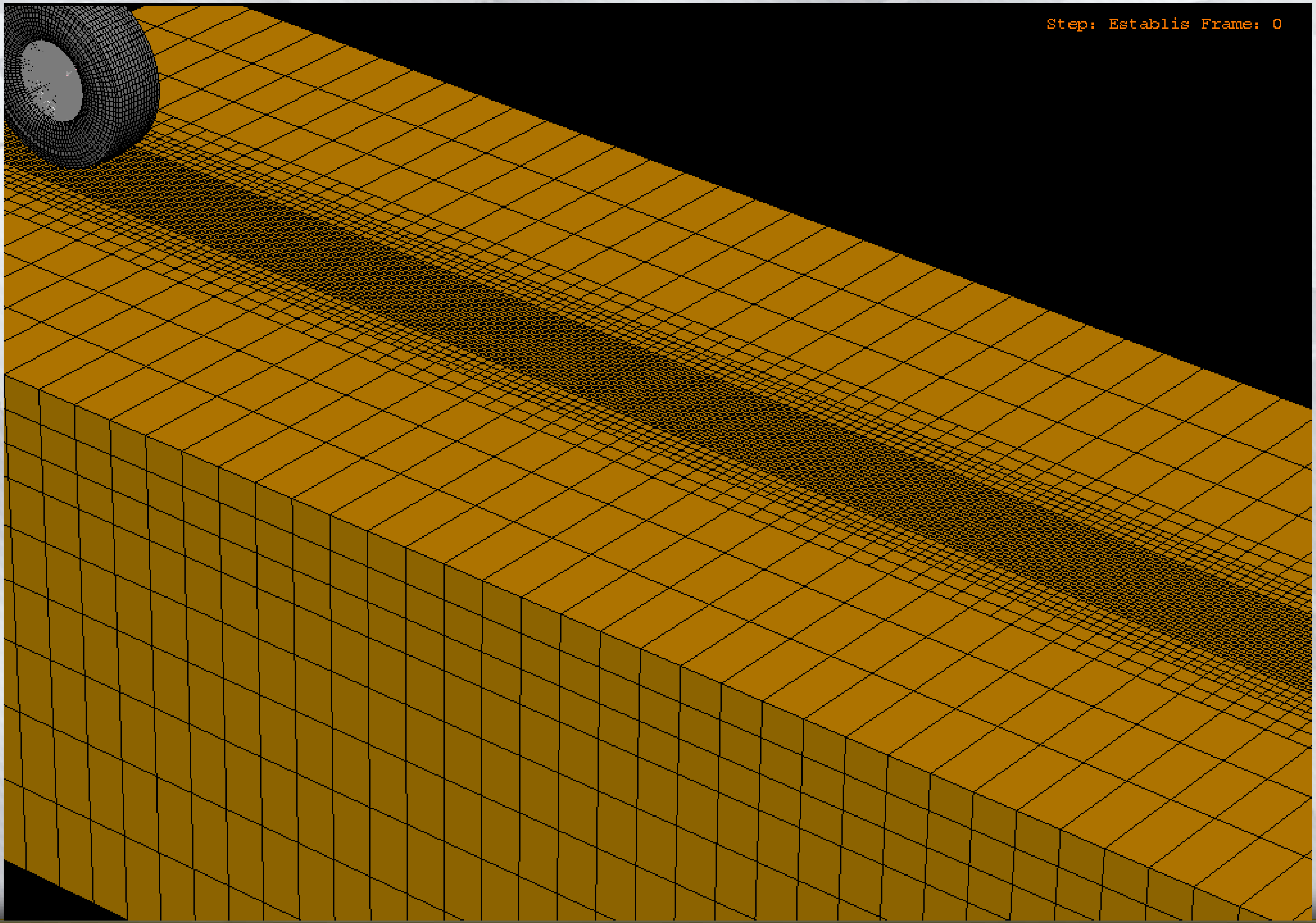
Model Examples Compactor – CEL-Level Ground



Compactor – CEL – Drawbar



Model Examples Mining Truck Tire Rolling on Tar Sand



Thank You