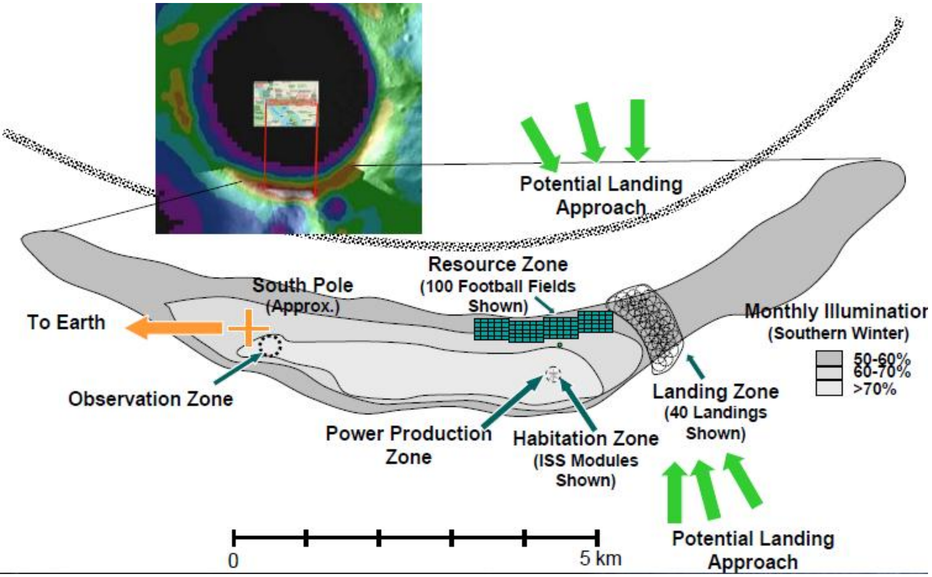
Finite Element Method to Calculate Forces and Stresses on Blades Excavating Lunar Simulants

Thursday 6/10/2010
Joint Meeting of
Space Resources Roundtable
&
Planetary and Terrestrial
Mining Sciences Symposium

Paul van Susante
Dr. R. King

Why Lunar Excavation?



- NASA develops an outpost on a planetary surface
- requires handling of dry granular lunar sand and dust called regolith.
- high cost of bringing each kilogram to the lunar surface,
- machines must be small and lightweight.

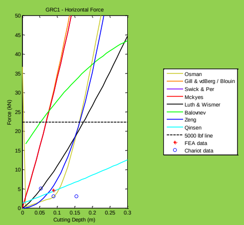
- Current models not sufficient
  - All over the map
  - Designed for very specific applications
  - FEA models exist for cutting – rarely compared to exp

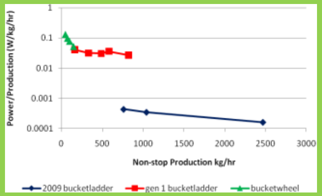
Lunar Excavation Goals

- Determining the input parameters of importance for analytical lunar soil-blade excavation models
- Determining the range of values for the important input parameters
- Experimentally determining the appropriate input parameter values for the constitutive model of JSC-1A lunar simulant for use in finite element analysis.
- Develop a finite element model to calculate the forces and stresses on a blade used to excavate lunar simulant and compare to the available experimental data

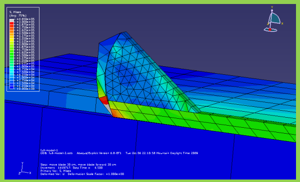
Overall CSM Integrated Picture

Analysis, theory





FE / analytical work

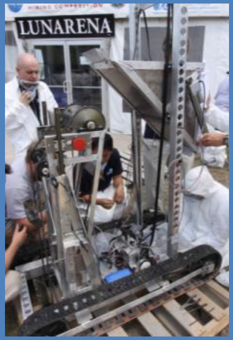


Prototypes

Lab - testing

Fidelity

Field testing

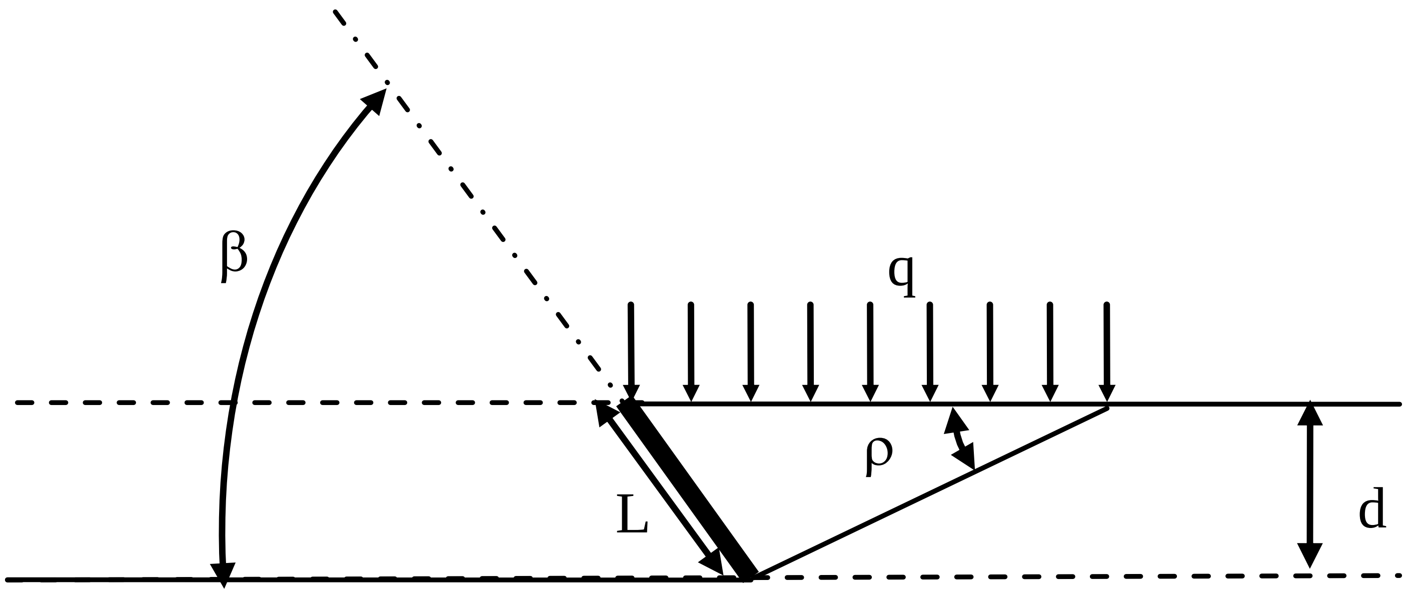


Science & System Engineering Inclusion

Simulations

- Determine input properties for soil models
  - Range, sensitivity
- Analytical models
- Finite Element Analysis

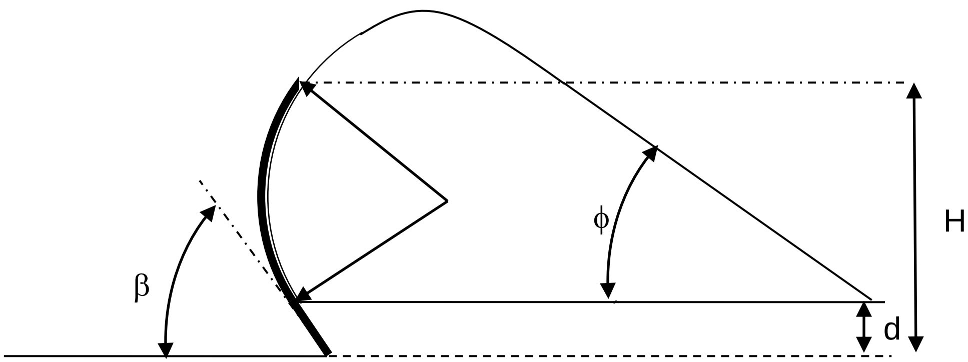
From Analytical Models



Geometry and Soil Mechanics

Input parameters of importance

$$T_{mckyes} = \left(\frac{wd}{\cos(\beta+\delta) + (\sin(\beta+\delta)\cot(\rho+\phi))} \right) \left[\begin{array}{l} \left(\frac{\gamma gd(\cot(\beta)+\cot(\rho))}{2} \right) + gq(\cot(\beta)+\cot(\rho)) + \\ c(1+\cot(\rho)\cot(\rho+\phi)) + C_a(1-\cot(\beta)\cot(\rho+\phi) \\ + \left(\frac{\gamma w^2(\tan(\rho)+\cot(\rho+\phi))}{1+\tan(\rho)\cot(\beta)} \right) \end{array} \right]$$

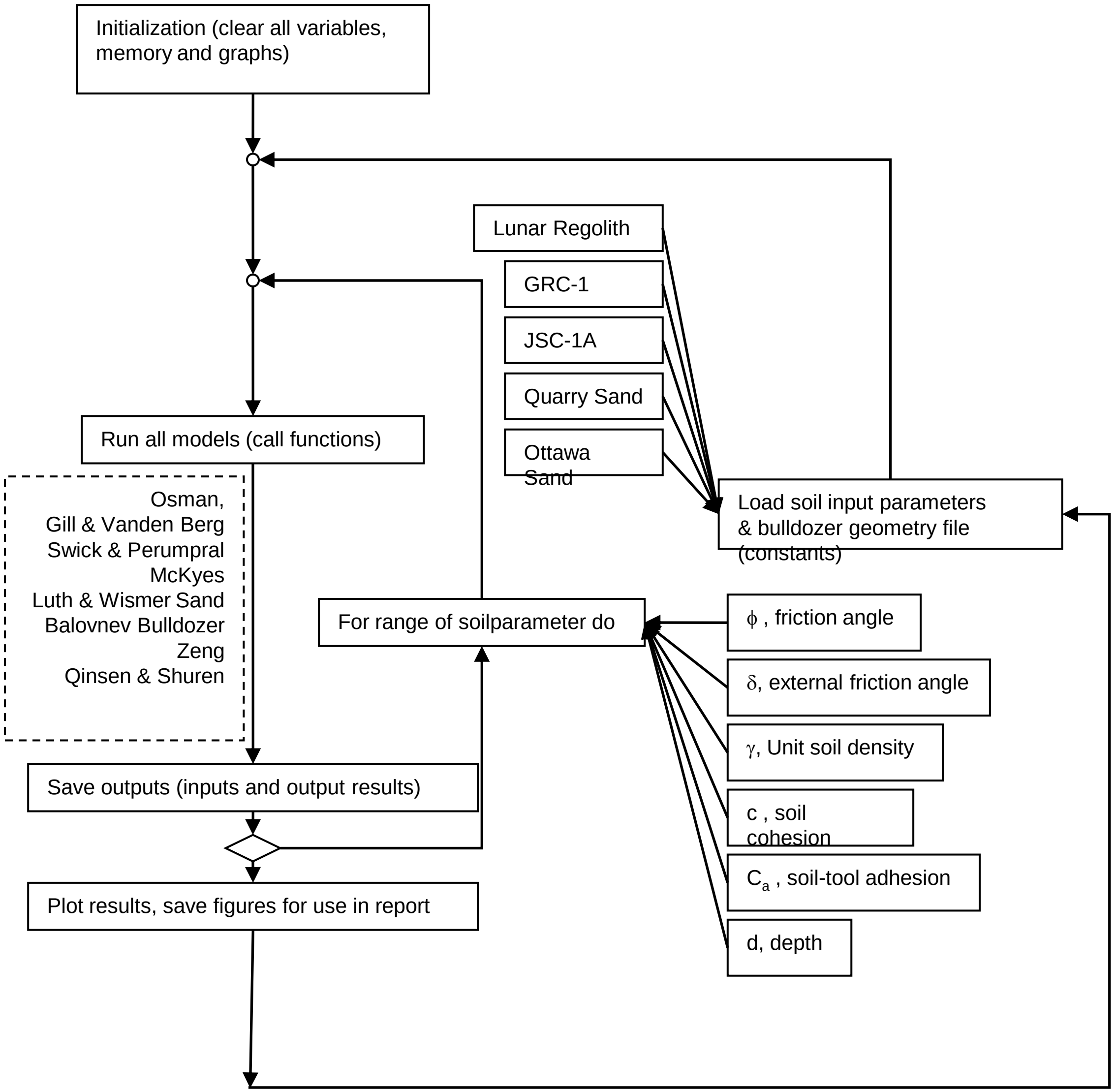


$$H_{mckyes} = T_{mckyes} \sin(\beta+\delta)$$

$$V_{mckyes} = T_{mckyes} \cos(\beta+\delta)$$

	Int friction angle ϕ (deg)			Ext friction angle δ (deg)			Unit Weight γ (g/cm^3)			Cohesion c (kN/m^2)			Adhesion c_a (kN/m^2)		
	Min	Exp	Max	Min	Exp	Max	Min	Exp	Max	Min	Exp	Max	Min	Exp	Max
Ottawa	29.1	35	41.6	11	15	32	0.9	1	1.07	0	1.51	3.03	0	0	0
Quarry	30	35	45	16	40	55	1.5	1.69	1.9	0	3.03	6.1	0	1	1
JSC-1A	37	50	57	16	40	64	1.45	1.5	1.9	0.827	3.8	6.83	0	1	1
GRC-1	30	40	45	16	40	64	1.58	1.73	1.89	0	4.96	9.92	0	1	1
Regolith	30	40	50	16	40	64	1.3	1.61	1.92	0.1	0.55	1	0	1	1

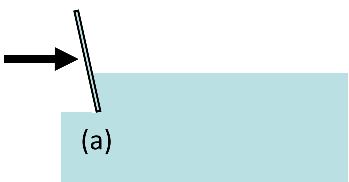
Limit Equilibrium Models



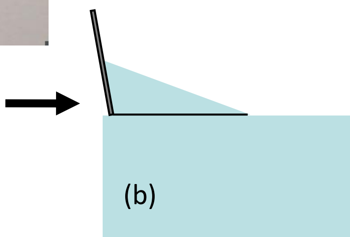
Force vs. depth results

Horizontal Force (kN) for 30 cm	Osman	Gill & VdB / Blouin	Swick & P	McKyes	L&W sand	Balovnev	Zeng	Qinsen & Shuren
GRC-1	87.29	142.2	127.1	127.1	44.59	43.44	91.77	12.49
JSC-1A	<0	173.2	1.48	5.09	38.66	34.36	126.89	9.97
Regolith	<0	108.56	77.2	77.2	41.49	7.62	66.92	2.24
sand	29.24	34.97	19.23	19.23	25.77	10.57	11.33	3.749
Quarry sand	47.48	106.8	70.1	70.1	43.04	27.19	37.91	7.684

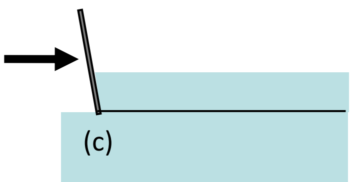
Max Depth (cm)	Osman	Gill & VdB / Blouin	Swick & P	McKyes	L&W sand	Balovnev	Zeng	Qinsen & Shuren
GRC-1	16.2	6.8	6.8	6.8	17.5	5	16.2	>>30
JSC-1A	n/a	5.8	n/a	n/a	19.5	3.5 or 41.8	14.5	64.5
Regolith	n/a	9.3	12	12	18.5	n/a	19.2	n/a
sand	25.4	21.7	35	35	22.5	>>30	38	>>30
Quarry sand	20.5	9	12	12	18	15.5	24	>>30



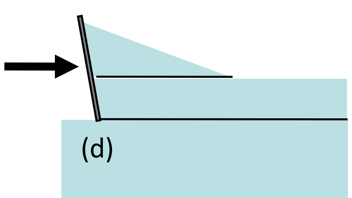
cut only



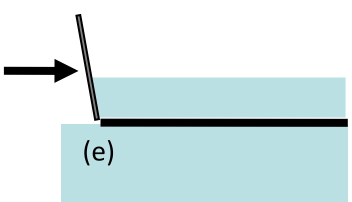
surcharge only



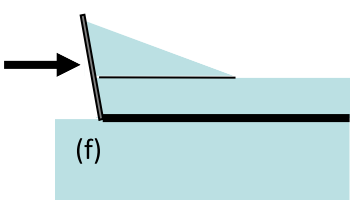
predefined cut only



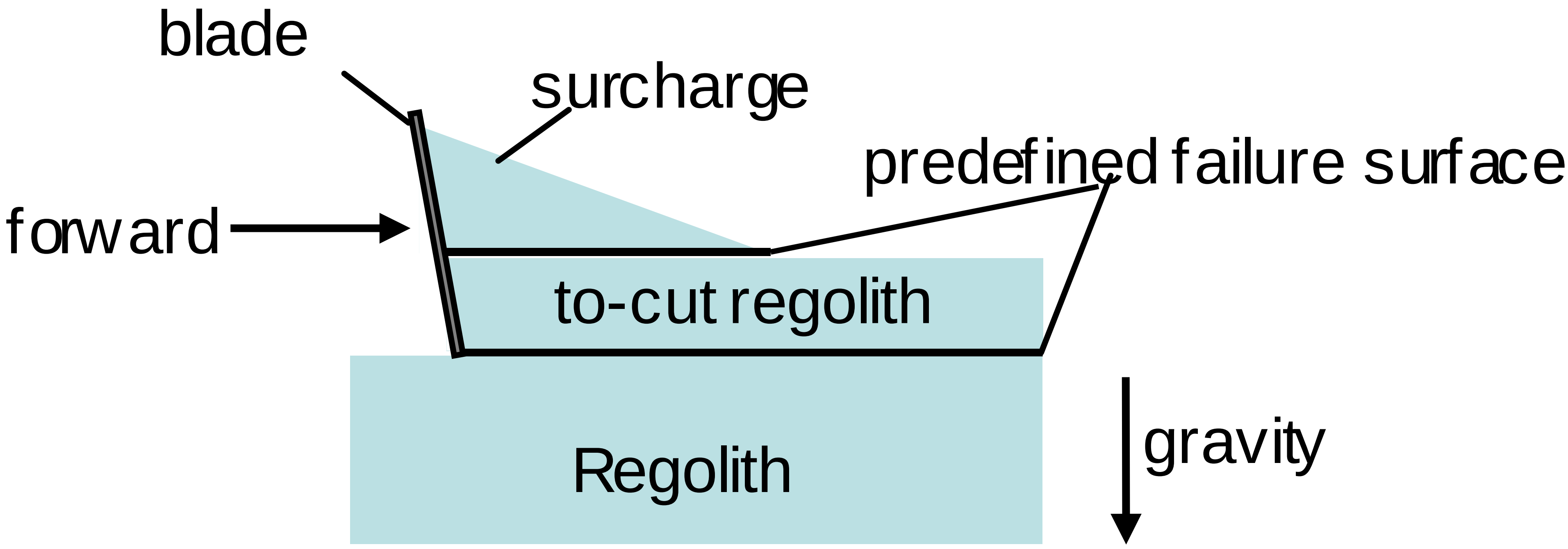
predefined cut plus surcharge



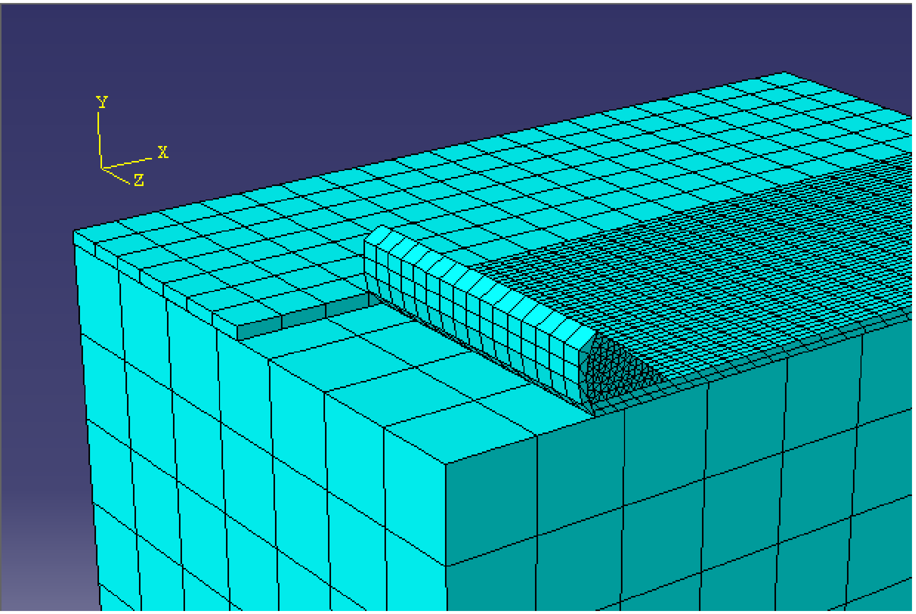
predefined coh cut



predefined coh cut plus surcharge


blade
surcharge
predefined failure surface
forward
to-cut regolith
Regolith
gravity

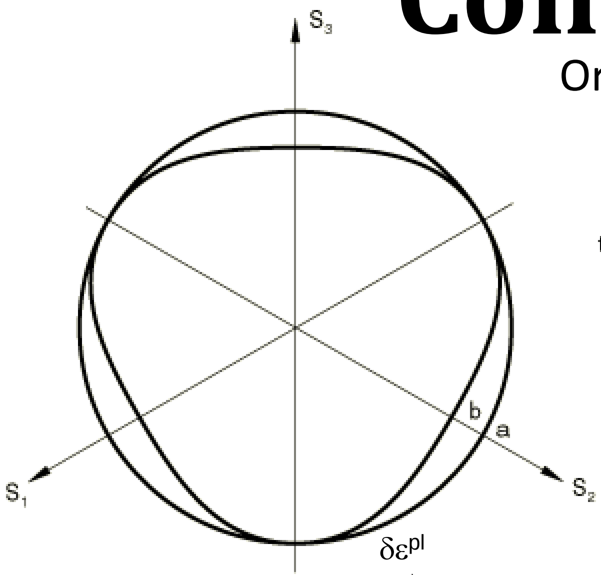
Finite Element Model



- Why FE
  - 3D
  - Forces & distributed stresses
  - More complex material behavior

Constitutive Model & Parameters

Original and Extended Drucker-Prager model

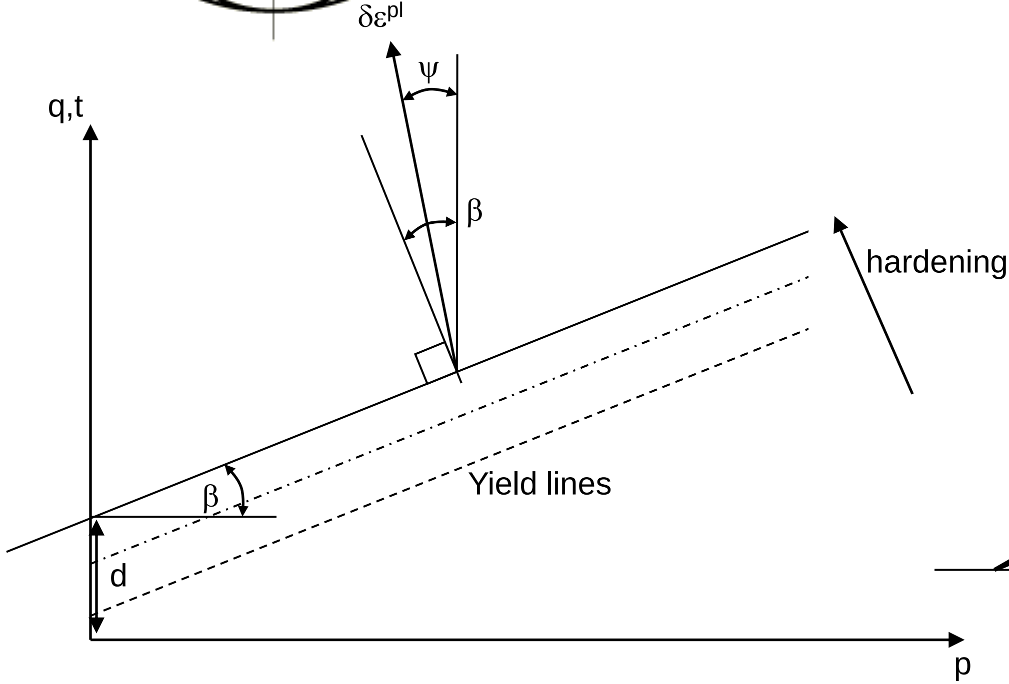


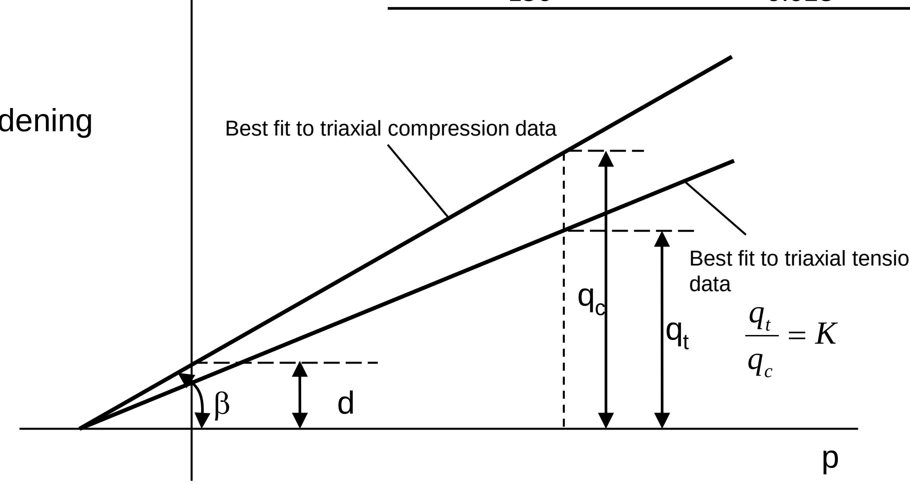
$$t = \frac{1}{2} q \left[1 + \frac{1}{K} - \left(1 - \frac{1}{K} \right) \left(\frac{r}{q} \right)^3 \right]$$

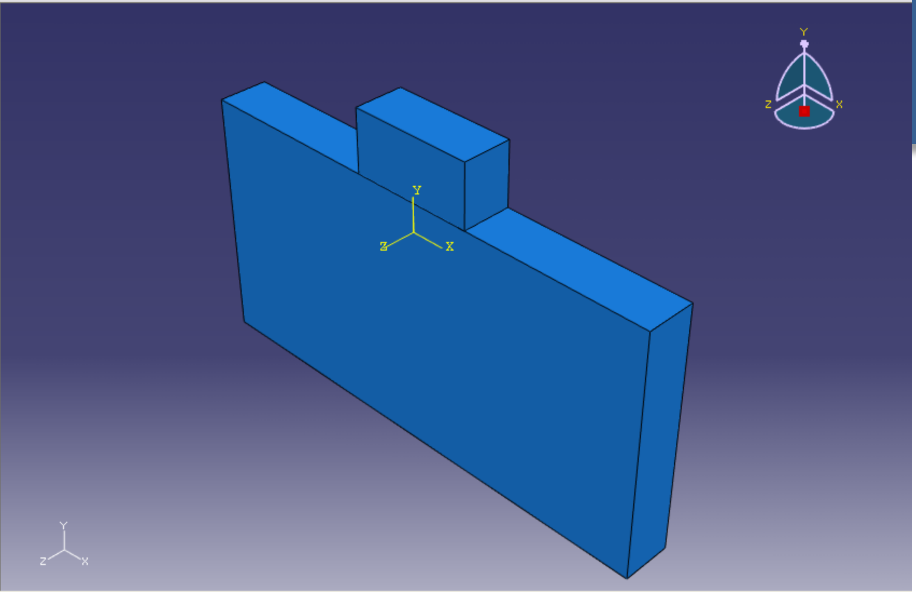
Curve	K
a	1.0
b	0.8

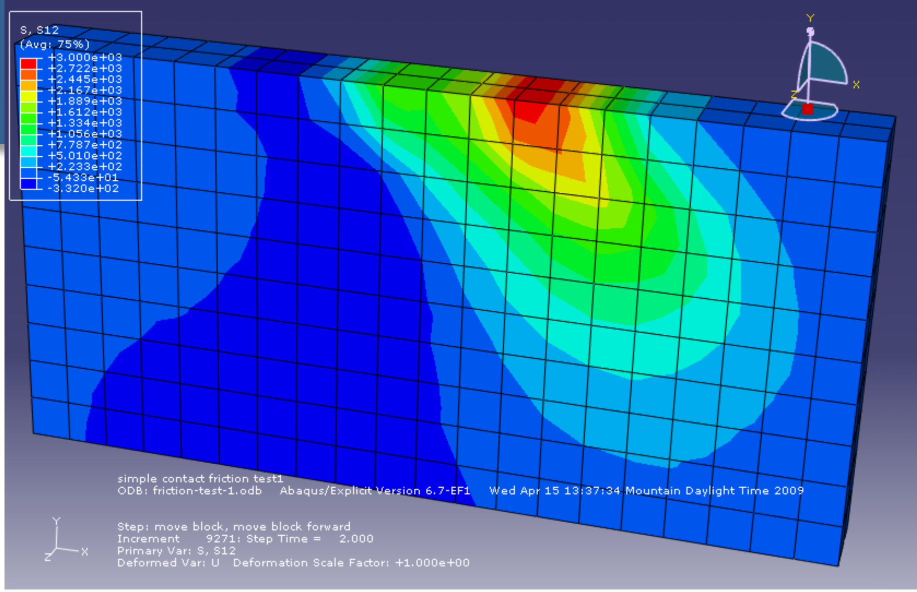
γ=1800 kg/m3
DP angle of friction= 55.6 degrees
Flowstress ratio (K) = 0.79
Dilation Angle = 15 degrees
E=36 Mpa
ν=0.3

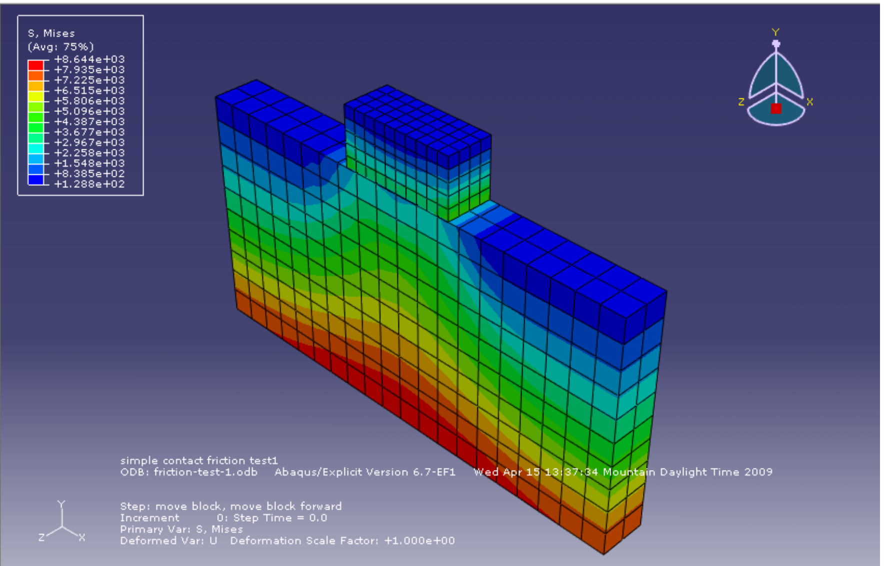
hardening 2	
yield stress (kPa)	absolute plastic strain
25	0
70	0.027
150	0.028



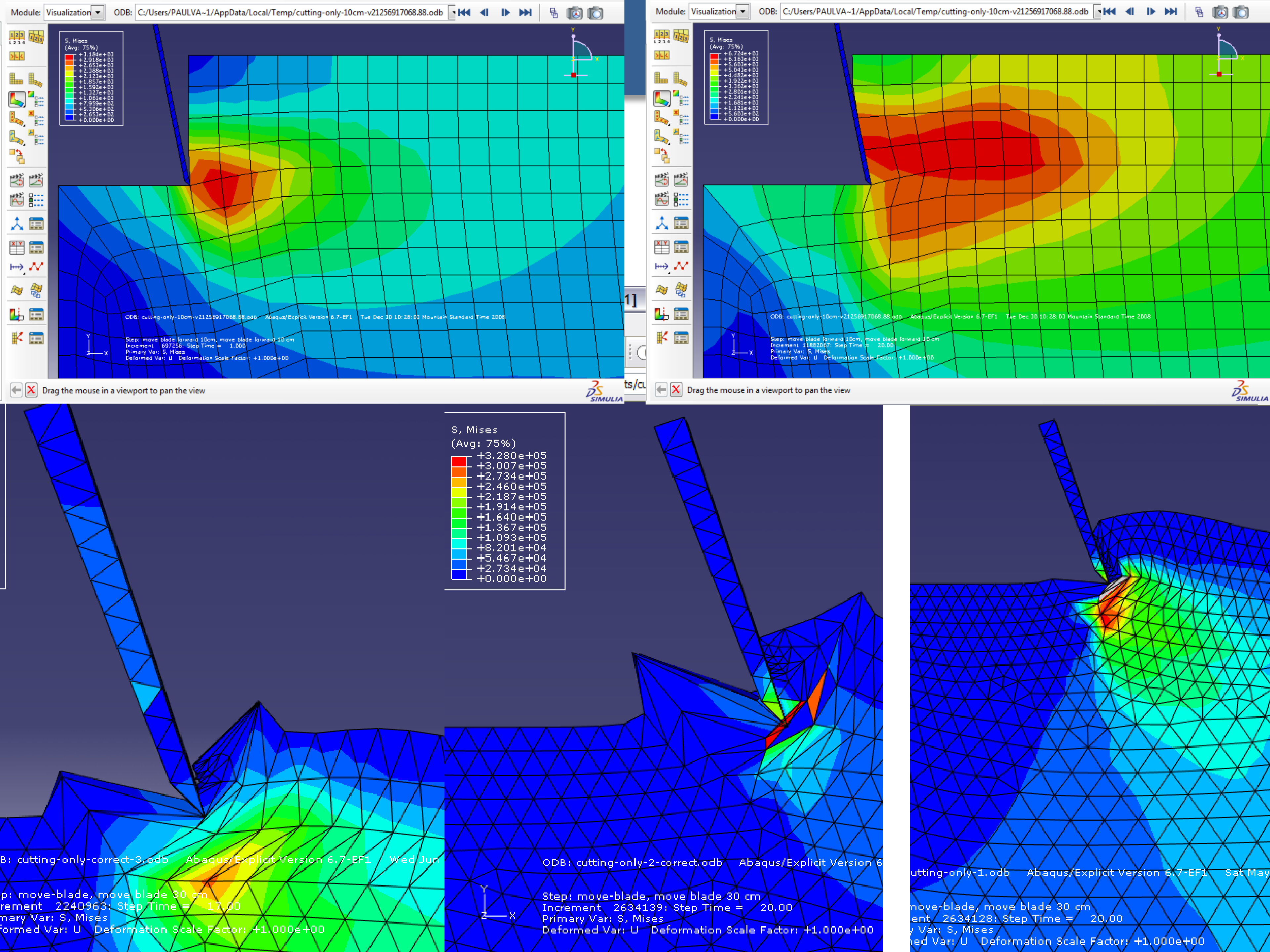


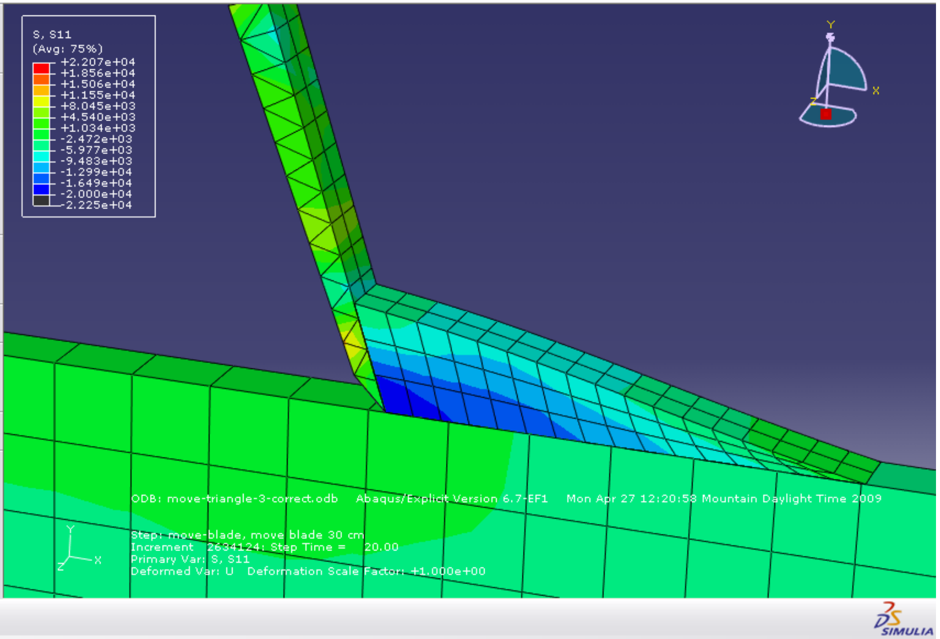


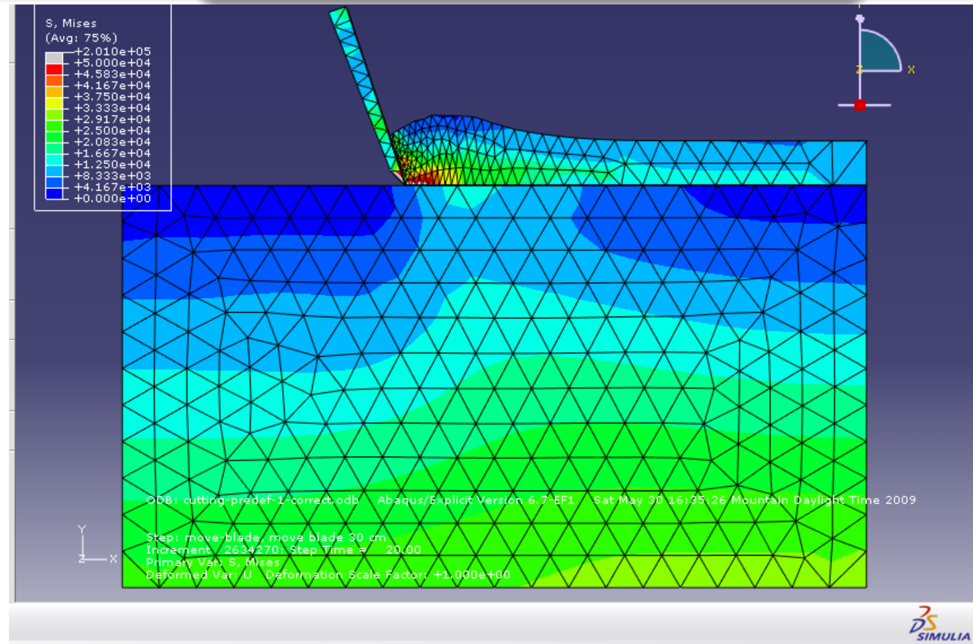


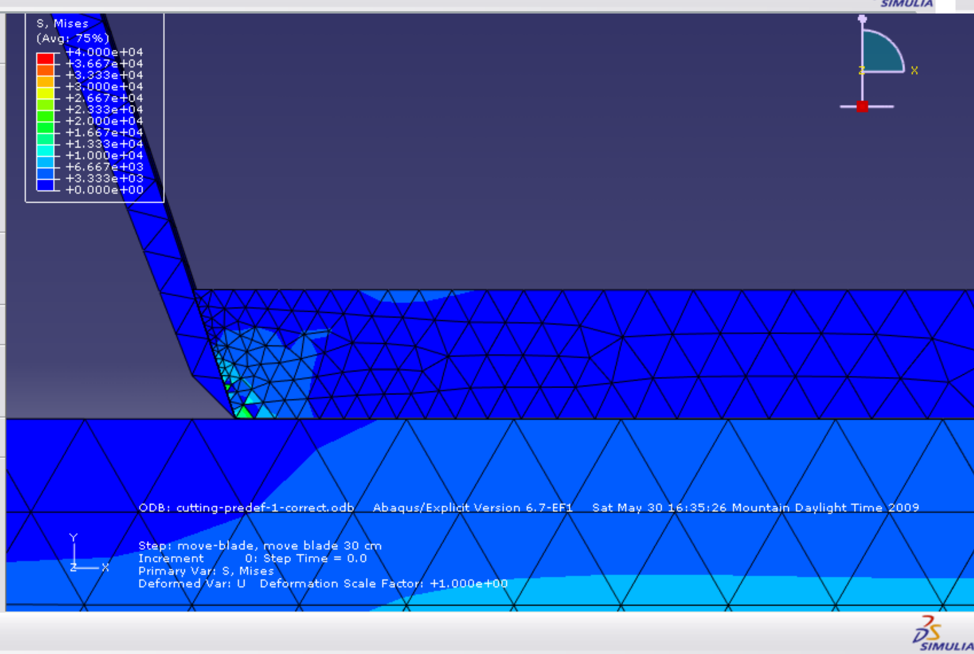


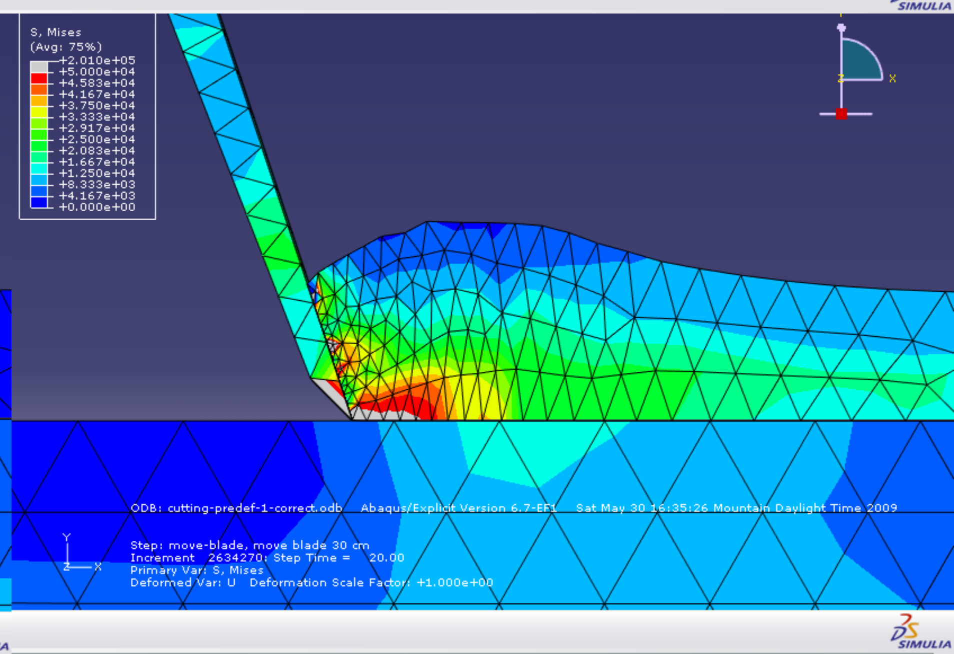
- Theoretical case
- Calibration of FEA model
- Damping in particular

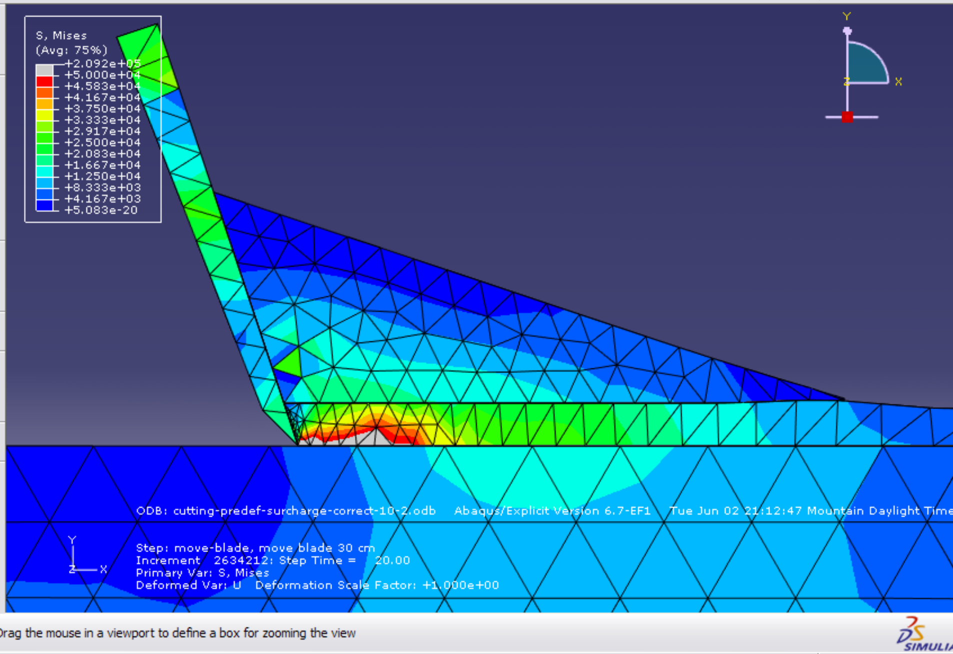

Module: Visualization
ODB: C:/Users/PAULVA~1/AppData/Local/Temp/cutting-only-10cm-v21256917068.88.odb
Drag the mouse in a viewport to pan the view
Module: Visualization
ODB: C:/Users/PAULVA~1/AppData/Local/Temp/cutting-only-10cm-v21256917068.88.odb
Drag the mouse in a viewport to pan the view
S, Mises
(Avg: 75%)
+3.280e+05
+3.007e+05
+2.734e+05
+2.460e+05
+2.187e+05
+1.914e+05
+1.640e+05
+1.367e+05
+1.093e+05
+8.201e+04
+5.467e+04
+2.734e+04
+0.000e+00
B: cutting-only-correct-3.odb Abaqus/Explicit Version 6.7-EF1 Wed Jun
p: move-blade, move blade 30 cm
rement 2240963: Step Time = 17.00
mary Var: S, Mises
formed Var: U Deformation Scale Factor: +1.000e+00
ODB: cutting-only-2-correct.odb Abaqus/Explicit Version 6
Step: move-blade, move blade 30 cm
Increment 2634139: Step Time = 20.00
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00
utting-only-1.odb Abaqus/Explicit Version 6.7-EF1 Sat May
move-blade, move blade 30 cm
ent 2634128: Step Time = 20.00
Var: S, Mises
ed Var: U Deformation Scale Factor: +1.000e+00

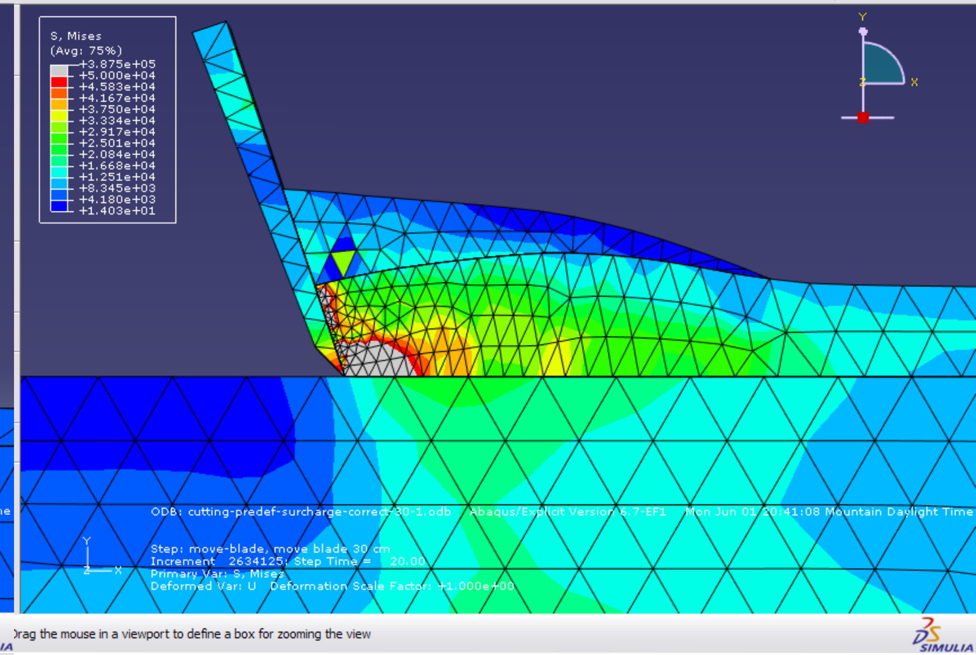

S, S11
(Avg: 75%)
+2.207e+04
+1.856e+04
+1.506e+04
+1.155e+04
+8.045e+03
+4.540e+03
+1.034e+03
-2.472e+03
-5.977e+03
-9.483e+03
-1.299e+04
-1.649e+04
-2.000e+04
-2.225e+04
ODB: move-triangle-3-correct.odb Abaqus/Explicit Version 6.7-EF1 Mon Apr 27 12:20:58 Mountain Daylight Time 2009
Step: move-blade, move blade 30 cm
Increment 2634124: Step Time = 20.00
Primary Var: S, S11
Deformed Var: U Deformation Scale Factor: +1.000e+00
SIMULIA

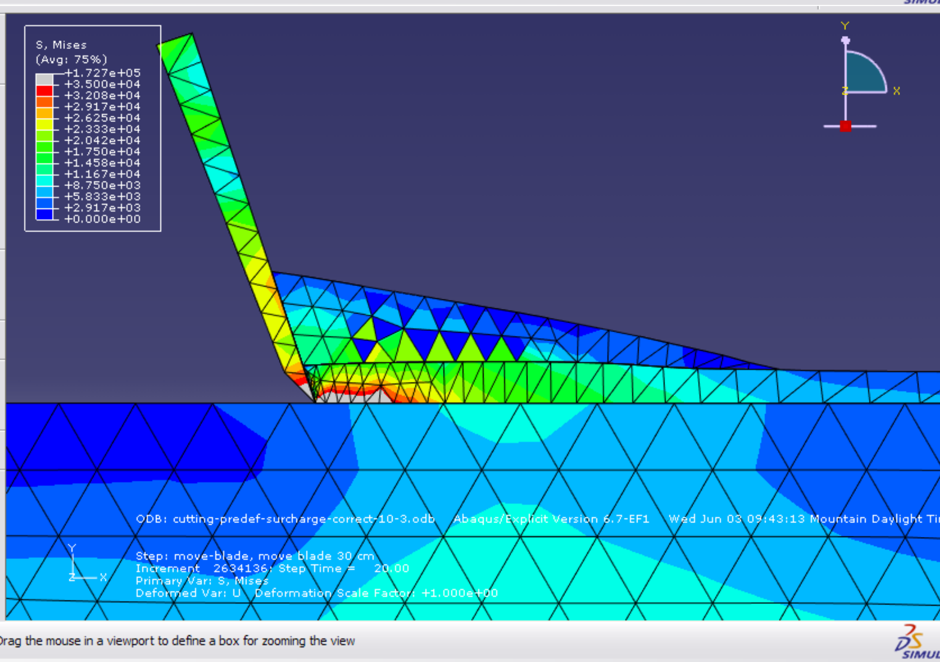

S, Mises
(Avg: 75%)
+2.010e+05
+5.000e+04
+4.583e+04
+4.167e+04
+3.750e+04
+3.333e+04
+2.917e+04
+2.500e+04
+2.083e+04
+1.667e+04
+1.250e+04
+8.333e+03
+4.167e+03
+0.000e+00
ODB: cutting-predef-1-correct.odb Abaqus/Explicit Version 6.7-EF1 Sat May 30 16:35:26 Mountain Daylight Time 2009
Step: move-blade, move blade 30 cm
Increment 2634270: Step Time = 20.00
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00
SIMULIA

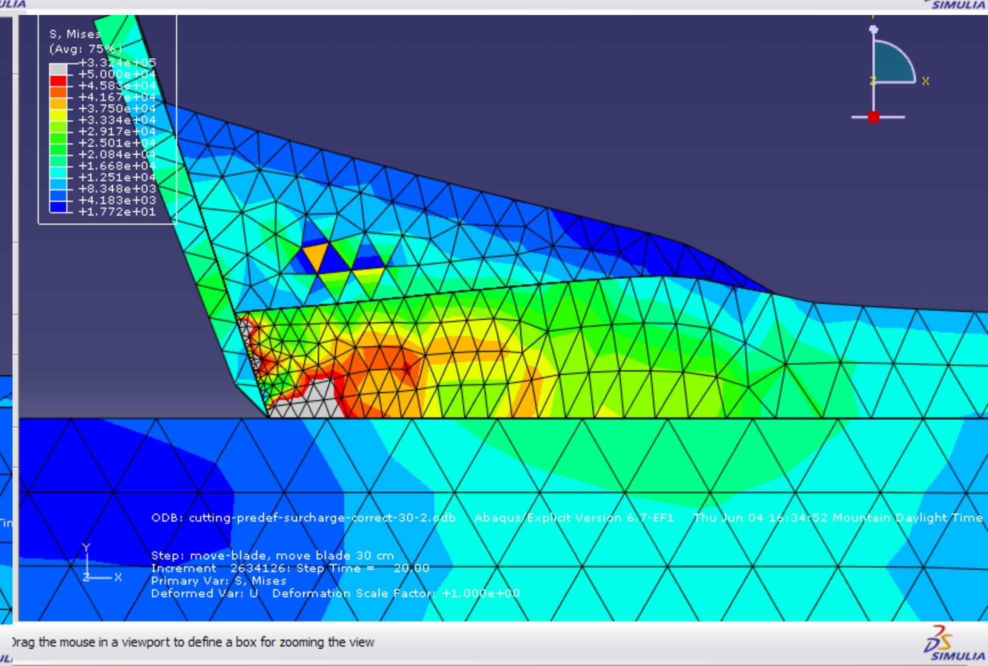

S, Mises
(Avg: 75%)
+4.000e+04
+3.667e+04
+3.333e+04
+3.000e+04
+2.667e+04
+2.333e+04
+2.000e+04
+1.667e+04
+1.333e+04
+1.000e+04
+6.667e+03
+3.333e+03
+0.000e+00
ODB: cutting-predef-1-correct.odb Abaqus/Explicit Version 6.7-EF1 Sat May 30 16:35:26 Mountain Daylight Time 2009
Step: move-blade, move blade 30 cm
Increment 0: Step Time = 0.0
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00
SIMULIA

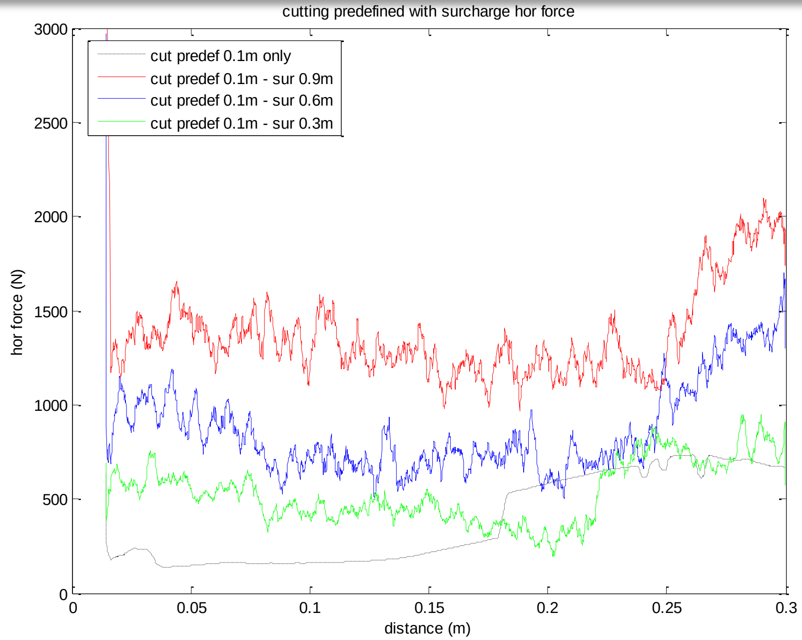

S, Mises
(Avg: 75%)
+2.010e+05
+5.000e+04
+4.583e+04
+4.167e+04
+3.750e+04
+3.333e+04
+2.917e+04
+2.500e+04
+2.083e+04
+1.667e+04
+1.250e+04
+8.333e+03
+4.167e+03
+0.000e+00
ODB: cutting-predef-1-correct.odb Abaqus/Explicit Version 6.7-EF1 Sat May 30 16:35:26 Mountain Daylight Time 2009
Step: move-blade, move blade 30 cm
Increment 2634270: Step Time = 20.00
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00
SIMULIA

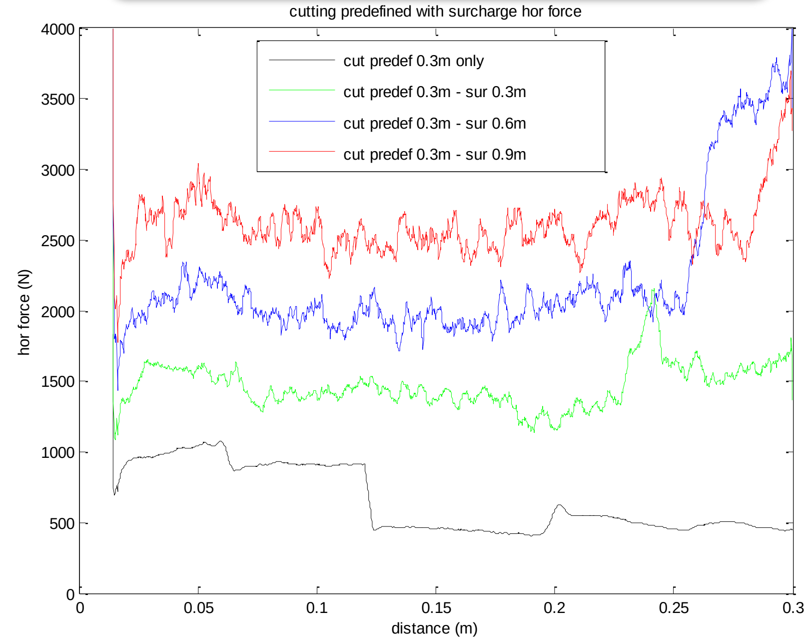

S, Mises
(Avg: 75%)
+2.092e+05
+5.000e+04
+4.583e+04
+4.167e+04
+3.750e+04
+3.333e+04
+2.917e+04
+2.500e+04
+2.083e+04
+1.667e+04
+1.250e+04
+8.333e+03
+4.167e+03
+5.083e-20
ODB: cutting-predef-surcharge-correct-10-2.odb Abaqus/Explicit Version 6.7-EF1 Tue Jun 02 21:12:47 Mountain Daylight Time
Step: move-blade, move blade 30 cm
Increment 2634212: Step Time = 20.00
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00
rag the mouse in a viewport to define a box for zooming the view
SIMULIA

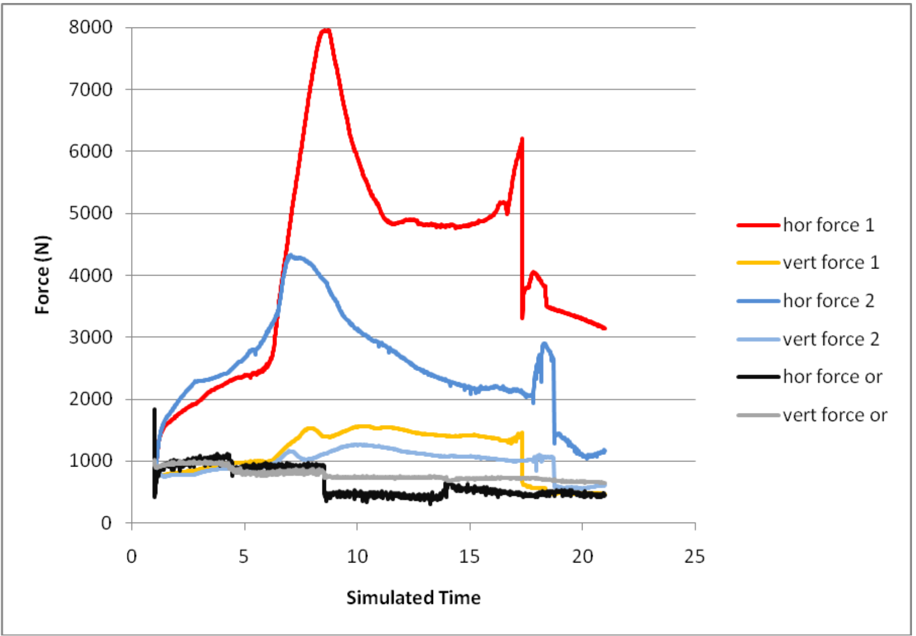

S, Mises
(Avg: 75%)
+3.875e+05
+5.000e+04
+4.583e+04
+4.167e+04
+3.750e+04
+3.334e+04
+2.917e+04
+2.501e+04
+2.084e+04
+1.668e+04
+1.251e+04
+8.345e+03
+4.180e+03
+1.403e+01
ODB: cutting-predef-surcharge-correct-30-1.odb Abaqus/Explicit Version 6.7-EF1 Mon Jun 01 20:41:08 Mountain Daylight Time
Step: move-blade, move blade 30 cm
Increment 2634125: Step Time = 20.00
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00
rag the mouse in a viewport to define a box for zooming the view
SIMULIA


S, Mises
(Avg: 75%)
+1.727e+05
+3.500e+04
+3.208e+04
+2.917e+04
+2.625e+04
+2.333e+04
+2.042e+04
+1.750e+04
+1.458e+04
+1.167e+04
+8.750e+03
+5.833e+03
+2.917e+03
+0.000e+00
ODB: cutting-predef-surcharge-correct-10-3.odb Abaqus/Explicit Version 6.7-EF1 Wed Jun 03 09:43:13 Mountain Daylight Tin
Step: move-blade, move blade 30 cm
Increment 2634136: Step Time = 20.00
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00
rag the mouse in a viewport to define a box for zooming the view


S, Mises
(Avg: 75%)
+3.324e+05
+5.000e+04
+4.583e+04
+4.167e+04
+3.750e+04
+3.334e+04
+2.917e+04
+2.501e+04
+2.084e+04
+1.668e+04
+1.251e+04
+8.348e+03
+4.183e+03
+1.772e+01
ODB: cutting-predef-surcharge-correct-30-2.odb Abaqus/Explicit Version 6.7-EF1 Thu Jun 04 16:34:52 Mountain Daylight Time
Step: move-blade, move blade 30 cm
Increment 2634126: Step Time = 20.00
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00
rag the mouse in a viewport to define a box for zooming the view
SIMULIA

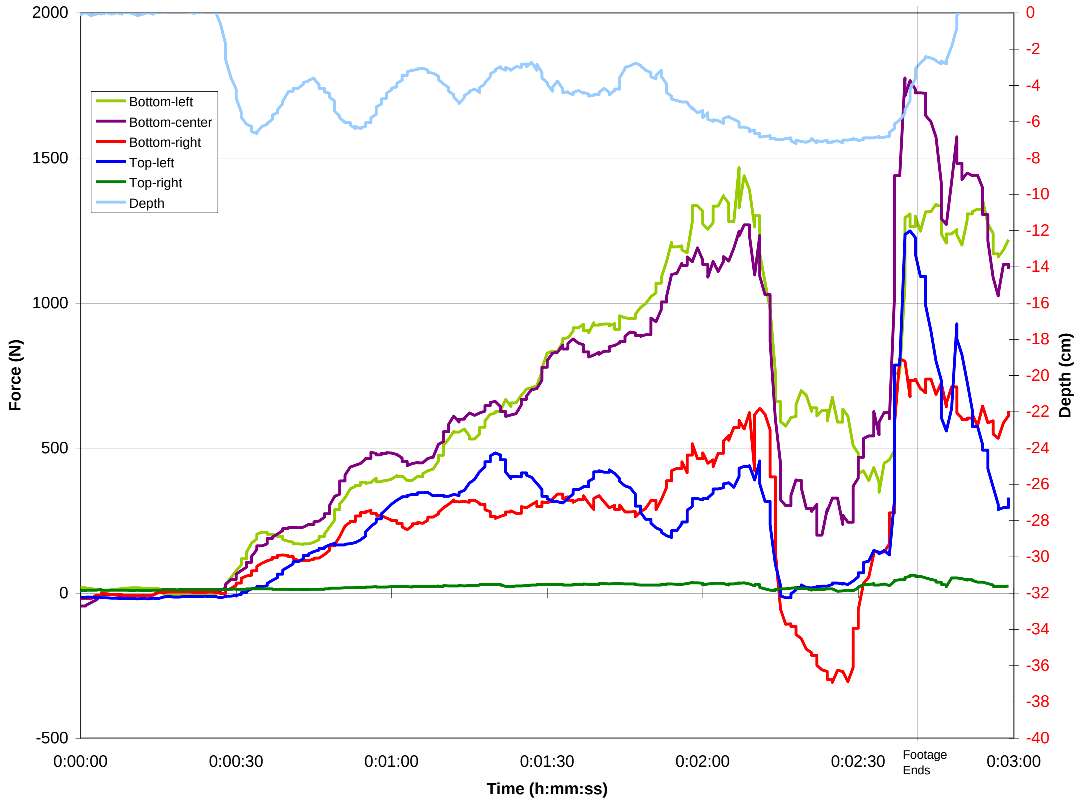


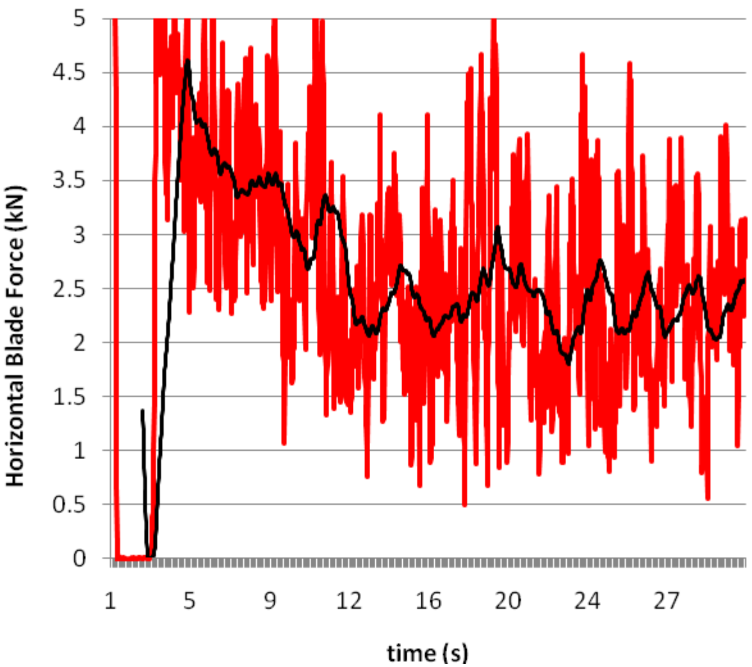


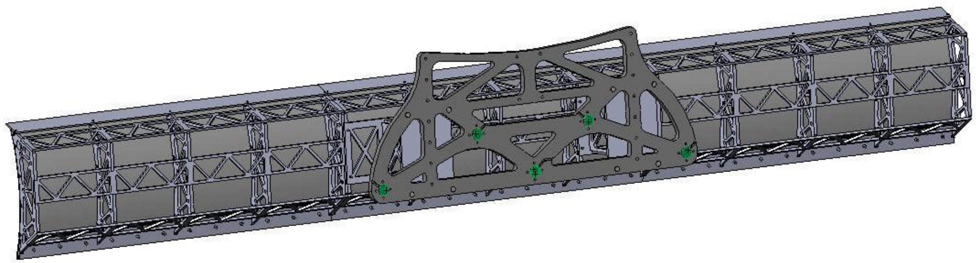


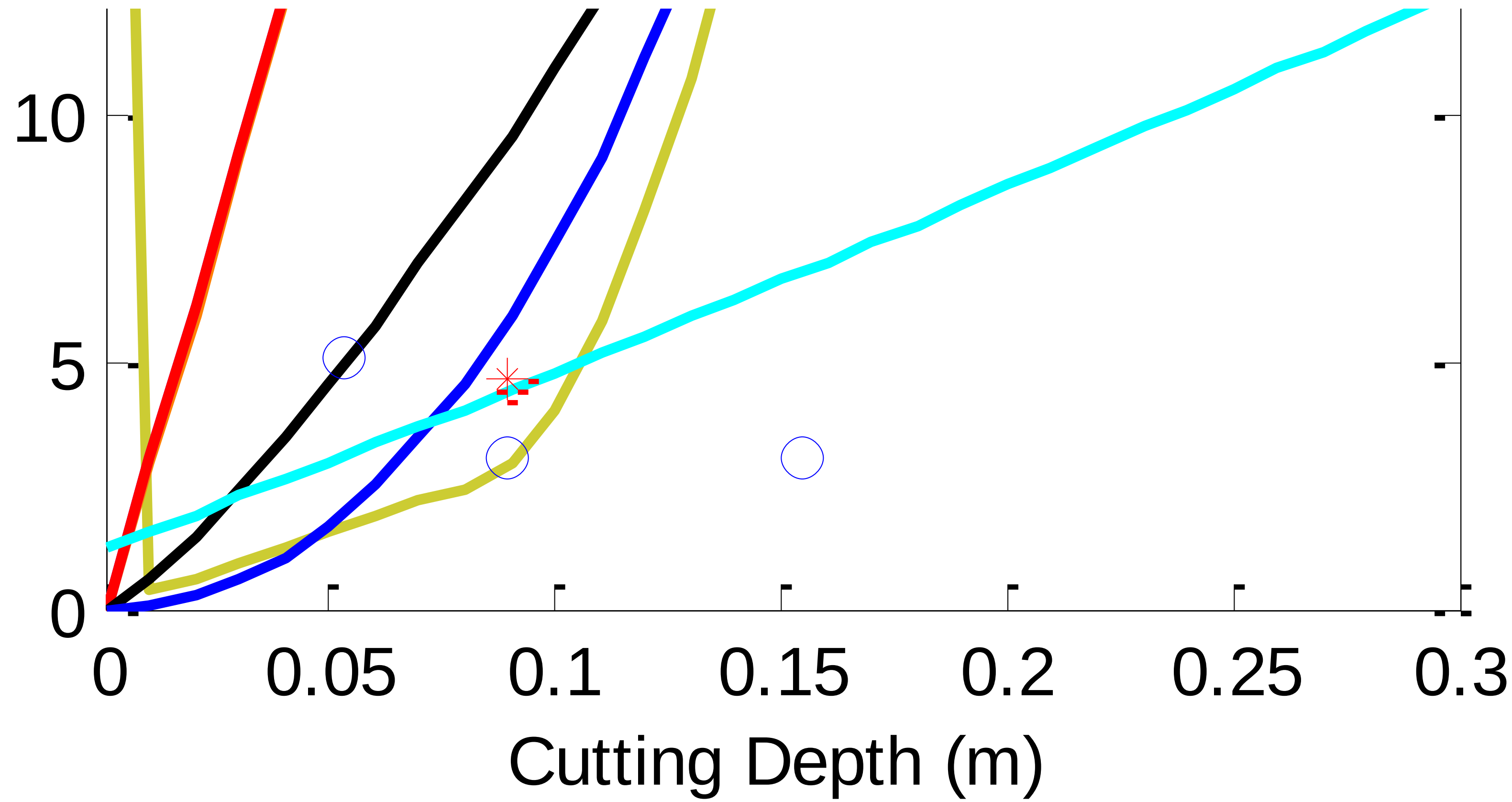
- Cut of 0.1 m & 0.3 m
- Surcharge 0.3, 0.6, 0.9 m
- Material model

Experimental data and FEA results

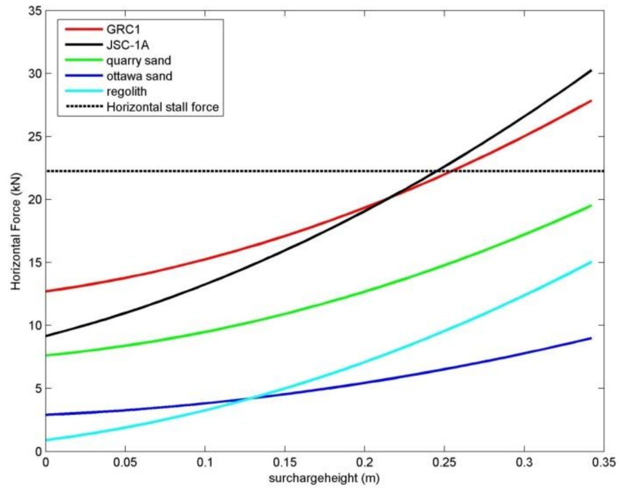


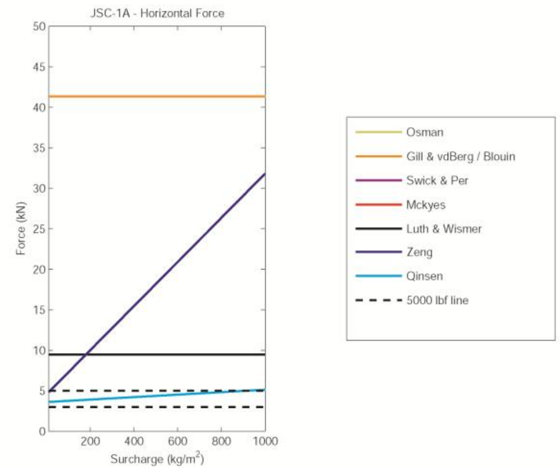


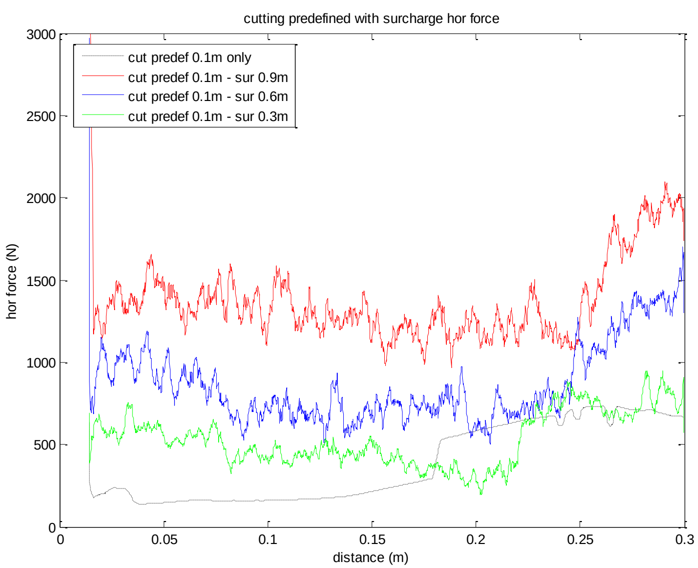


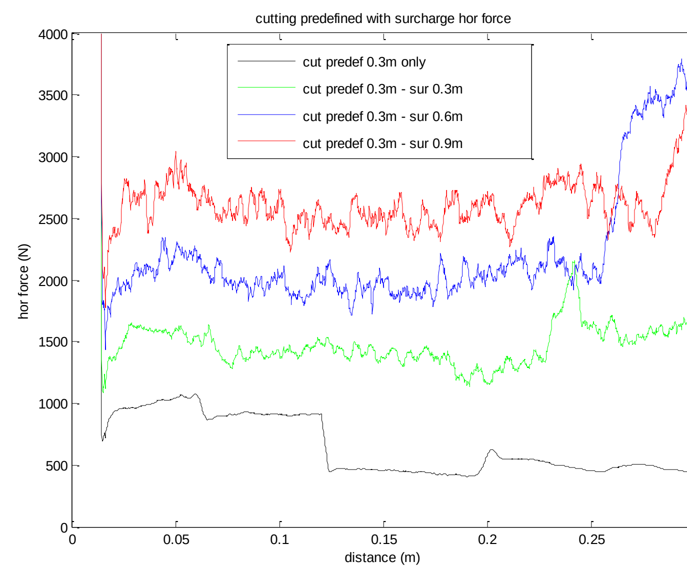

10
5
0
0
0.05
0.1
0.15
0.2
0.25
0.3
Cutting Depth (m)

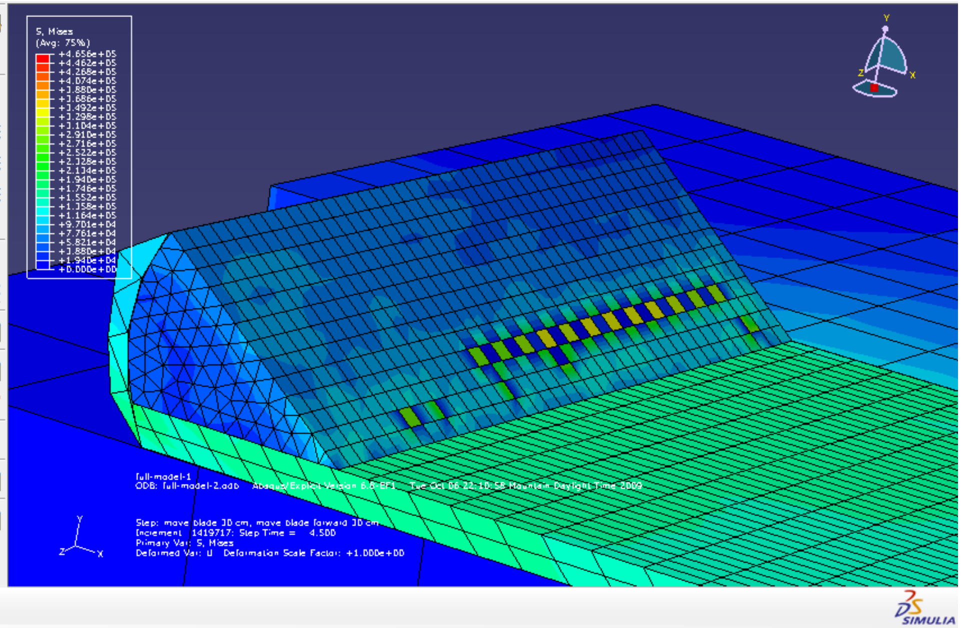
Effect of Surcharge



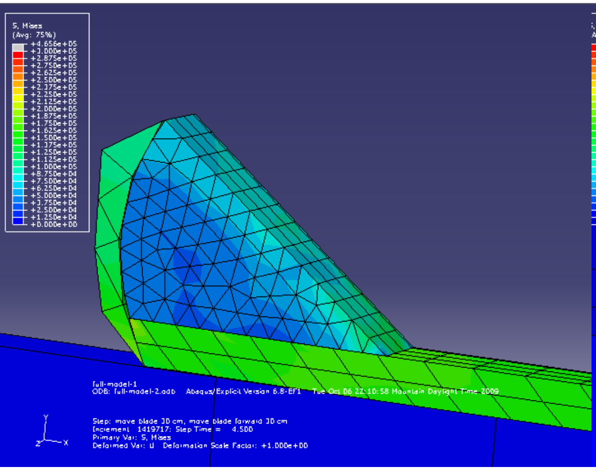


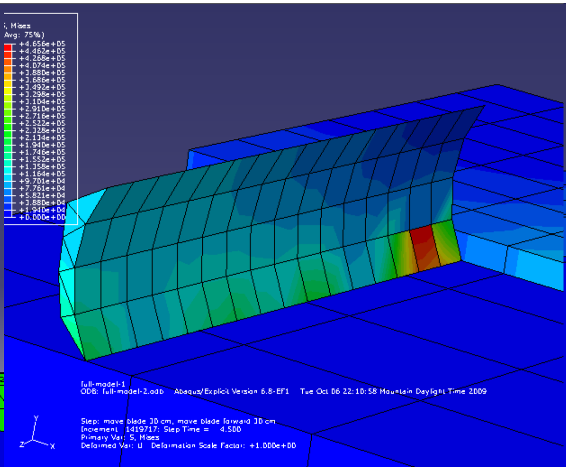


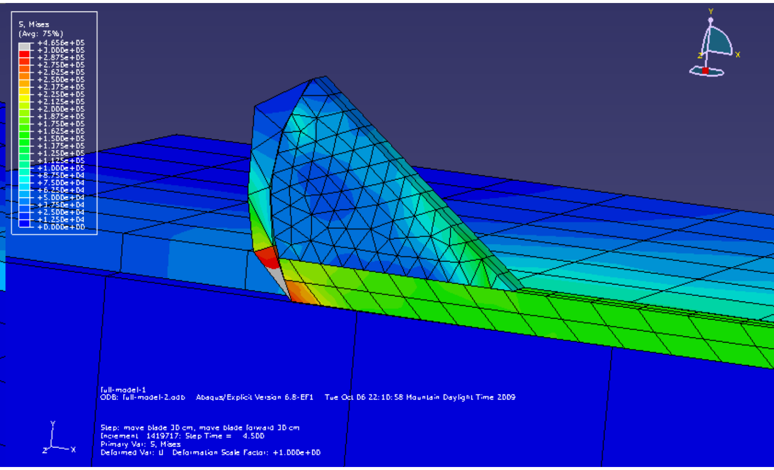




- Full size model
- Symmetric around center plane
- 3D FEA
- Constitutive model







Conclusions

- FEA modeling possible
- Gives good ballpark results
- Only can model first cut and first part of pushing
- Constitutive model problematic
- Large variability in soil properties
- Very little good experimental data available at the right scales and in the right materials
- FEA/DEM combo might yield more accurate time results
- Computationally intensive (full model takes 3-4 days to run one case)
- Future work to include FEA of small scale experiments completed in mean time

Thanks

- NASA Surface Systems (Rob Mueller)
- Dr. R. King
- Mark Gefreh, Andrew Brewer, Brian Dreiling

QUESTIONS?