Experimental Investigation of Bucket Excavation Force Reduction with an Ultrasonic Leading Edge

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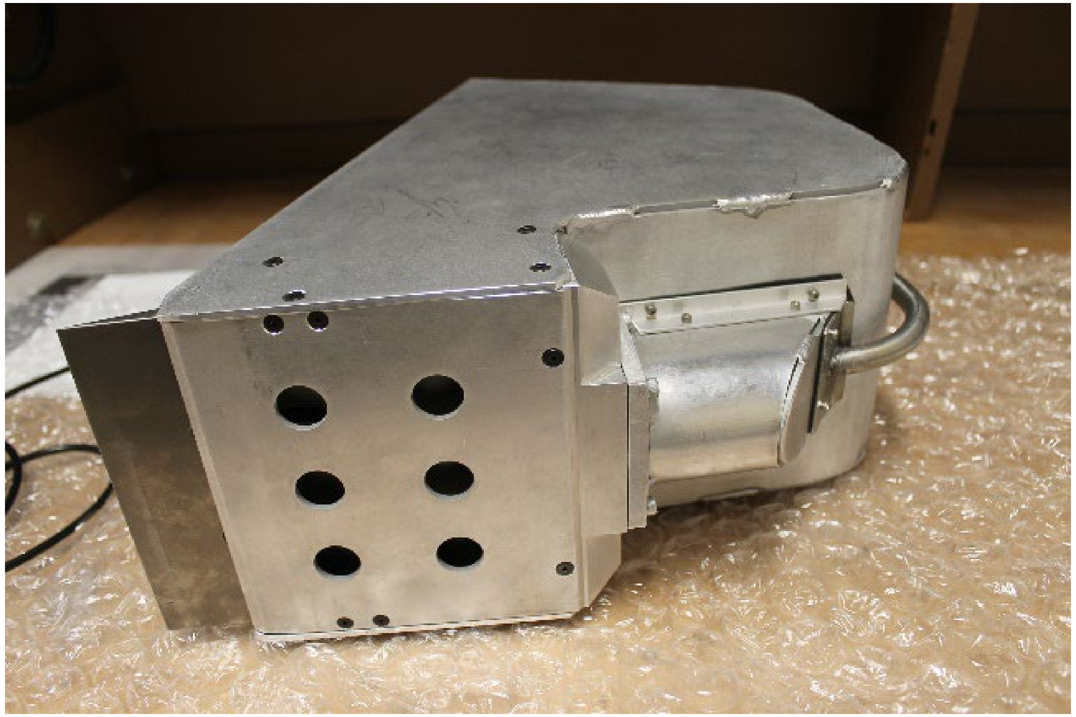
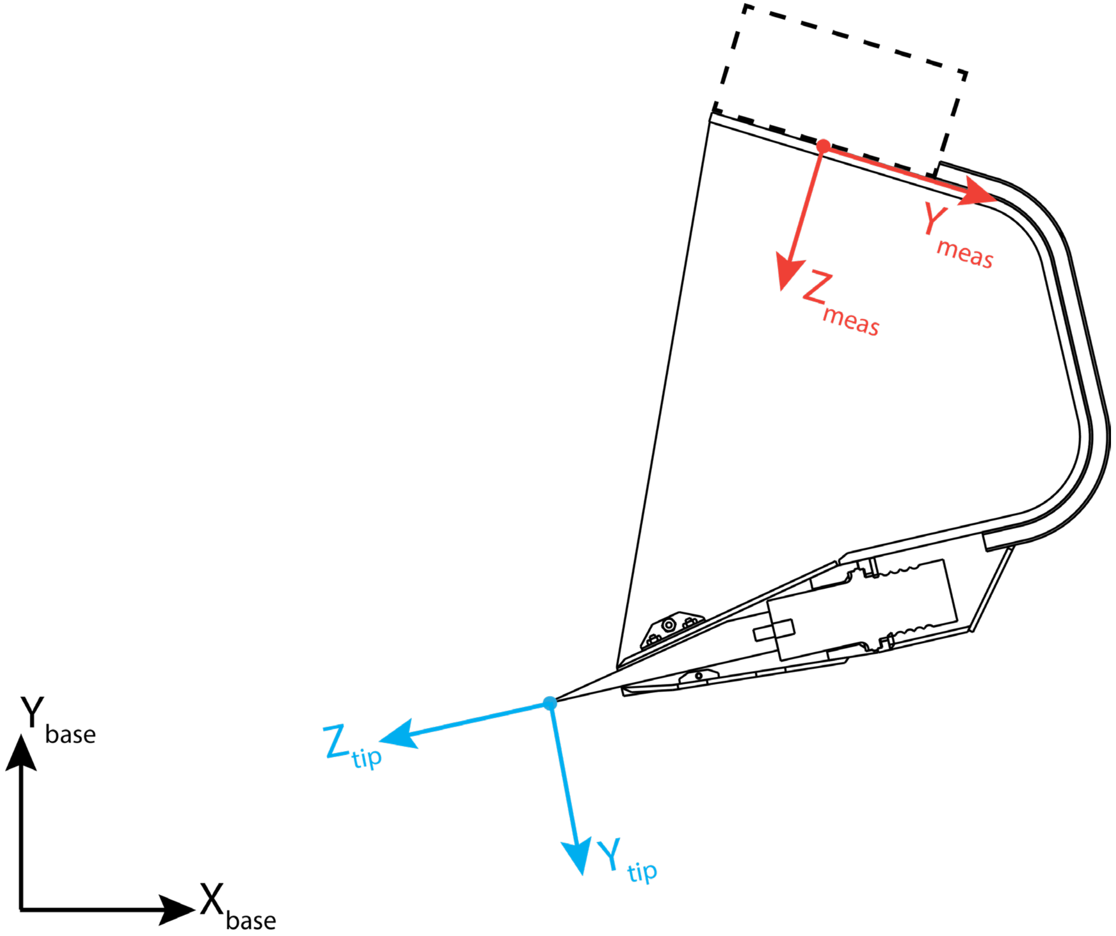
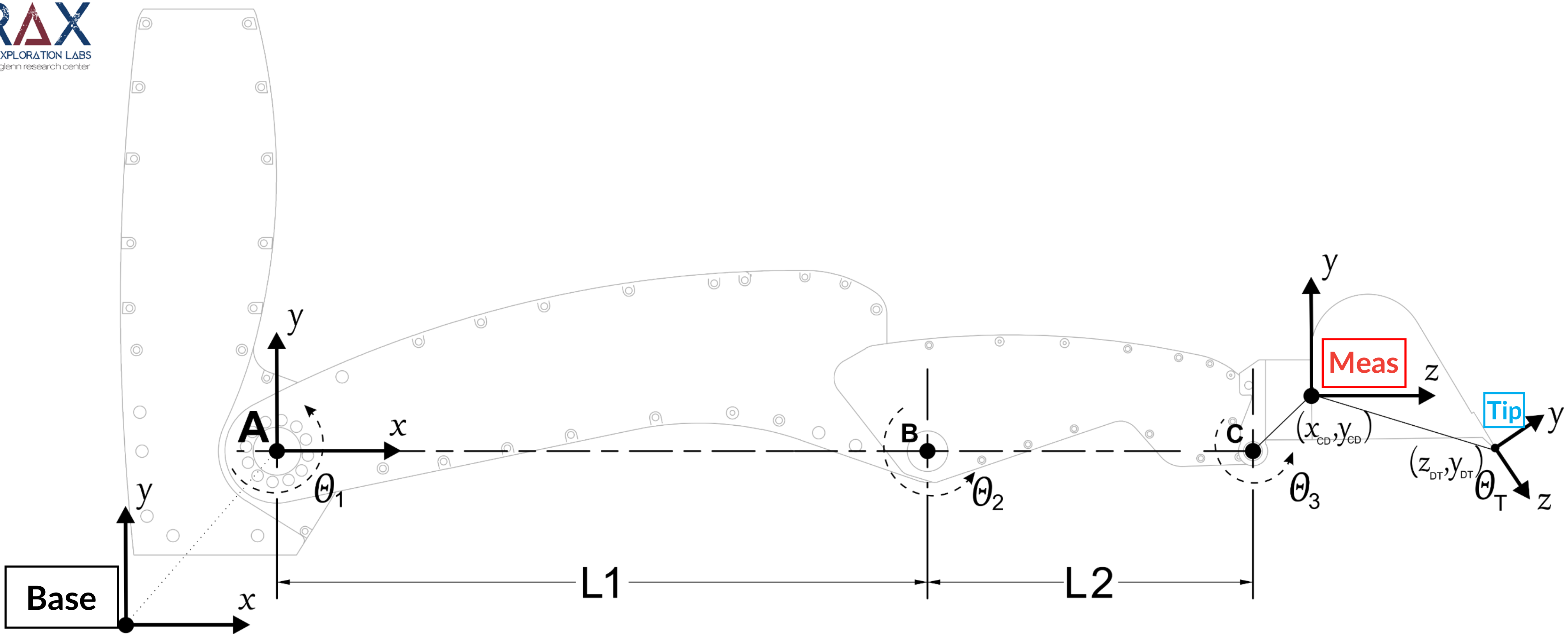
Prototype Ultrasonic Bucket Test Article



Load Cell Frame and APEX Position Frame

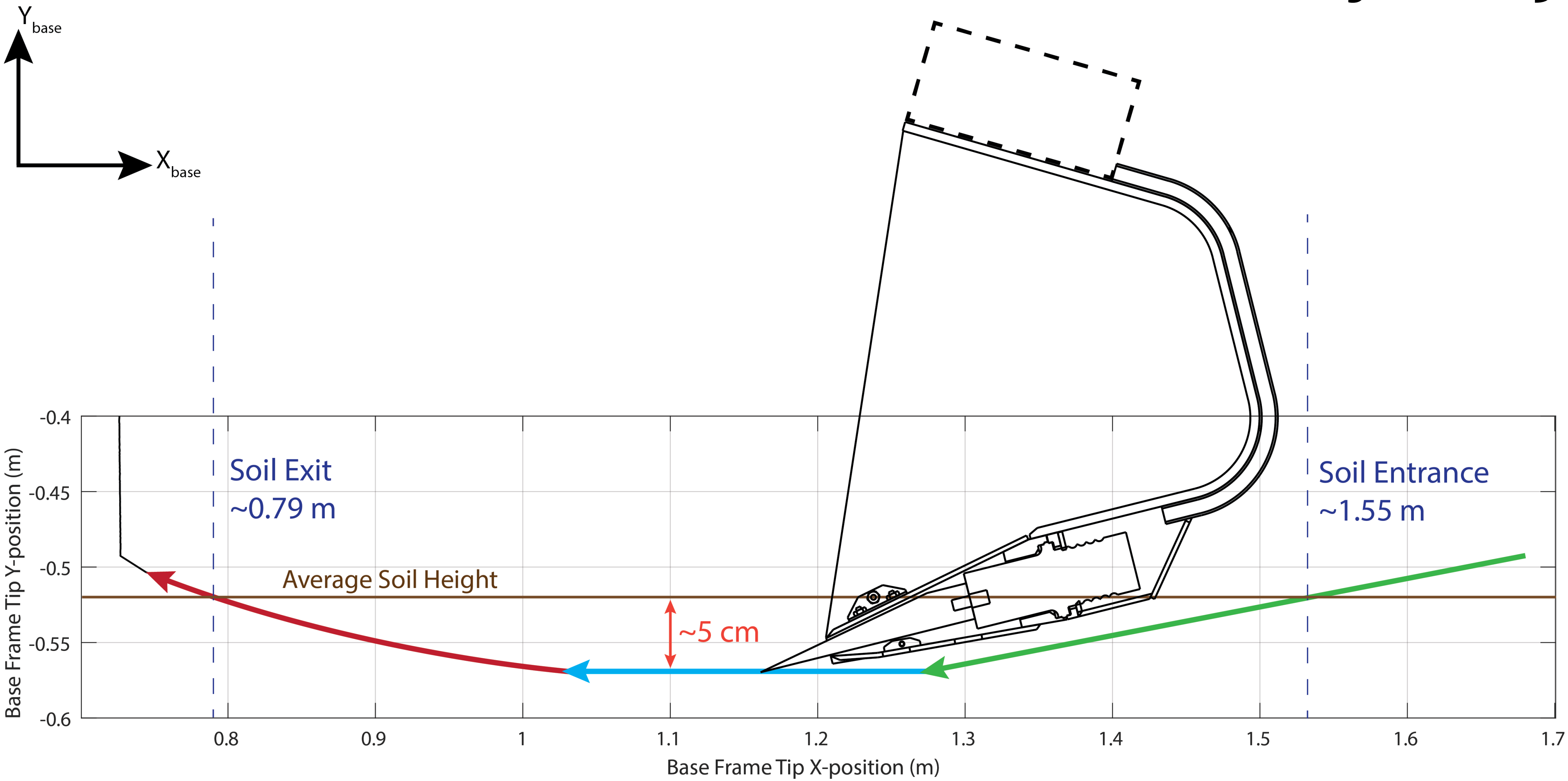




Reference Frames

- **Base** is the stationary base frame
  - All positions are reported in this frame
- Meas is the force transducer frame in which force and torque data are natively measured
- Tip is the tip/tool frame

APEX Test Trajectory



Definitions

- $\left(\boldsymbol{F}_{\boldsymbol{DIRECTION}}^{\boldsymbol{LOCATION}}\right)^{\boldsymbol{FRAME}}$

  i.e. $\left(\boldsymbol{F}_{\boldsymbol{X}}^{\boldsymbol{Meas}}\right)^{\boldsymbol{Base}}$ = Force applied in the x-direction of the base frame at the load cell (Meas)
- Force magnitude, location independent

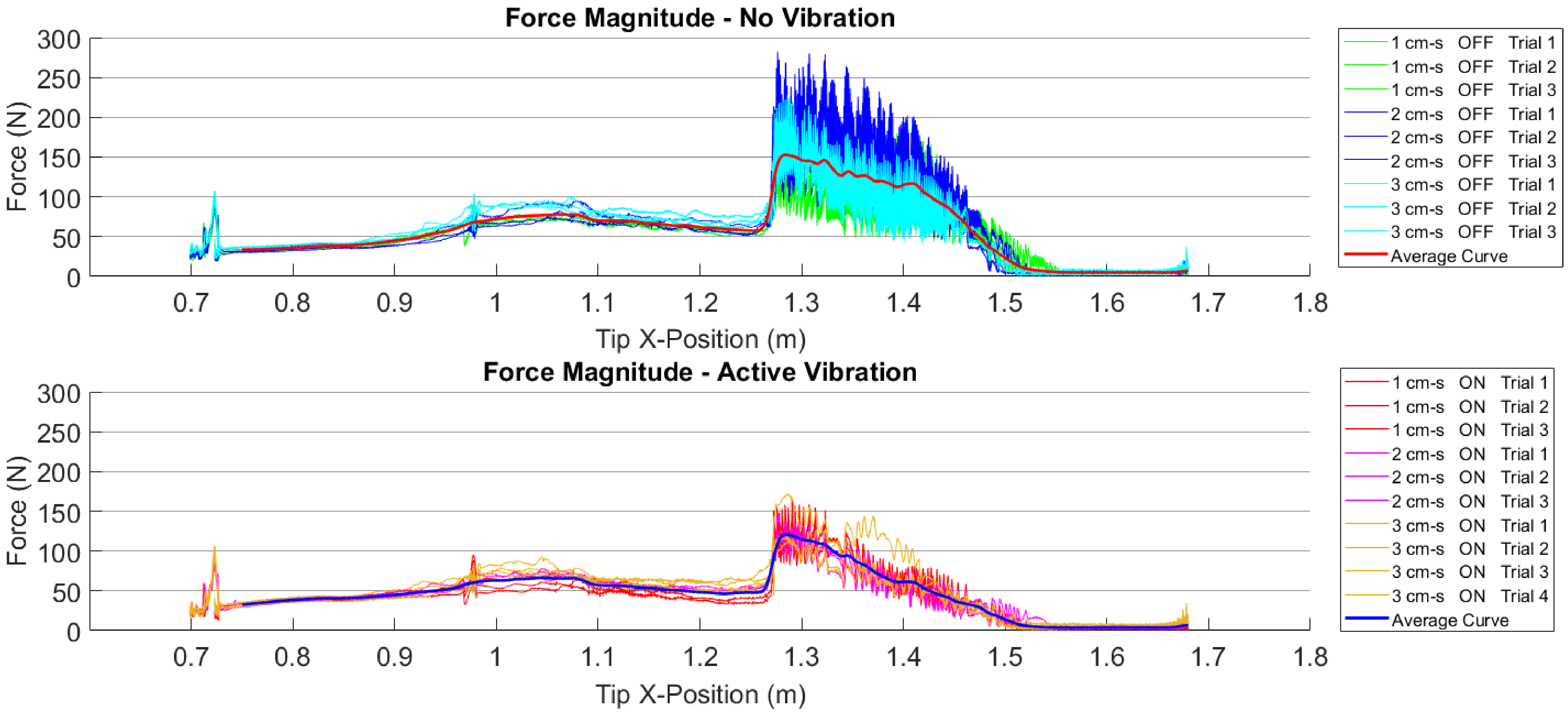
$$\|F\| = \sqrt{F_x^2 + F_y^2 + F_z^2}$$

- Torque magnitude, location dependent

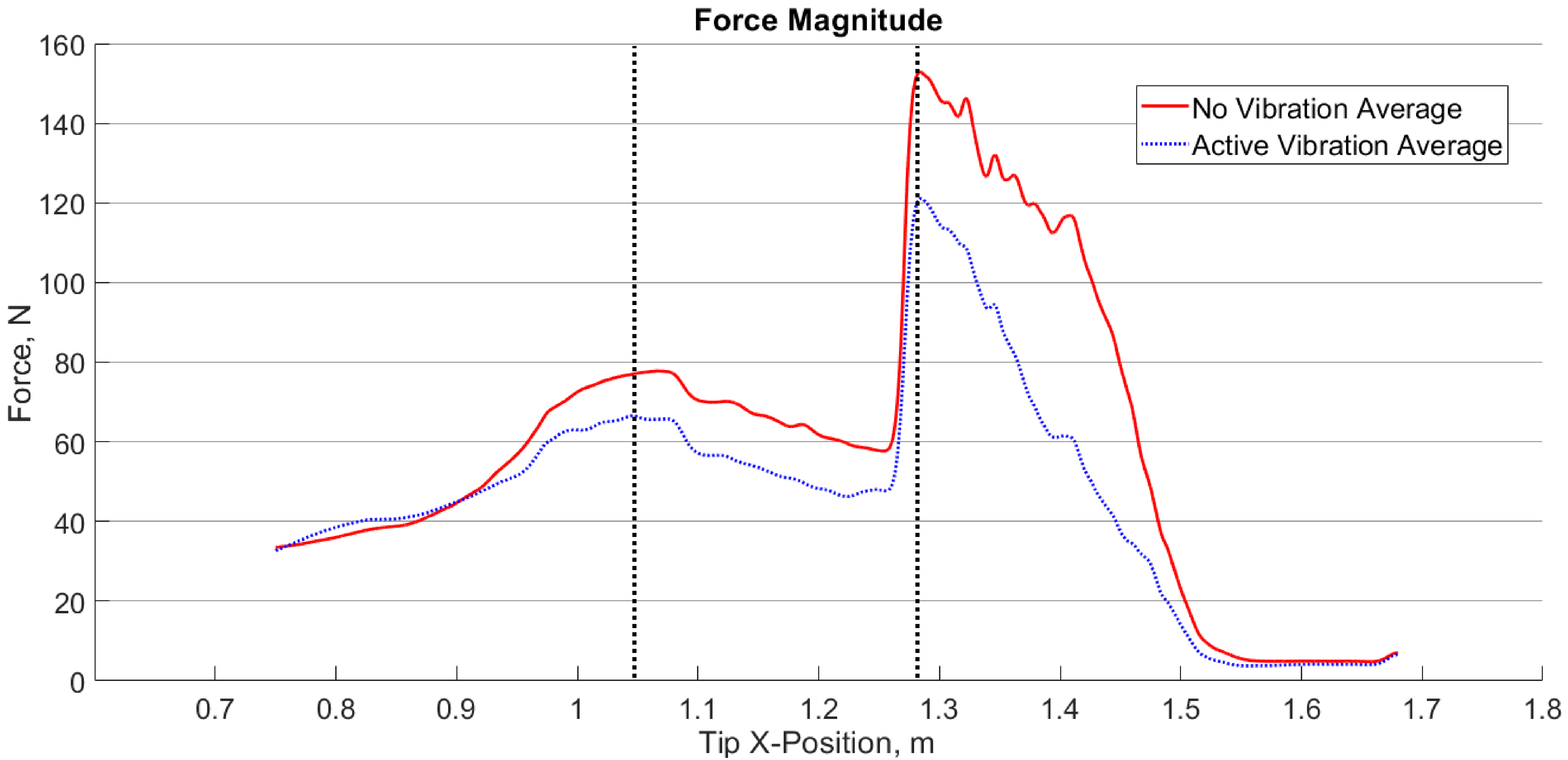
$$\|T\| = \sqrt{T_x^2 + T_y^2 + T_z^2}$$

- $\left(\boldsymbol{Pos}_{\boldsymbol{X}}^{\boldsymbol{Tip}}\right)^{\boldsymbol{Base}}$ = X-position of the tip in the base frame coordinates
- “Air Dig” – a trial conducted outside of the soil to capture the inertial state of the robotic assembly.
- “Air Offset” – the force and torque results from the air digs were averaged and that average was tared from soil trial results to isolate contributions from actually digging.

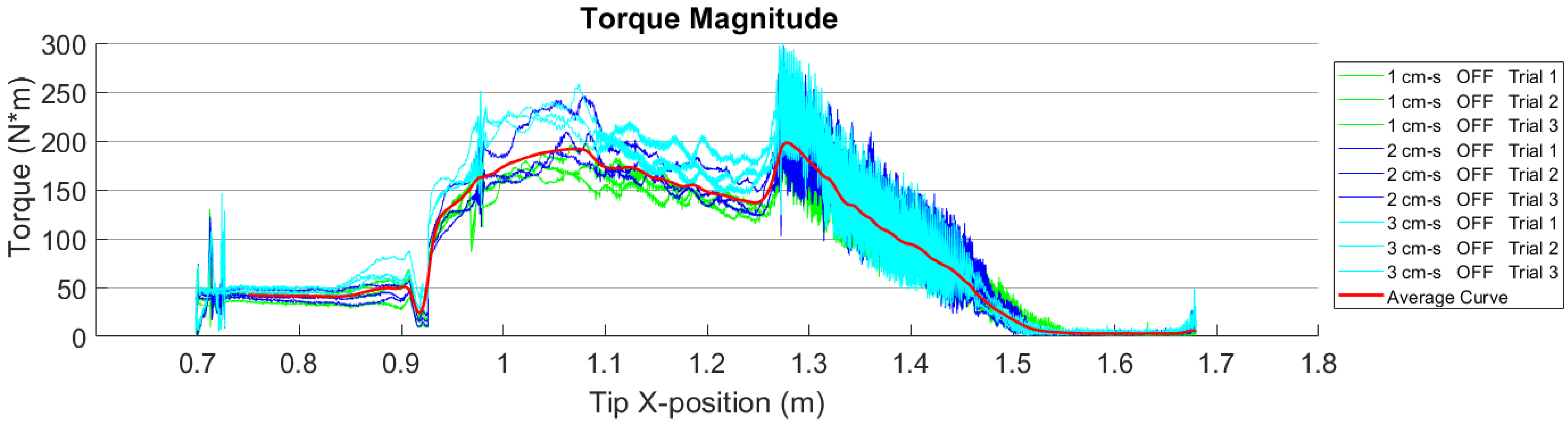
$\left\| \left(F^{Tip}\right)^{Tip} \right\|$ vs $\left(Pos_X^{Tip}\right)^{Base}$, Air Offset

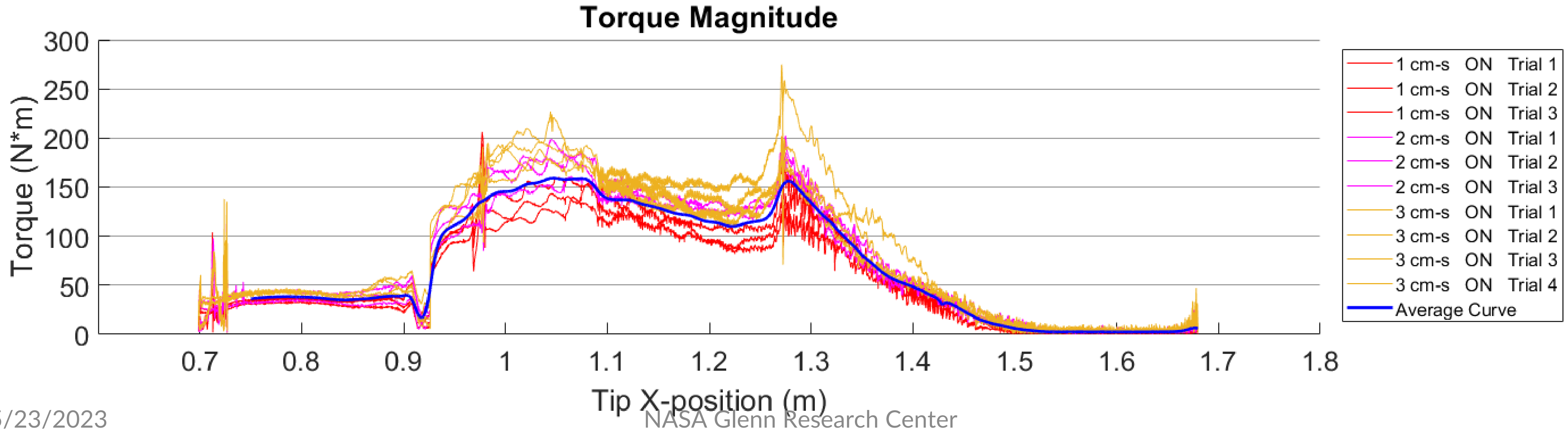


$\left\|\left(F^{Tip}\right)^{Tip}\right\|$ vs $\left(Pos_X^{Tip}\right)^{Base}$ Air Offset, Average Curves

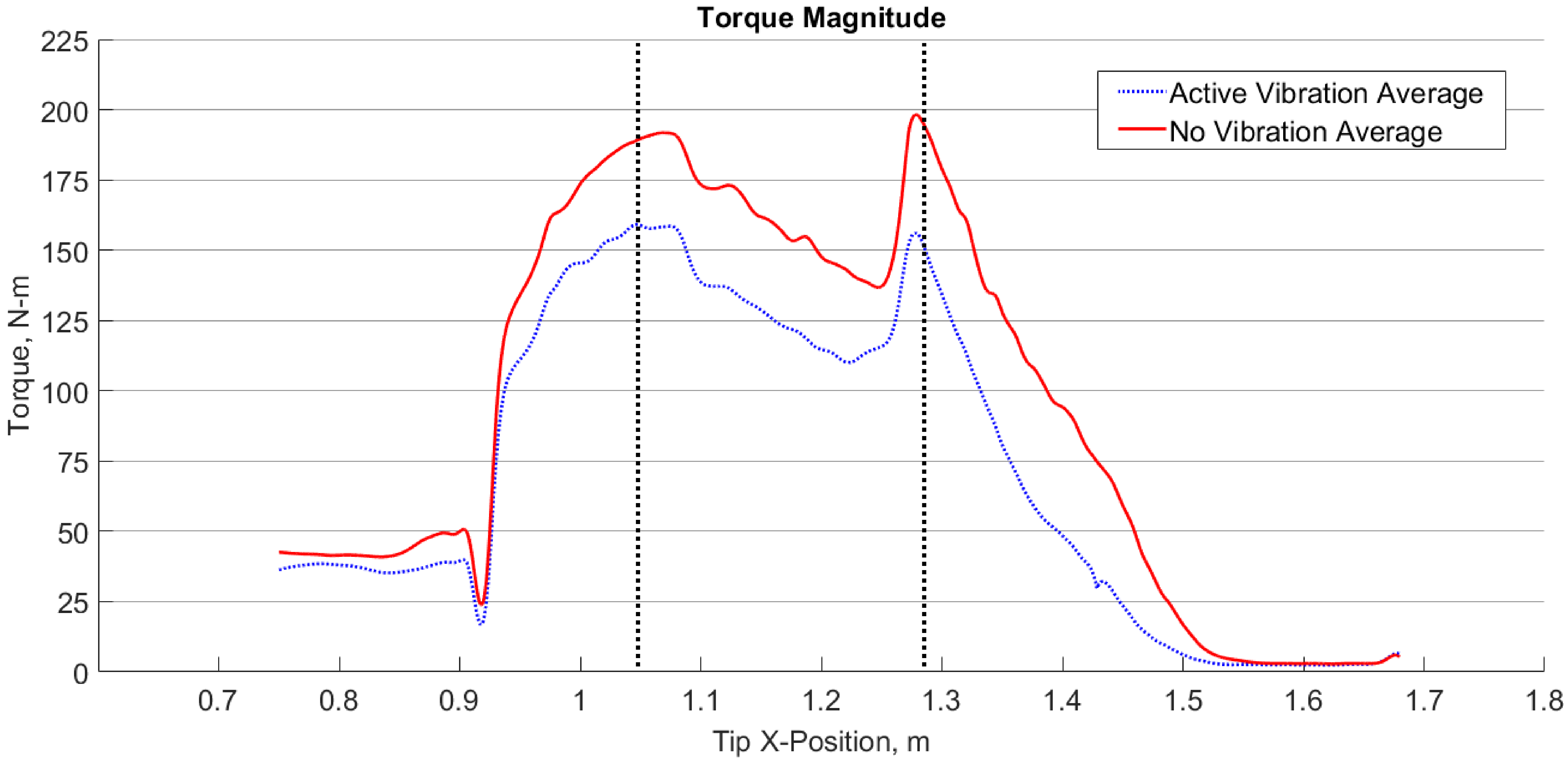


$\left\| \left(T^{Meas}\right)^{Meas} \right\|$ vs $\left(Pos_X^{Tip}\right)^{Base}$ Air Offset





$\left\| \left(T^{Meas} \right)^{Meas} \right\|$ vs $\left(Pos_X^{Tip} \right)^{Base}$ Air Offset, Average Curves



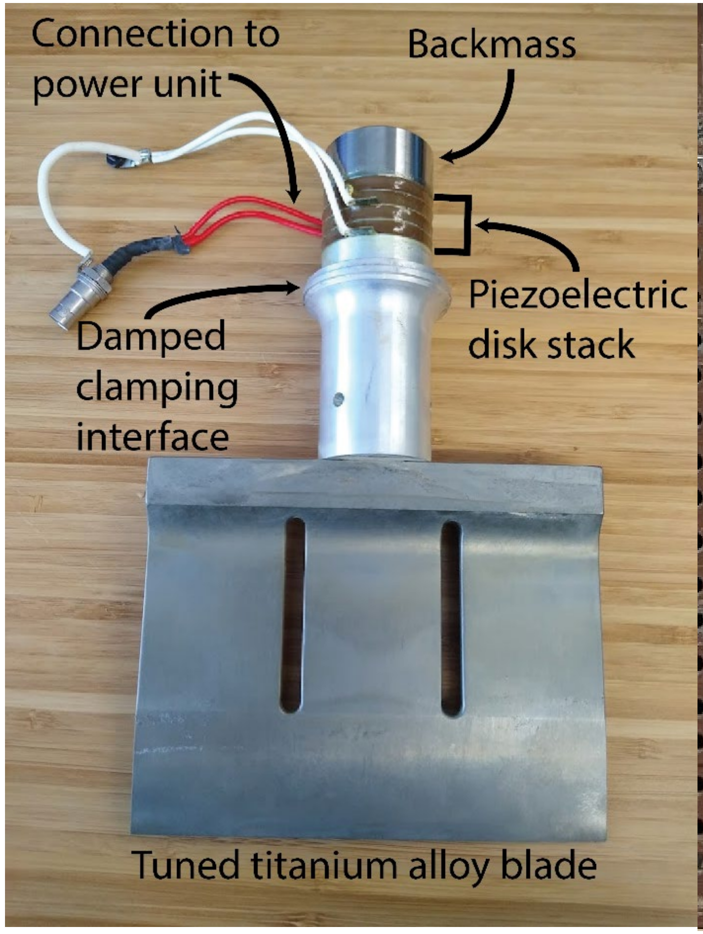
Key Takeaways

1. The use of ultrasonic vibration in a bucket leading edge significantly reduced load signal noise, likely due to stick-slip reduction.
   - This effect has implications for increased capability in force-control applications
2. Within the range tested, velocity seems to have a minimal impact for test cases with and without vibration.
   - Data spread is more likely due to slight differences in soil compaction
3. Average curves indicate that there are advantageous times to initiate vibration within a given toolpath.
4. Average curves indicate measurable reductions in force on the leading edge for almost all the given toolpath.
5. Average curves indicate measurable reductions in torque at the load cell interface for almost all the given toolpath.
6. There are energy optimizations that need to be conducted to determine when net benefits are incurred from the use of active vibration which lowers the load on drive motors.

Questions?

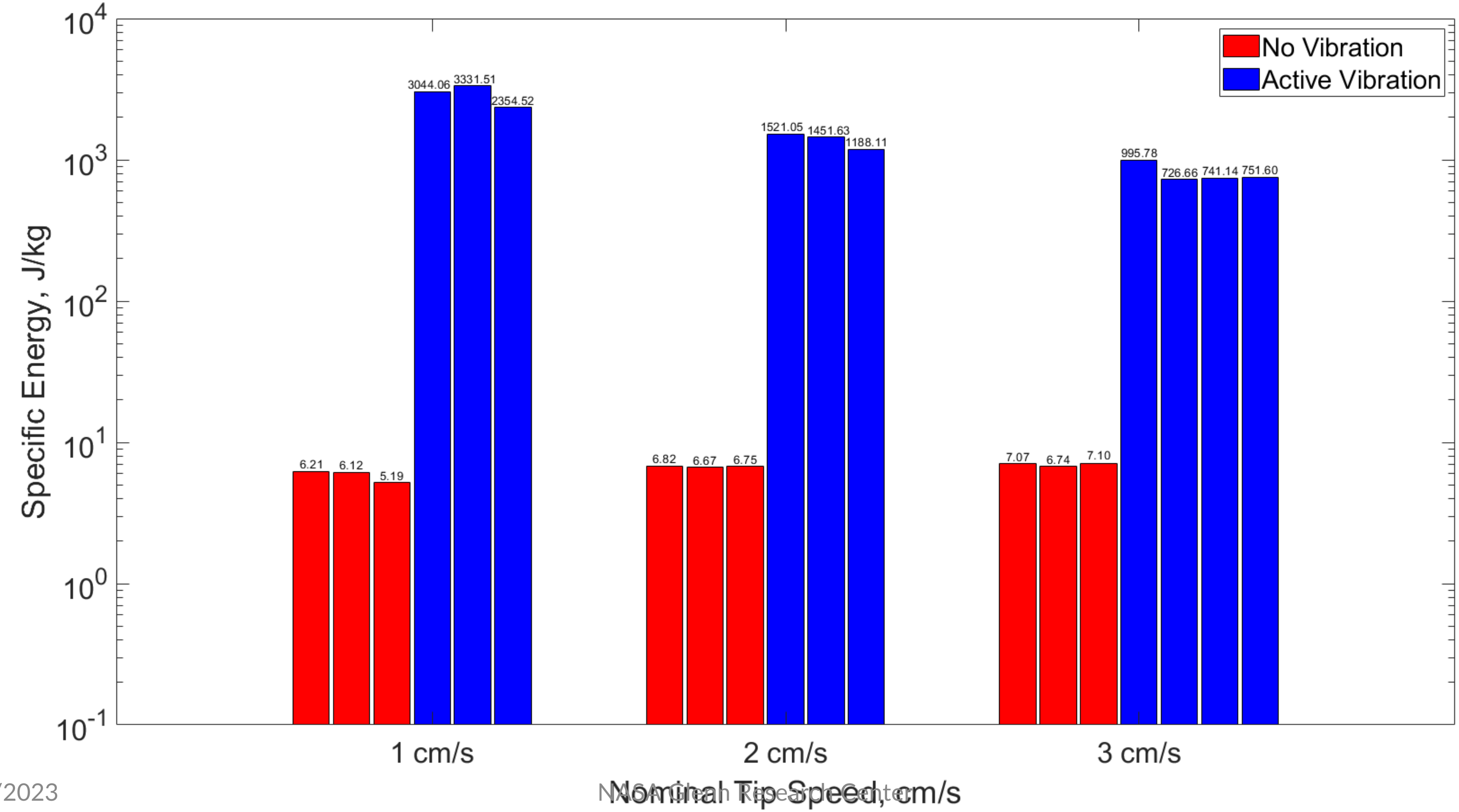
Backup Slides

Piezo-Stack Breakout



LEFT: Ultrasonic Blade assembly comprised of a piezoelectric stack actuator and a tuned titanium alloy blade.
RIGHT: Frequency feedback-controlled power unit that allows for amplitude control.

Tooling Specific Energy



Tooling Specific Energy, E_{sp}

- Forces and torques are at point T and described in the S frame
- Work: $\boldsymbol{W}$
- Ultrasonic Energy: $\boldsymbol{E_{US}}$
- Baseline ultrasonic energy usage in air over 60 seconds: $\boldsymbol{E_{Base}}$
- Measured input ultrasonic power: $\boldsymbol{P_{Measure}}$

- Work due to forces in the z^S direction and torques about the x^S and y^S axes are omitted from the energy analysis because they are due to unmeasured deflection (slop and backlash) in the system and are therefore indeterminate.

$$W_{tot} = W + W_{rot}$$

$$W = \int F_x^S dx^S + \int F_y^S dy^S + \int F_z^S dz^S$$

$$W_{rot} = \int T_x^S d\theta_x^S + \int T_y^S d\theta_y^S + \int T_z^S d\theta_z^S$$

$$E_{US} = \int P_{Measure}\, dt$$

$$\boldsymbol{E_{sp} = \frac{W_{tot} + E_{US} - E_{Base}}{M_{disp}}}$$

$$\boldsymbol{E_{sp} = \frac{\int F_x^S dx^S + \int F_y^S dy^S + \int T_z^S d\theta_z^S + E_{US} - E_{Base}}{M_{disp}}}$$

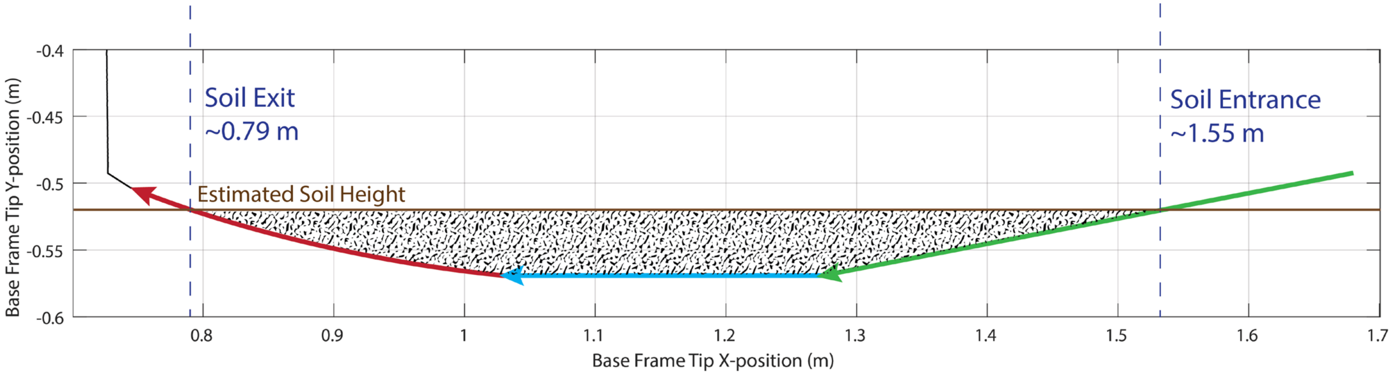
Calculated Soil Parameters

Soil bin density:

$$\rho_{est.} = \frac{(M_{soil,est.})}{(L_{soil\ bin})(W_{soil\ bin})(D_{measured})}$$

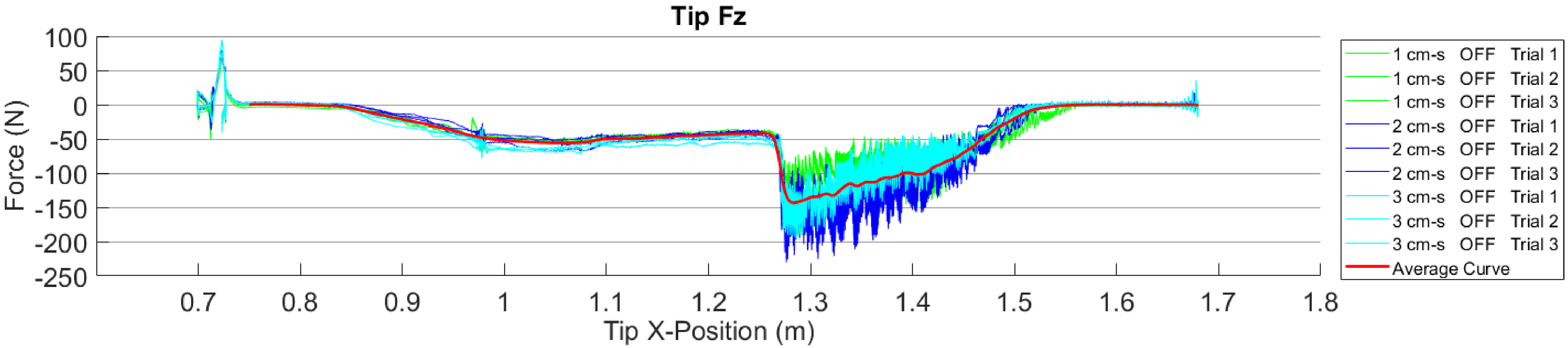
Soil Displaced:

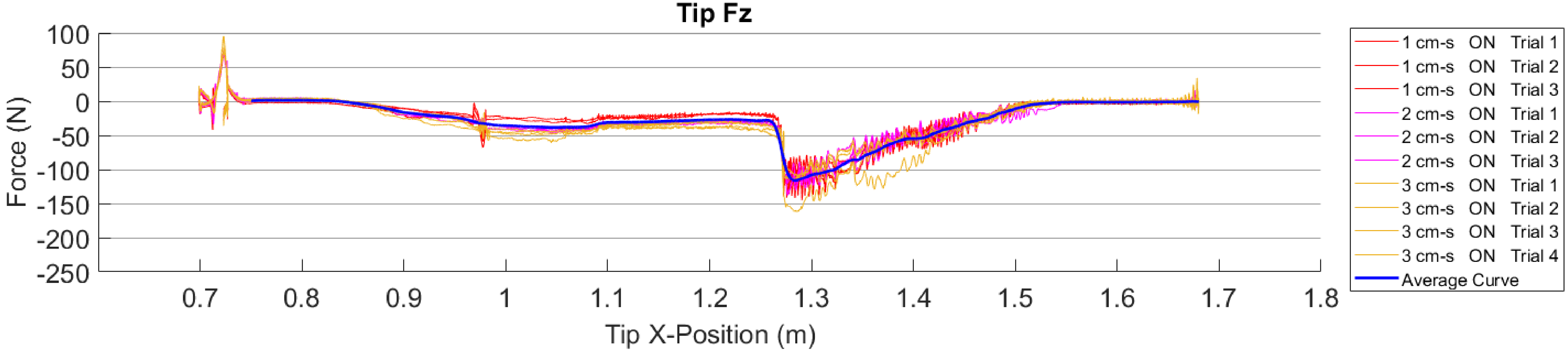
$$M_{displ.} = (A_{toolpath})(D_{measured})(\rho_{est.})$$



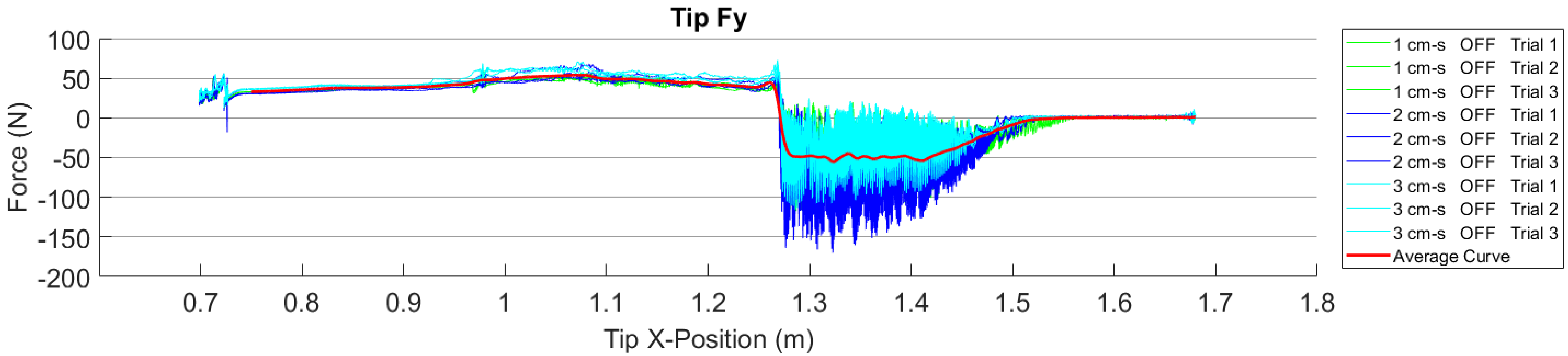
Commanded Tip Velocity [cm/s]	Ultrasonic Status [on/off]	Est. Soil Displaced [kg]	Est. Soil Density [g/cm^3]
1	off	7.59	1.67
1	off	7.90	1.67
1	off	8.54	1.66
1	on	7.60	1.66
1	on	7.26	1.66
1	on	7.57	1.67
2	off	7.55	1.67
2	off	6.96	1.67
2	off	6.78	1.67
2	on	7.56	1.67
2	on	8.58	1.67
2	on	7.41	1.66
3	off	7.23	1.66
3	off	7.25	1.68
3	off	7.37	1.67
3	on	7.88	1.66
3	on	7.56	1.67
3	on	7.26	1.67
		7.43	1.67
	Average	**7.54**	**1.67**
	Std. Deviation	**0.449**	**0.005**

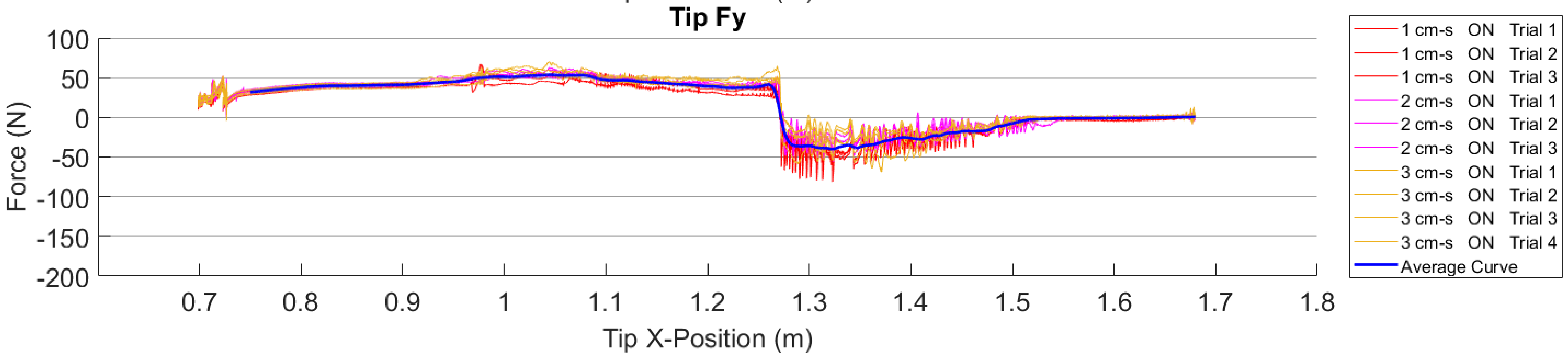
$\left(F_Z^{Tip}\right)^{Tip}$ vs $\left(Pos_X^{Tip}\right)^{Base}$, Air Offset





$\left(F_Y^{Tip}\right)^{Tip}$ vs $\left(Pos_X^{Tip}\right)^{Base}$, Air Offset





$\left(T_X^{Meas}\right)^{Meas}$ vs $\left(Pos_X^{Tip}\right)^{Base}$, Air Offset