Consolidated Material Mining for ISRU

Space Resources Roundtable

6/14/19

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Excavation Element Lead: Phil Abel

Excavation for ISRU

- **Previous work has focused on unconsolidated material**

Review of objective

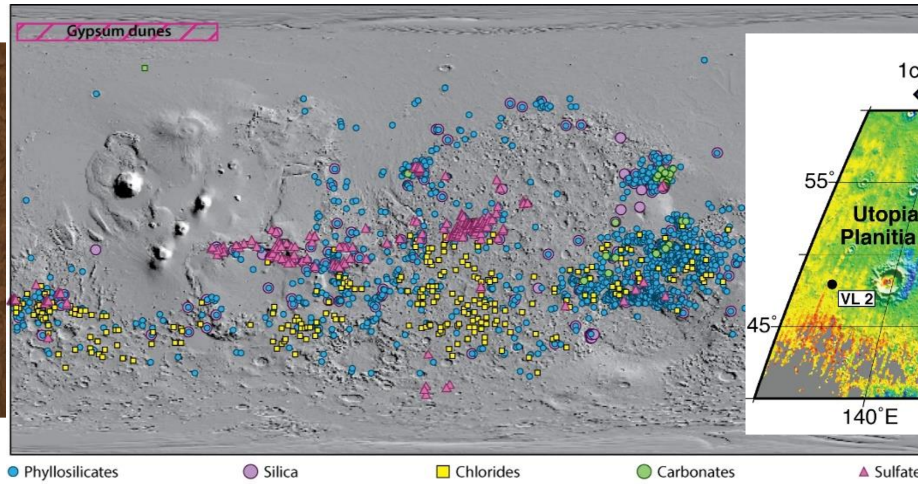
- **Can we predict what it takes to excavate this…**

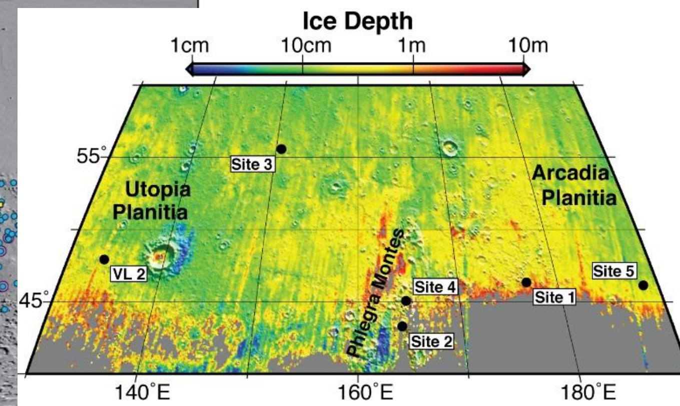
Instead of this…

The material we want might not be just loose regolith

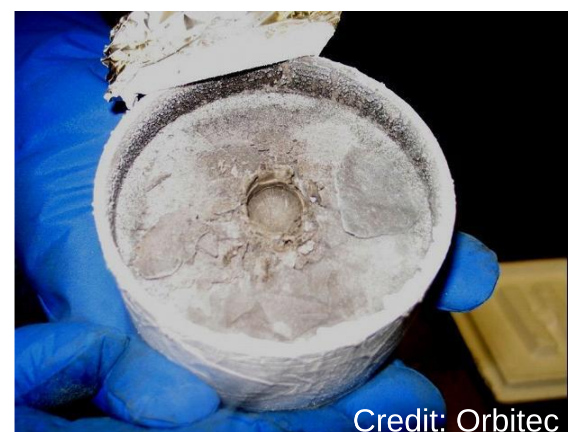
- **High yield deposits might be in the form of harder/consolidated material**
  - **Mars** – polyhydrated sulfates (e.g. gypsum) or mid-latitude ice
    - gypsum estimate: 20% water content @ 40% abundance = 8% water available (M-WIP)

Gypsum vein at “homestake” - Opportunity





  - **Moon** – Ice cemented regolith



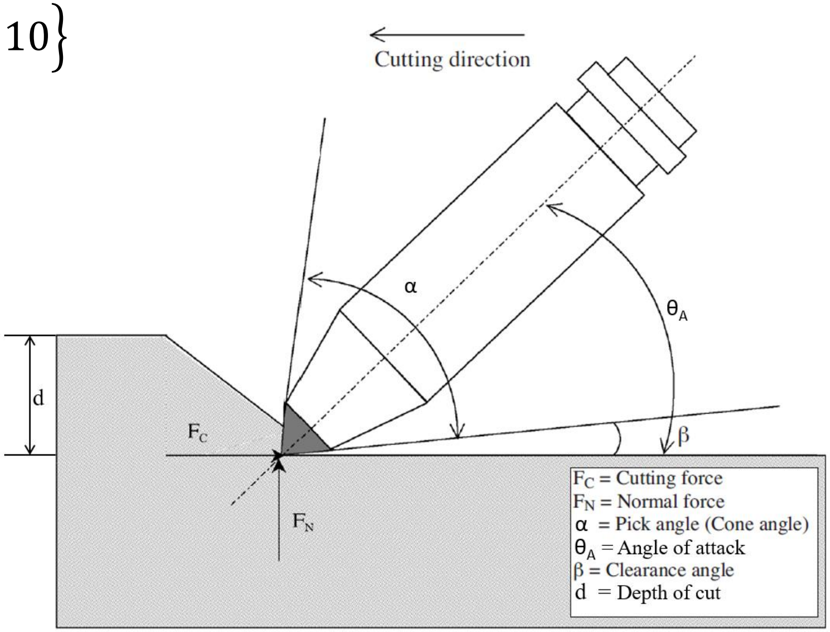
Why don't we trust existing models?

- **Terrestrial rock mining techniques may be applicable to the Moon and Mars but one major concern is reaction force.**
  - Without relying on anchoring the excavation reaction force is based upon the vehicle mass. (drawbar pull of ~1000s of lbf for the largest vehicles)

- **Models exist that predict the forces for rock cutting**
  - The top ones are: Evans, Roxborough, and Goktan and take the form of:

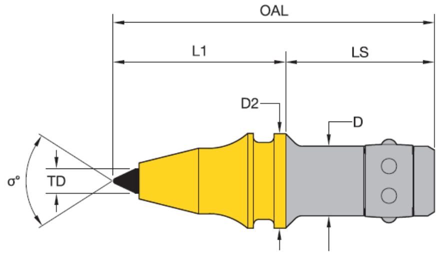
$$FC = \frac{12\pi\sigma_t d^2 \sin^2\left\{{}^1/_2\left[90-\left(90-\frac{\alpha}{2}+\theta_A\right)\right]+10\right\}}{\cos\left\{{}^1/_2\left[90-\left(90-\frac{\alpha}{2}+\theta_A\right)\right]+10\right\}}$$

  - **Variables**: tensile strength of rock (σ_t), cutting depth (d), pick tip angle (α), and attack angle (θ_A)
  - **Limitations**:
    - Empirical tests have mostly been done on harder rock
    - Full scale mining tests produce reaction forces that may exceed our capacity



The Plan

- **Plan overview:**
  - Fundamental - single pick cutting in gypsum
  - Use the smallest scale picks currently available
  - Instrument the pick with a 3-axis load cell
  - Perform Unconfined Compressive Strength and Brazilian Tensile Strength tests on test articles.
  - Measure the excavation forces and cuttings volume, mass, and particle size distribution.



Conical picks

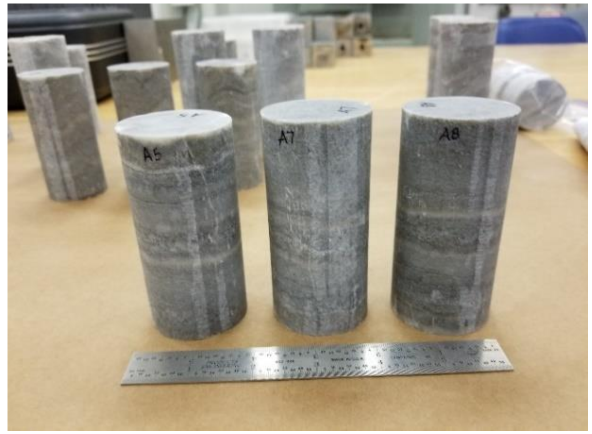
3-axis loadcell

We will validate or extend the existing models for reduced scale cutting in gypsum rocks.

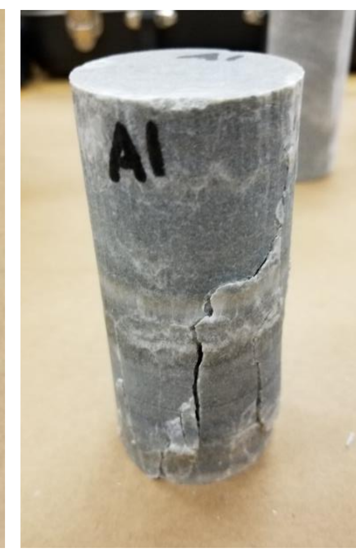
Gypsum Rocks

- **2.6 tons of gypsum rock at KSC**
- **Thank you to Paul van Susante (MTU) and USG in Fort Dodge, IA**

Material characterization



Test	Literature (MPa)	Measured (MPa)
Unconfined Compressive Strength (UCS)	17-29	**26.93**
Brazilian Tensile Strength (BTS)	2.3-5	**3.4**



Material characterization

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Wheat Ridge, CO 80033 - (303) 463-8270

Petrographic Analysis

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Client:		Analysis Date:	8-21-18
	Laurent Sibille, PhD	Reporting Date:	8-22-18
	c/o LASSO Labs	Receipt Date:	7-27-18
	Building M6-744	Client Job No.:	None Given
	Kennedy Space Center, FL 32899	Project Title:	Gypsum Excavation
		DCMSL Project:	AECURS1

The purpose of this project is to determine the bulk mineralogy of one gypsum sample (client no. KSC-GYP-Slab-A) with an emphasis on metal sulfides and the nature of the dark laminations. The sample was prepared as a standard polished thin section for study by polarized light (PL) and reflected light (RL) microscopy. Color photomicrographs are included for documentation of relevant features.

Sample No.: **KSC-GYP-Slab-A**

Hand Specimen Description

In hand specimen this sample is a dense evaporite composed of gypsum. The specimen shows alternating bands of grey and water clear white gypsum. Individual layers vary from 2mm to greater than 1cm in thickness.

Microscopic Description

Mineralogy: Gypsum 98% Quartz 2%

Trace Mineralogy: Illite, Dolomite, Pyrite, Mica, Iron oxide, Organic (carbon)

In thin section the rock is composed of simple mineralogy. The primary phase is gypsum showing a variety of habits. In the grey looking seams, gypsum occurs as fine to medium anhedral, mosaic grains with dimensions of 20µm to 100µm. Cutting the mosaic aggregates are single elongated or bladed crystals up 250µm in size. In other areas of the grey seams, gypsum occurs as radiating groups of elongated crystals set in a mosaic of anhedral gypsum. In the clear white seams seen in hand specimen, gypsum occurs primarily as interlocking prisms with a grain size up to 600µm. The prisms have the appearance of being squeezed along their length. The discoloration seen in the grey areas is largely due to impurities that were incorporated during precipitation of the gypsum. Thin strings and thicker seams of clay mixed with carbon, pyrite,

Test Setup

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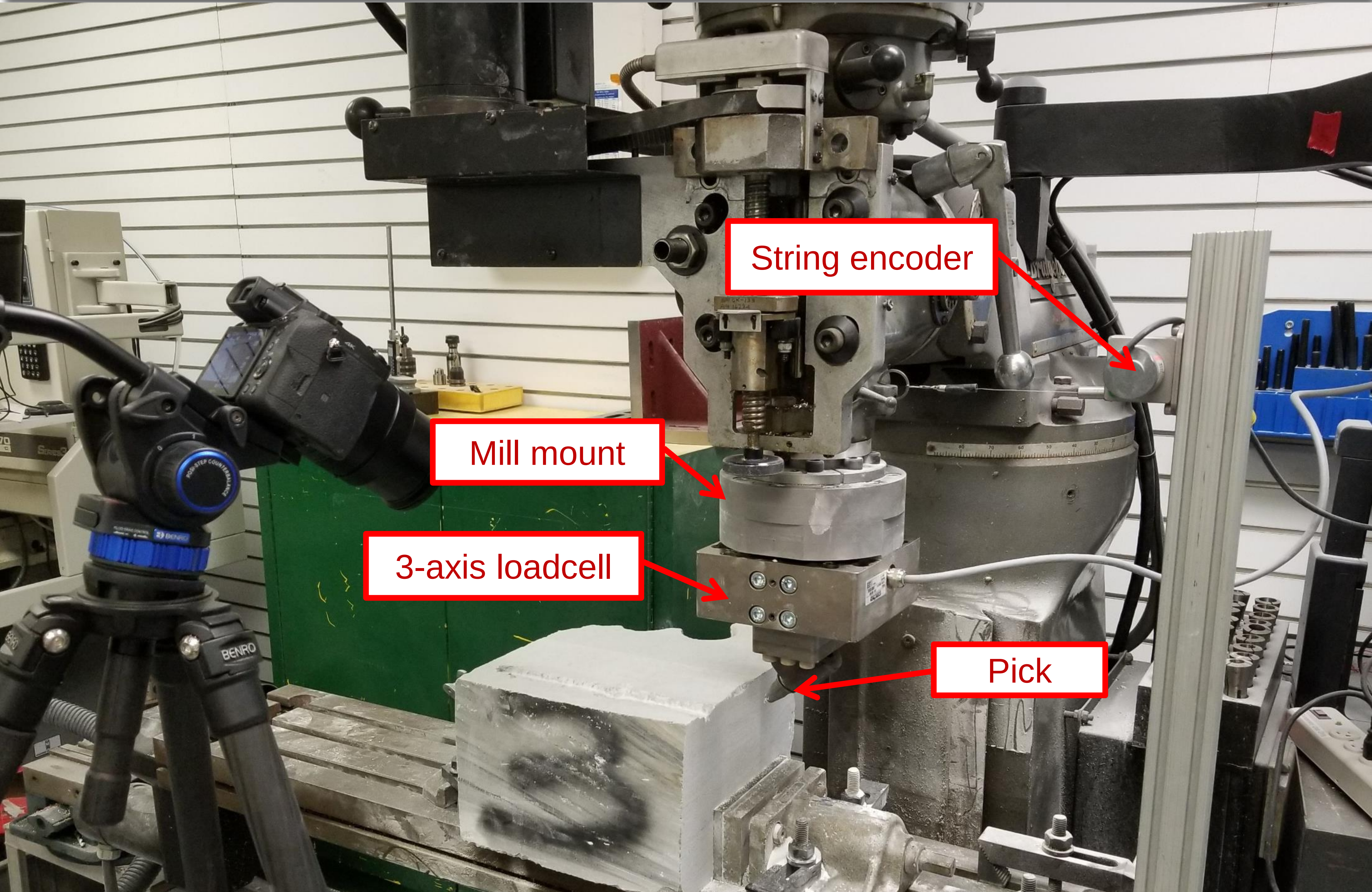


Test Variables and Matrix

Parameters	Notation	Unit	Levels of parameters		
			1	2	3
Attack Angle	Θ_A	Degree	40	45	50
Depth of Cut	d	in	0.1	0.25	0.35
Cutting Speed	v	in/min	30	50	100
Pick Tip Angle	α	degree	50	68	75

Test No	Attack Angle	Depth of Cut	Cutting Speed	Pick Tip Angle
1	40	0.1	30	50
2	40	0.25	50	68
3	40	0.35	100	75
4	45	0.1	50	75
5	45	0.25	100	50
6	45	0.35	30	68
7	50	0.1	100	68
8	50	0.25	30	75
9	50	0.35	50	50

Taguchi L_9 (4^3) Orthogonal Array
Ref:http://www.mne.psu.edu/cimbala/me345/Lectures/Taguchi_orthogonal_arrays.pdf

- **Attack angle varies from 40 – 50 degrees.**
- **Depth of cut – the predicted highest force test was run first and the maximum depth of cut was adjusted to meet the CNC mill's capacity.**
- **Cutting speed: Not a factor in the latest models but could be a contributor in our regime.**
- **Pick Tip Angle: Limited to 3 angles that were commercially available.**
- **Each test was repeated 5 times.**

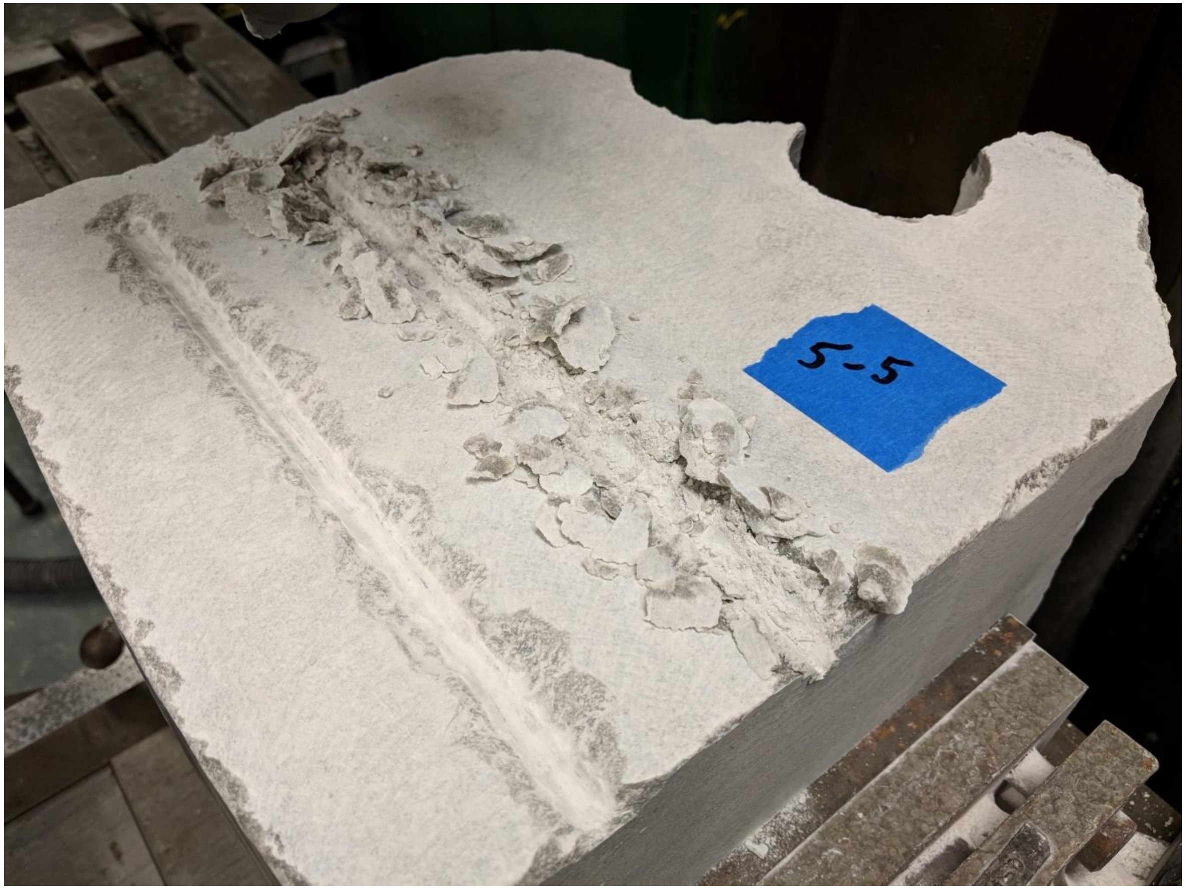
Normal speed video of cutting test

Test No	Attack Angle	Depth of Cut	Cutting Speed	Pick Tip Angle
5	45	0.25	100	50

High speed video of cutting test

Test No	Attack Angle	Depth of Cut	Cutting Speed	Pick Tip Angle
6	45	0.35	30	68

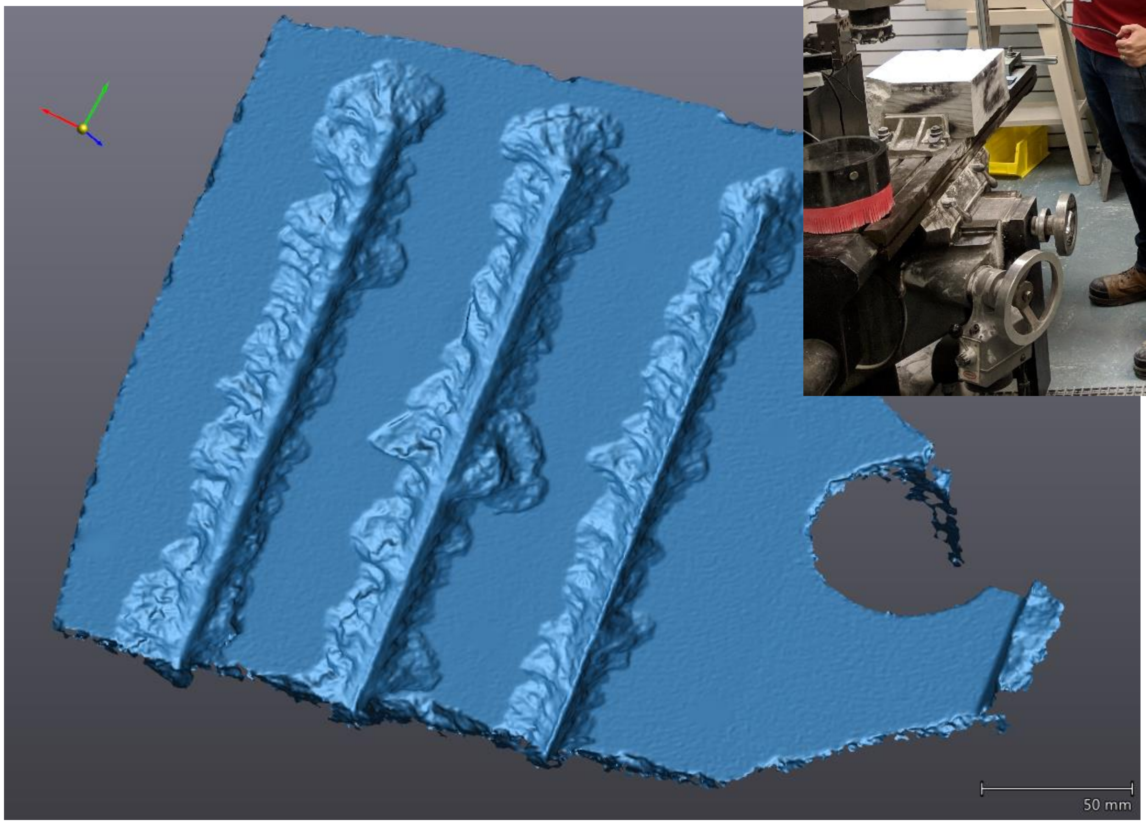
Post test

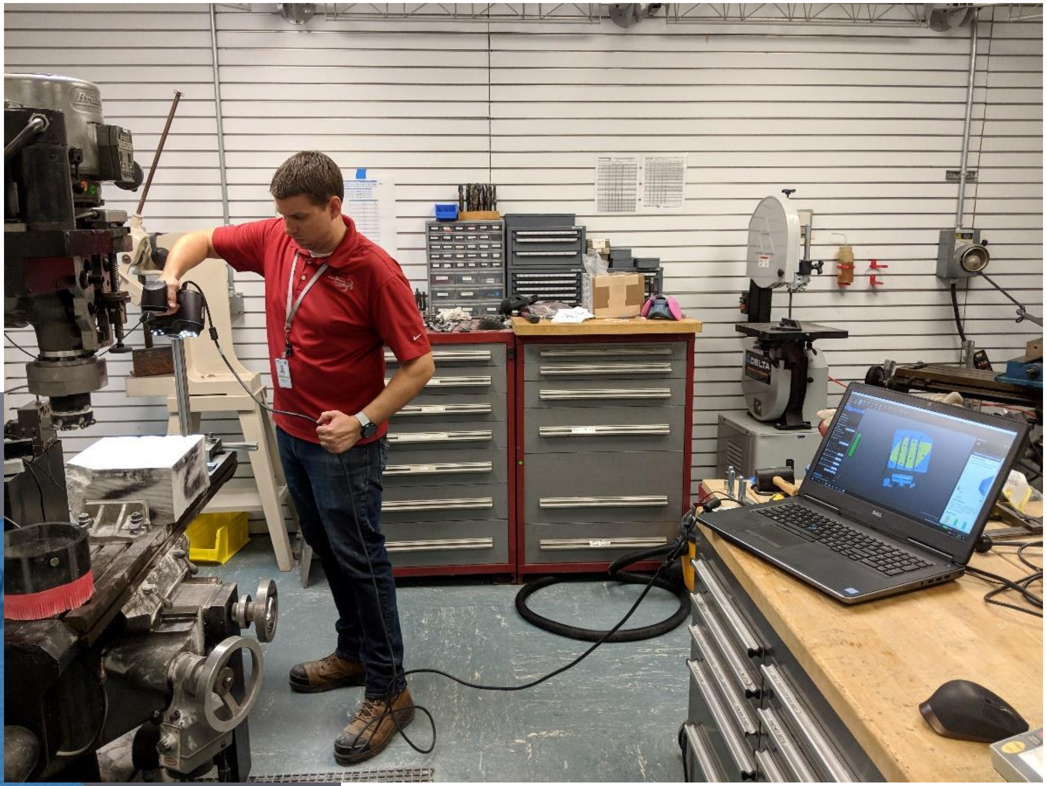

5-5


SCIENTECH
SA 410
SEND
RANGE/ FUNCTION
MODE
41.0873 g
ZERO
ZERO

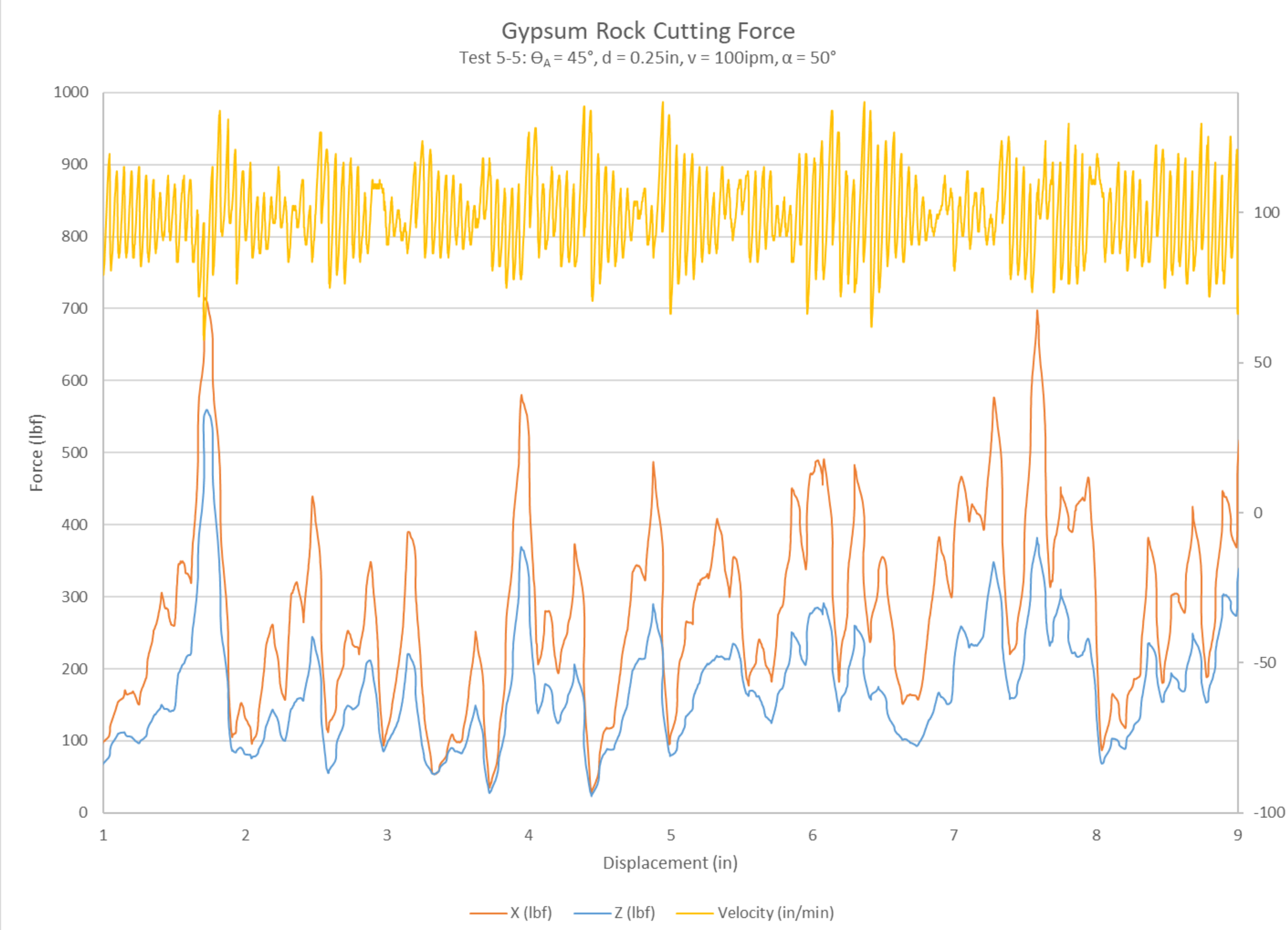
Post test

- 3D scanned the surface for excavated volume



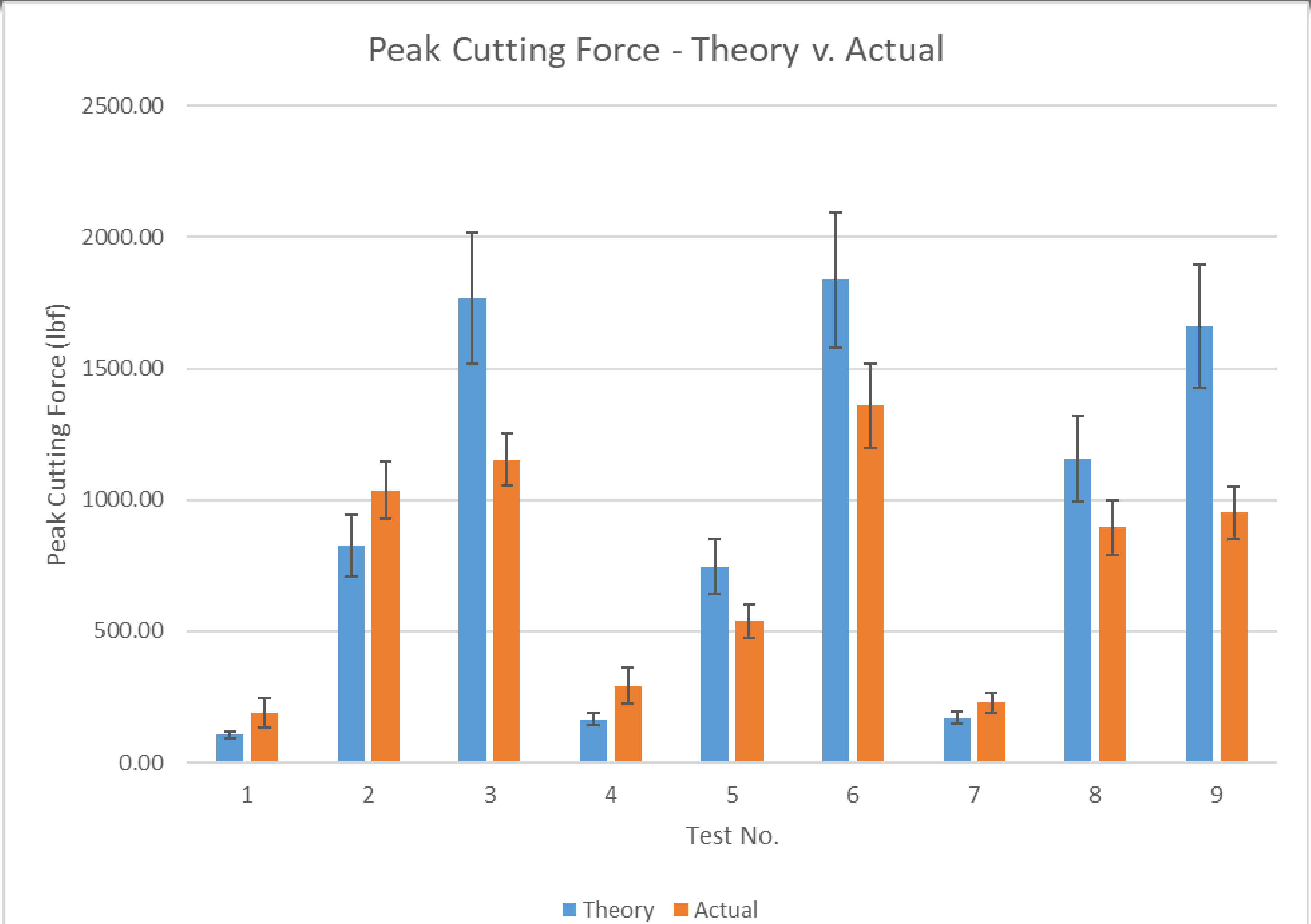


Output data



Gypsum Rock Cutting Force
Test 5-5: $\Theta_A = 45°$, d = 0.25in, v = 100ipm, $\alpha = 50°$
Force (lbf)
1000
900
800
700
600
500
400
300
200
100
0
100
50
0
-50
-100
1
2
3
4
5
6
7
8
9
Displacement (in)
X (lbf)
Z (lbf)
Velocity (in/min)

Cutting force comparison to theory

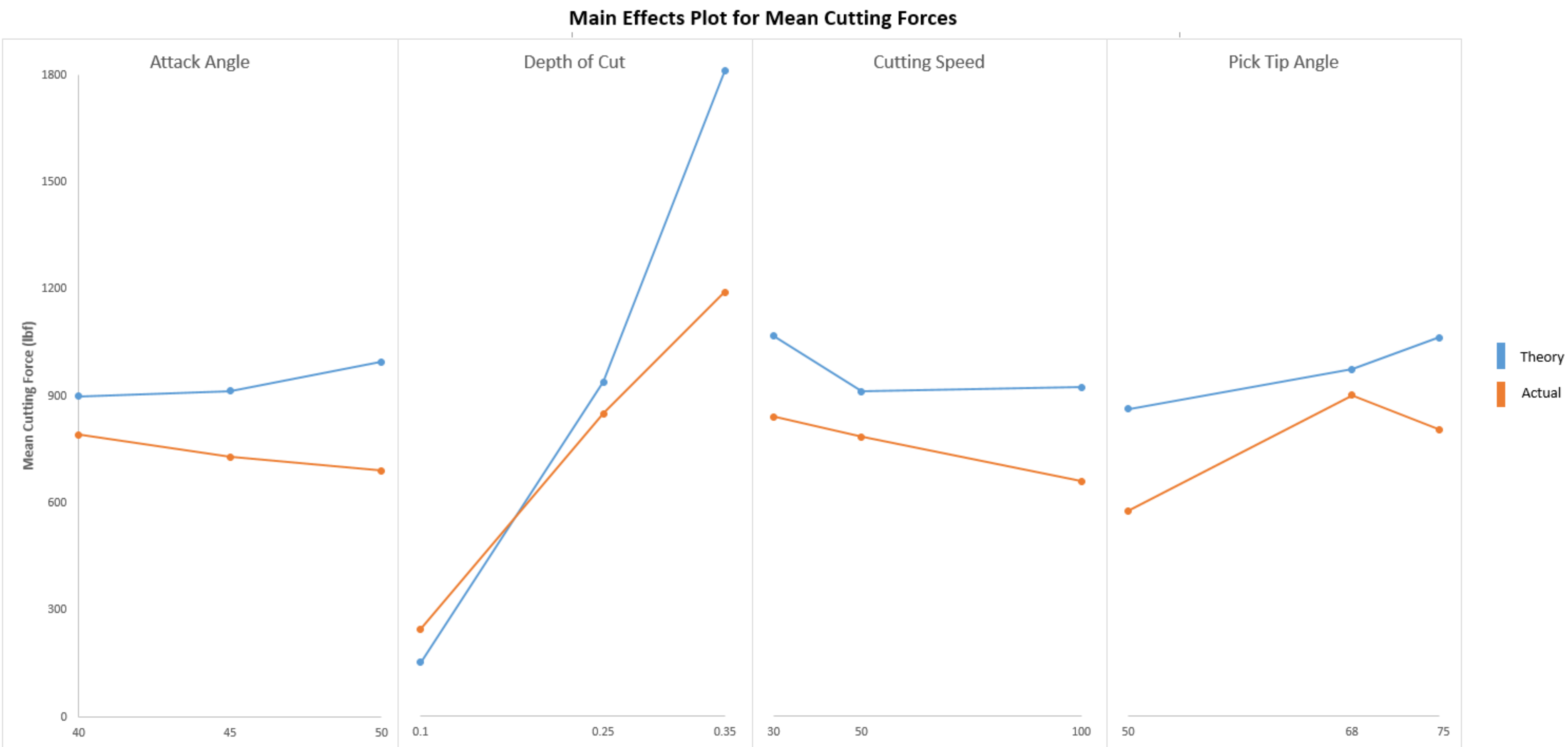


Error between measured and theory

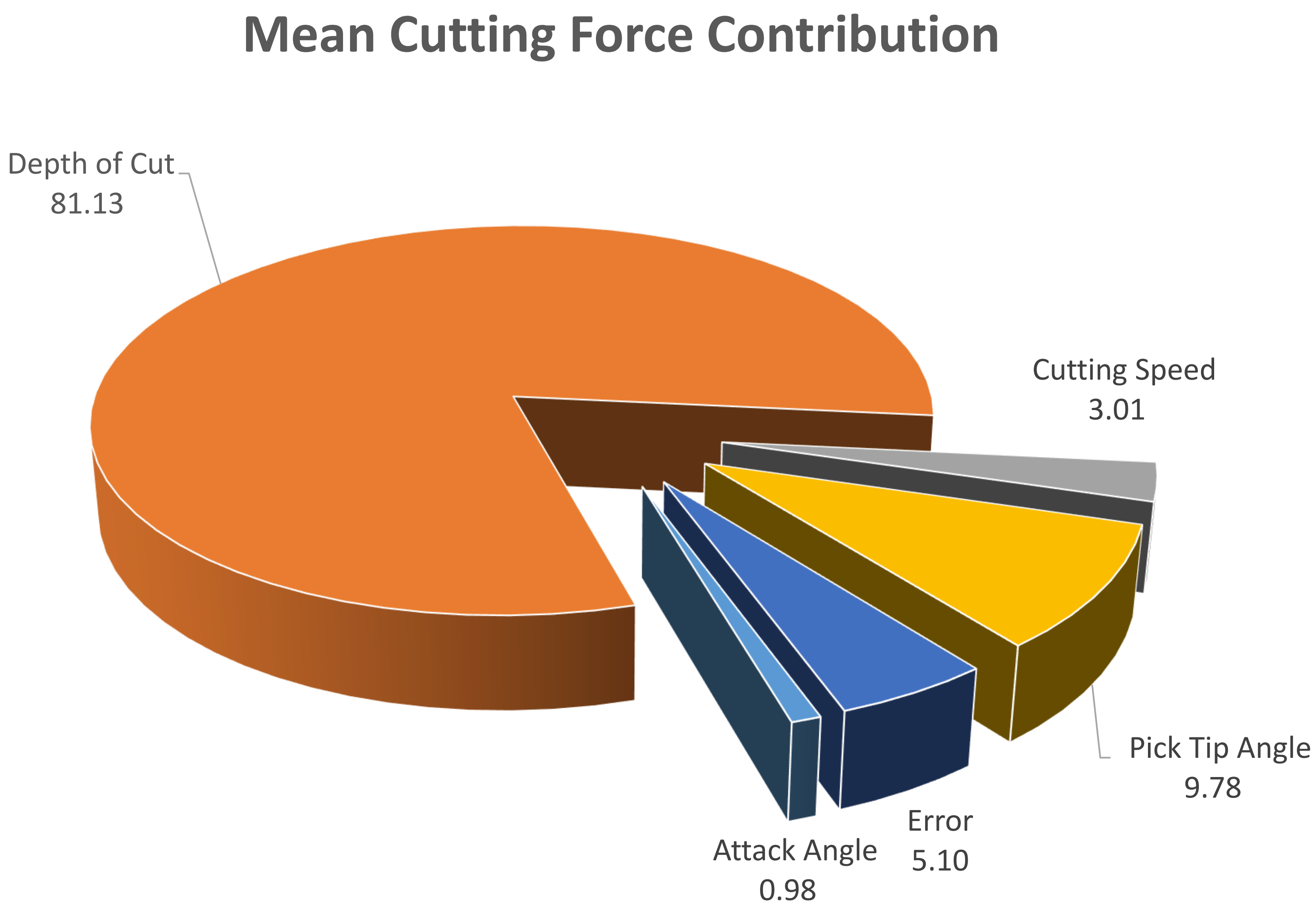
Peak Cutting Force			
Test No.	**Theory**	**Actual**	**% Difference**
1	104.26	188.38	57
2	825.50	1035.15	23
3	1768.63	1151.285	42
4	163.65	291.8025	56
5	744.27	538.47	32
6	1836.73	1358.25	30
7	169.86	226.70	29
8	1157.65	894.73	26
9	1659.83	950.00	54

- Average % difference = 39%
- Goktan 2005 average % difference = 28%

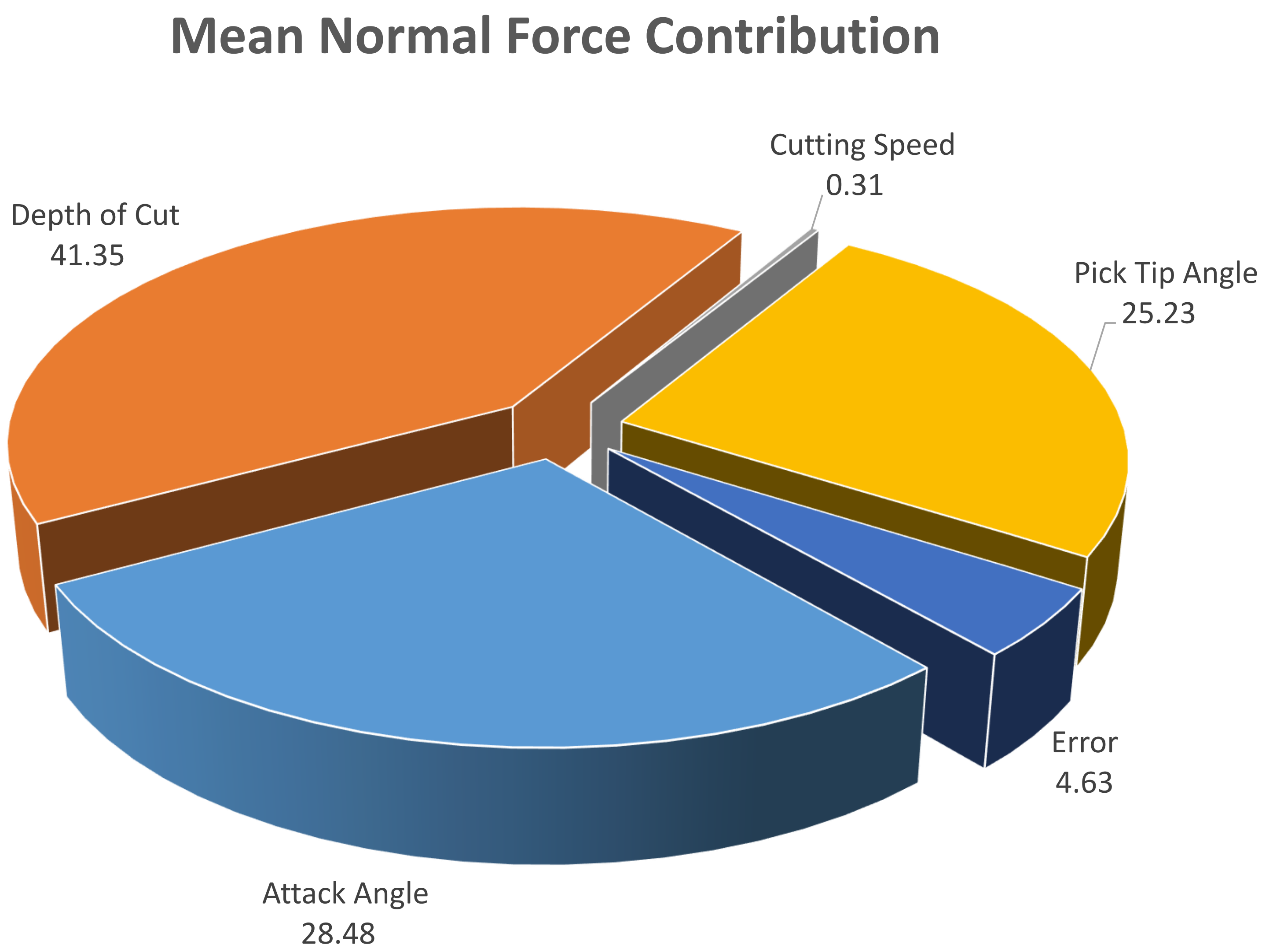
Sensitivity analysis



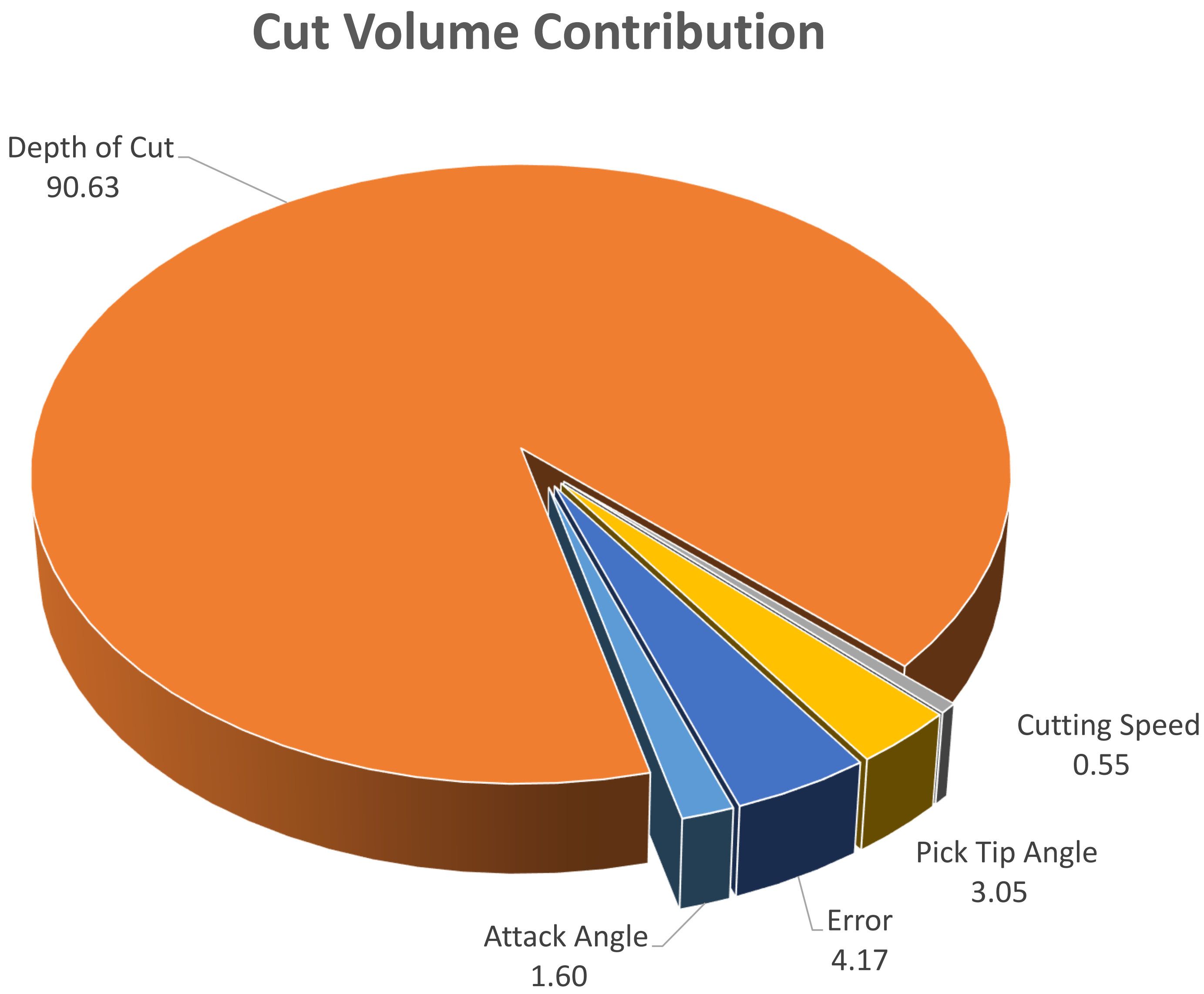
Variables that affect cutting force



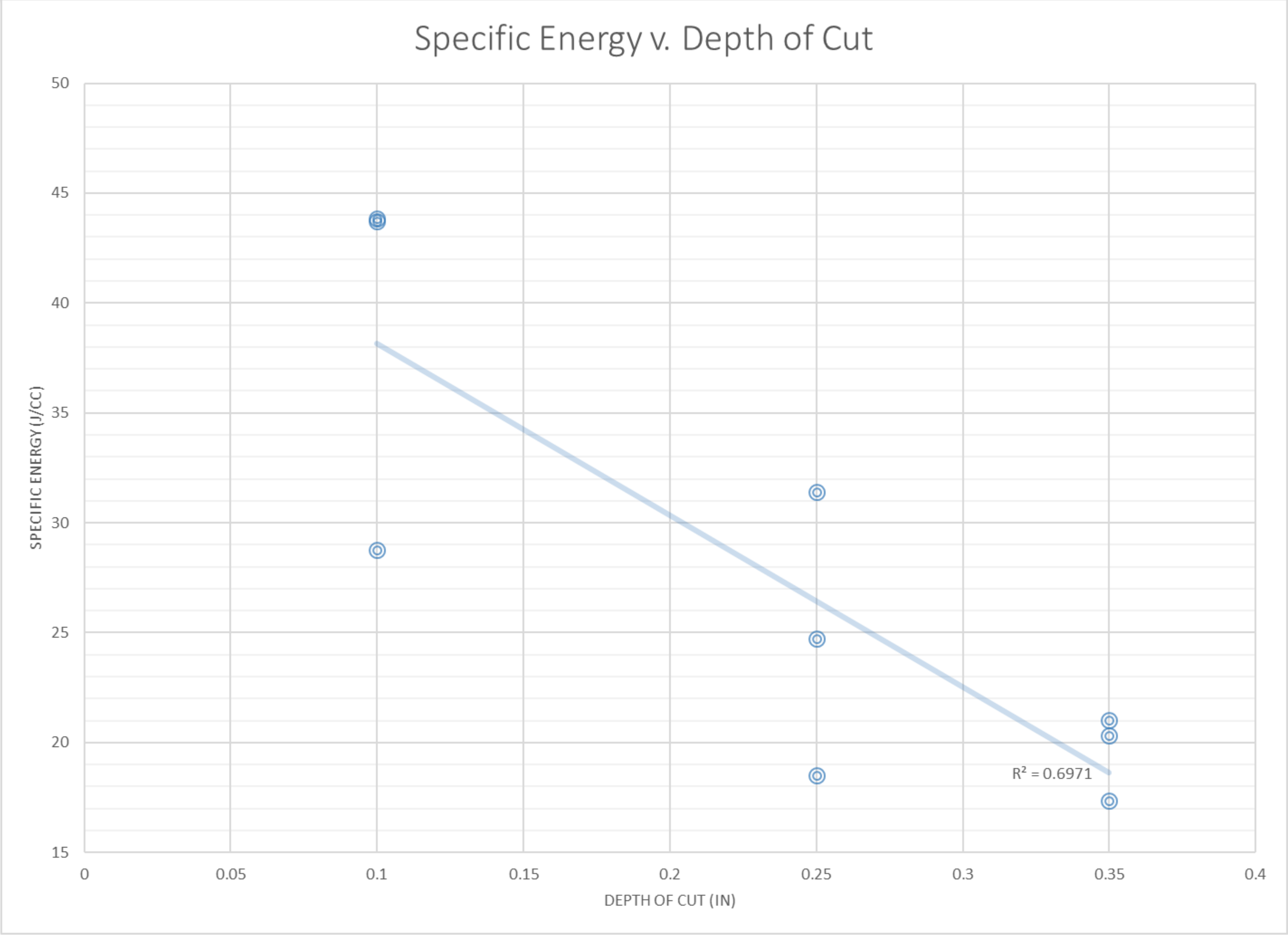
Variables that affect normal force



Variables that affect cuttings volume

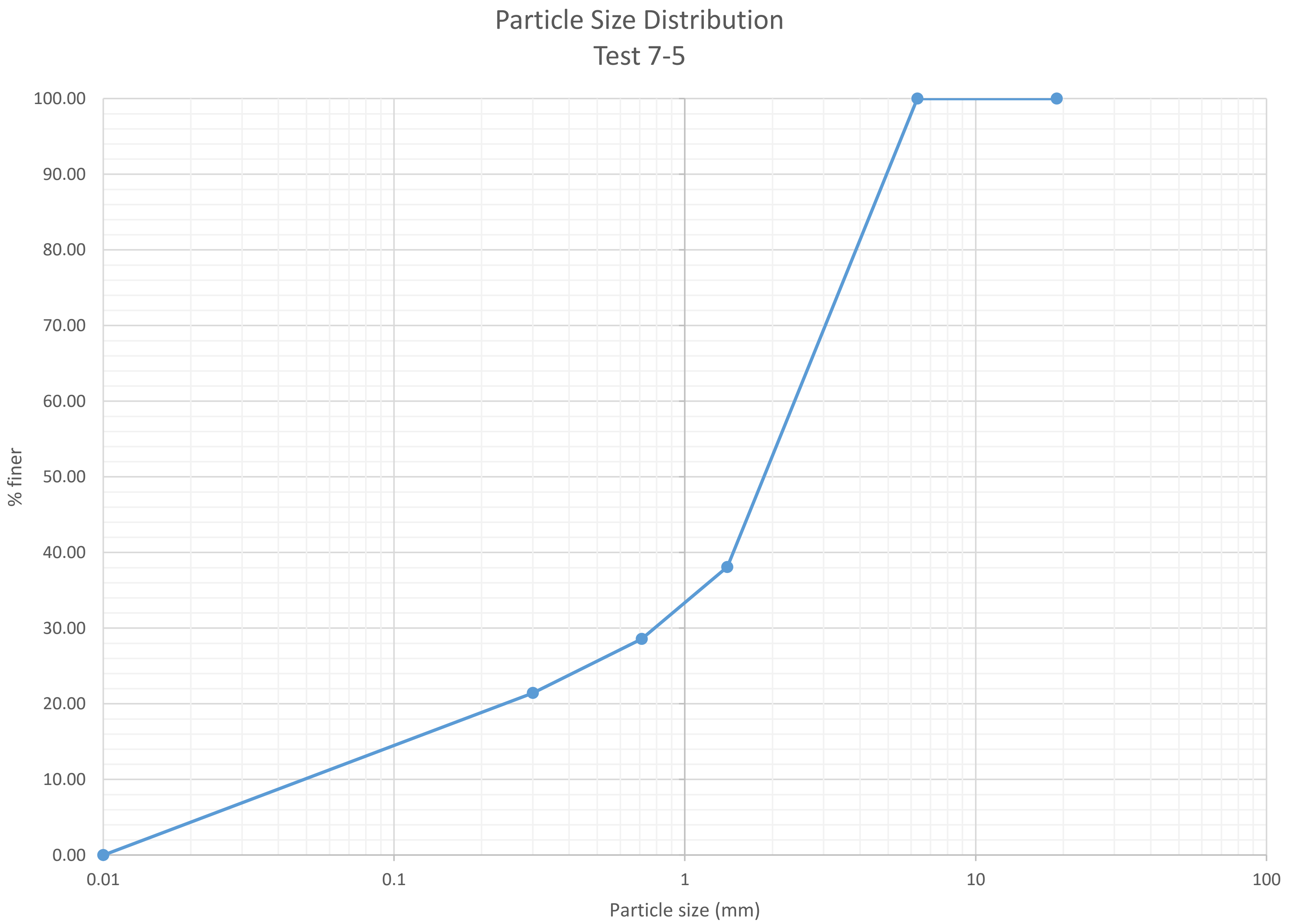


Deeper cuts are more efficient, but produce large particles

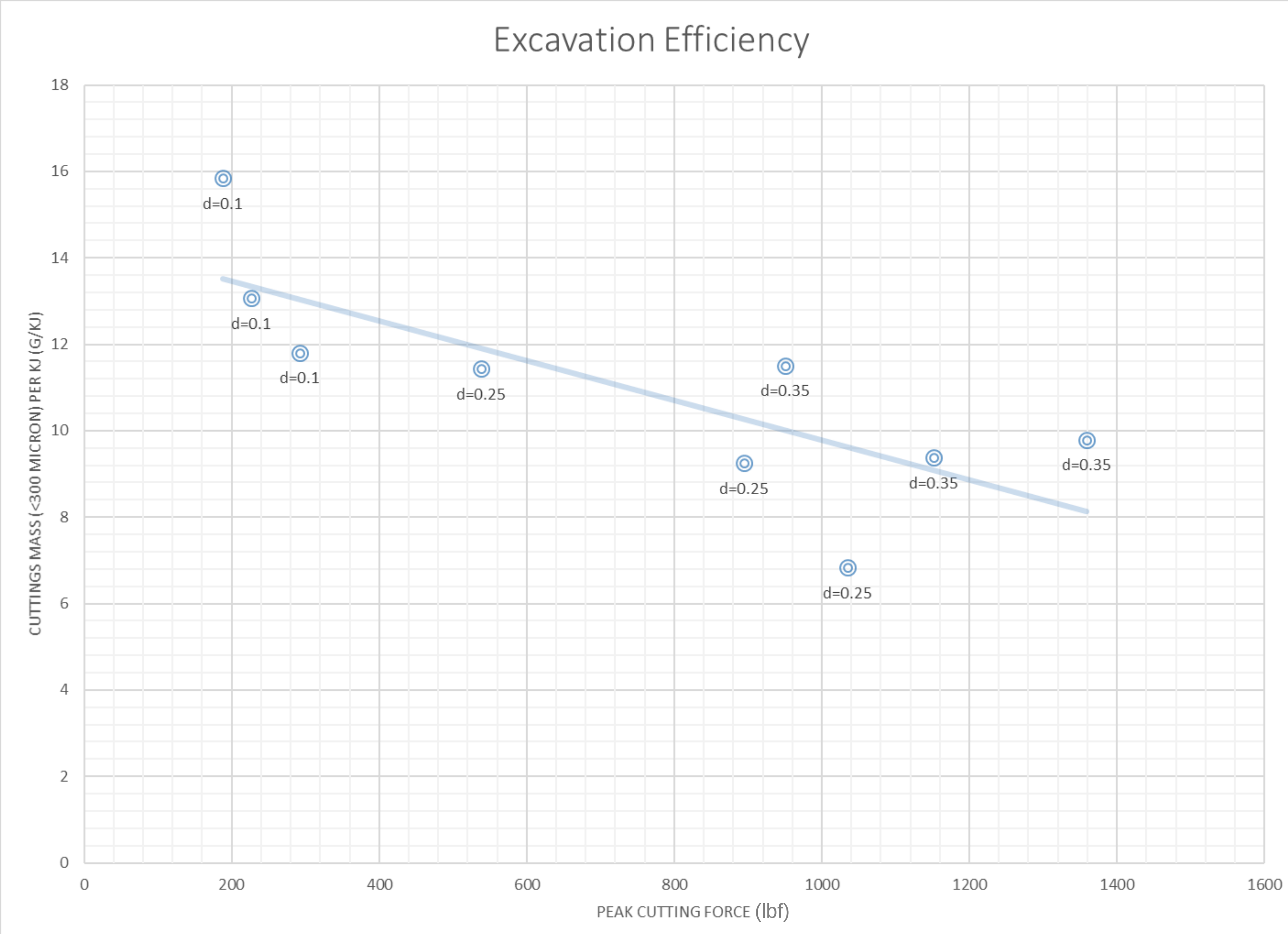


Cuttings analysis

Particle size distribution – 0.1” depth of cut



Shallow cuts produce more fine particles for less energy and cutting force



Conclusions

- Existing rock cutting models such as Goktan (2005) are appropriate for predicting low force cutting in soft rock such as Gypsum
- The trends and contributing variables as measured in this work agree with the existing models
- Between 6%-20% of cuttings are finer than 300μ depending on the cut geometry
- Shallower cuts produce less material overall per unit energy but they produce more material in the <300μ range for less excavation force.

What's next?

- **Follow-on Work:**
  - Additional tests in other hard materials
    - Ice-cemented Regolith
    - Salem Limestone
  - Multiple pick/pick spacing tests
    - Determine critical crack length per material
  - Develop/Test force reducing pick alternatives (i.e. percussion, cutting disks, etc.)

Questions?