A Comparison Between the NORCAT Rover Test Results and the ISRU Excavation System Model Predictions

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Presentation Outline

- Excavation System Model Overview
- White Bin Bucket Testing
- Drawbar Pull Rover Testing
- Plow Rover Testing
- Bucket Rover Testing
- Conclusions

Excavation System Model Overview

- The In Situ Resource Utilization (ISRU) system produces oxygen from lunar regolith by either hydrogen reduction, carbothermal reduction or molten electrolysis
- The excavation system is one part of the overall process
- The objective of the excavation system model is to simulate a vehicle that can excavate and transport a given quantity of regolith on the lunar surface

Excavation System Model Overview

Excavation parameters are input through a spreadsheet:

- Regolith properties (density, cohesion, friction angle, etc.)
- Vehicle dimensions
- Bucket or plow dimensions
- Wheel properties (dimensions, number, grousers)
- Operational durations and distances

The primary outputs from the Excavation System Model are:

- Bucket or plow excavation force
- Wheel traction force
- Vehicle mass and volume estimates
- Power and energy estimates

White Bin Test Facility

- The purpose of the White Bin is to test conceptual implements for use on lunar excavation vehicles
- Filled with GRC-3 sand mix which is a mixture of sands to mimic the lunar regolith particle size distribution
- Bin Size: 2.9 m length x 2.3 m width x 0.7 m depth

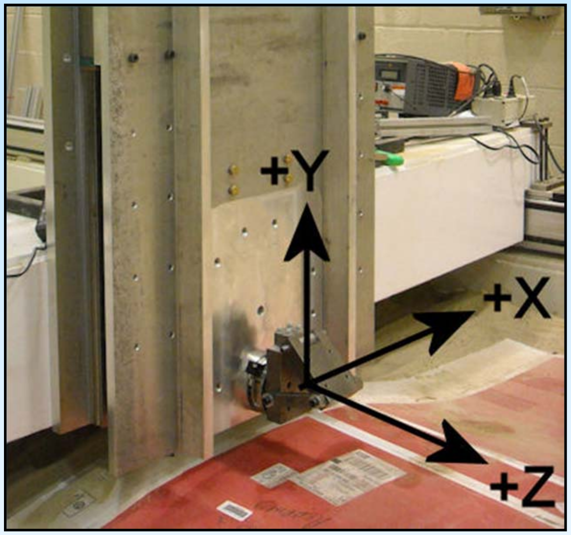
- Includes a mechanism that translates horizontally and vertically
- A load cell is mounted behind the bucket to measure excavation forces
- Soil is prepared by raking the soil and then leveling with a straight edge

White Bin Bucket Test Description

- Eleven tests were performed in unpacked GRC-3 soil (two repeats)
- One test in compacted GRC-3 with a ~20% increase in soil density
- One test in a separate bin filled with JSC-1A lunar soil simulant
- For all 13 tests, the bucket was fixed at a 5^{o} rake angle to the soil
- Bucket velocities tested were 2, 5 and 10 cm/sec
- Bucket cut depths tested were 3, 5 and 7 cm/sec
- Soil density, cohesion and friction angle were measured before each test with a cone penetrometer
- A laser recorded the soil profile in the bucket during each test which was used to calculate the surcharge mass parameter vs. elapsed test time in the Balovnev bucket force equations

White Bin Bucket Test Results

- The Excavation System Module predicted forces on the bucket based on dimensions, soil data and cut depth
- The 5^{o} rake angle of the bucket was low which resulted in unrealistically high code predicted vertical forces because of the trigonometry function values at low angles
- Increasing the rake angle to 12^{o} in the code improved the correlation between the predicted and actual forces for most runs
- The 7 cm cut depth tests still had the vertical force predicted by the Balovnev equations higher than those measured by the load cells



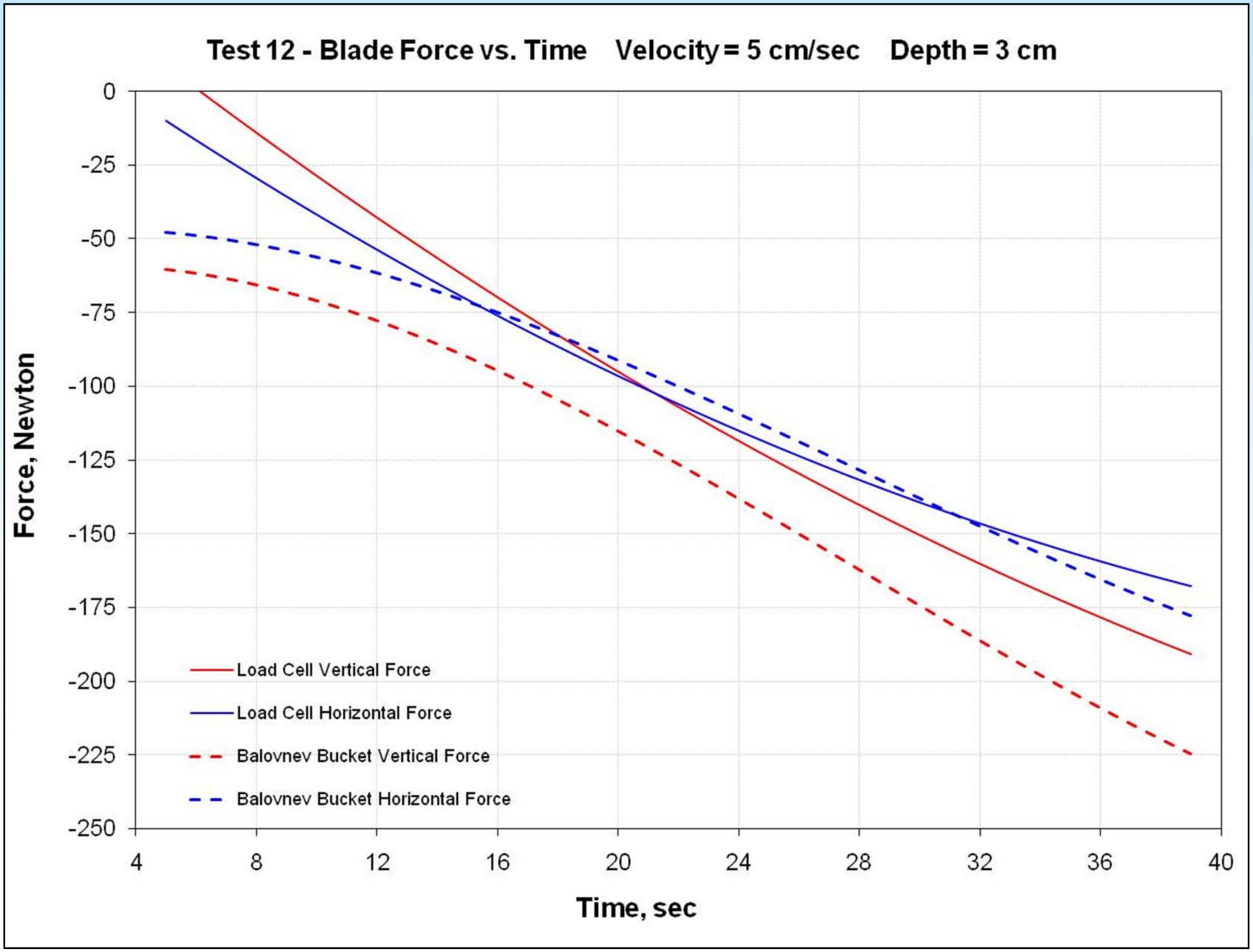
White Bin Bucket Test Results

Soil	Vertical Cut Depth	Bucket Velocity	Cohesion	Internal Friction Angle	Regolith Specific Mass	Load Cell Average Force, N	Balovnev Average Force, N	Load Cell Average Force, N	Balovnev Average Force, N
	cm	cm/sec	N/m^2	degree	kg/m^3	vertical		horizontal	
GRC-3	3	2	1	30.0	1600	102	128	89	98
GRC-3	3	5	1	31.0	1600	108	134	106	106
GRC-3	3	5	1	31.0	1560	102	132	100	104
GRC-3*	3	5	100	32.0	1900	135	209	200	161
GRC-3	3	10	1	38.0	1600	112	159	102	111
GRC-3	5	2	1	31.5	1550	192	258	177	155
JSC-1A	5	2	1	30.0	1600	115	172	127	106
GRC-3	5	5	1	30.0	1600	207	271	192	157
GRC-3	5	10	1	31.0	1550	203	248	192	147
GRC-3	7	2	130	30.0	1600	298	608	292	310
GRC-3	7	5	300	32.0	1550	297	705	291	375
GRC-3	7	10	1	31.5	1580	301	538	298	283
GRC-3	7	10	10	30.0	1550	305	474	309	274

* Compacted Soil

Table of Parameters for Each Run and the Resulting Forces

White Bin Bucket Test Results



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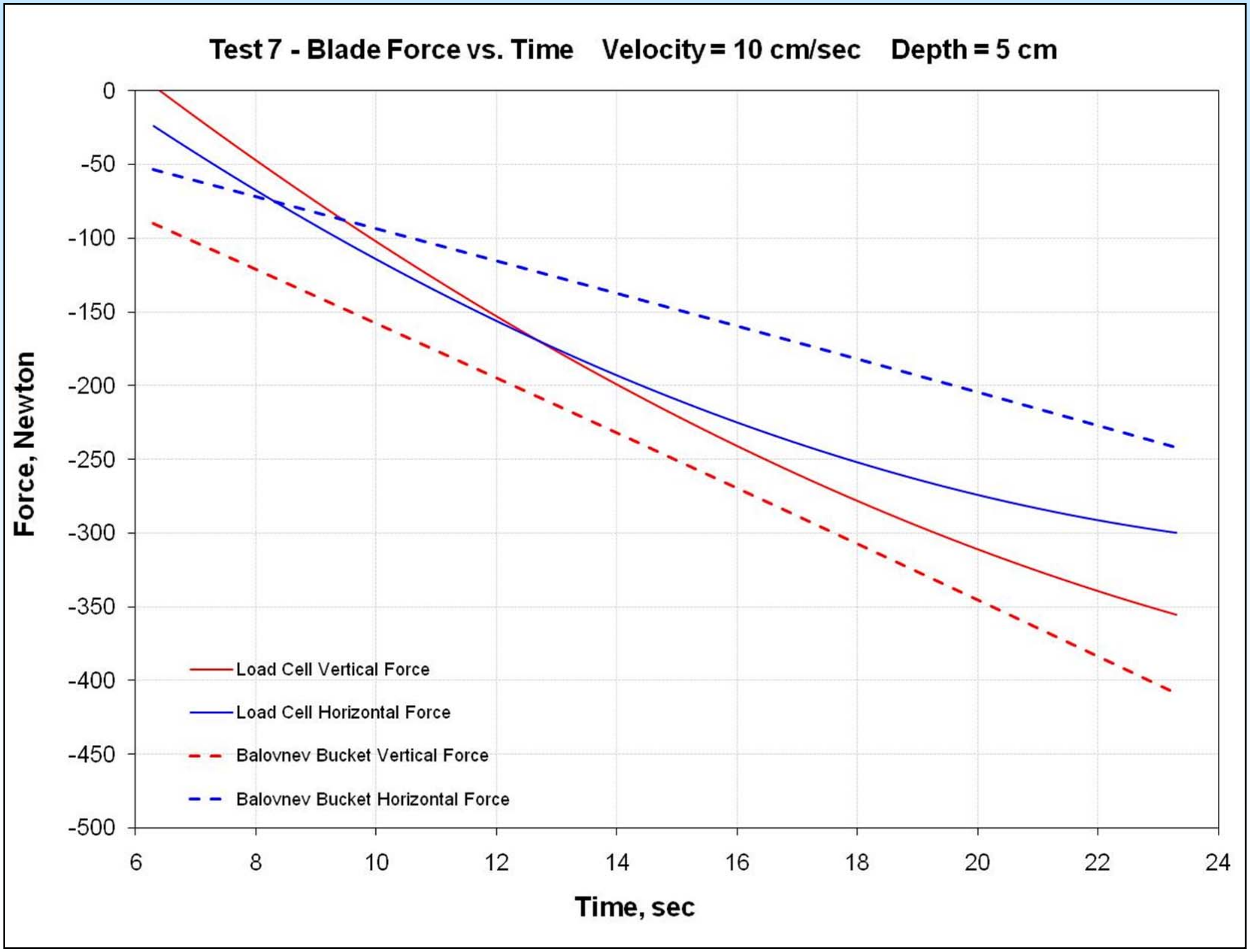

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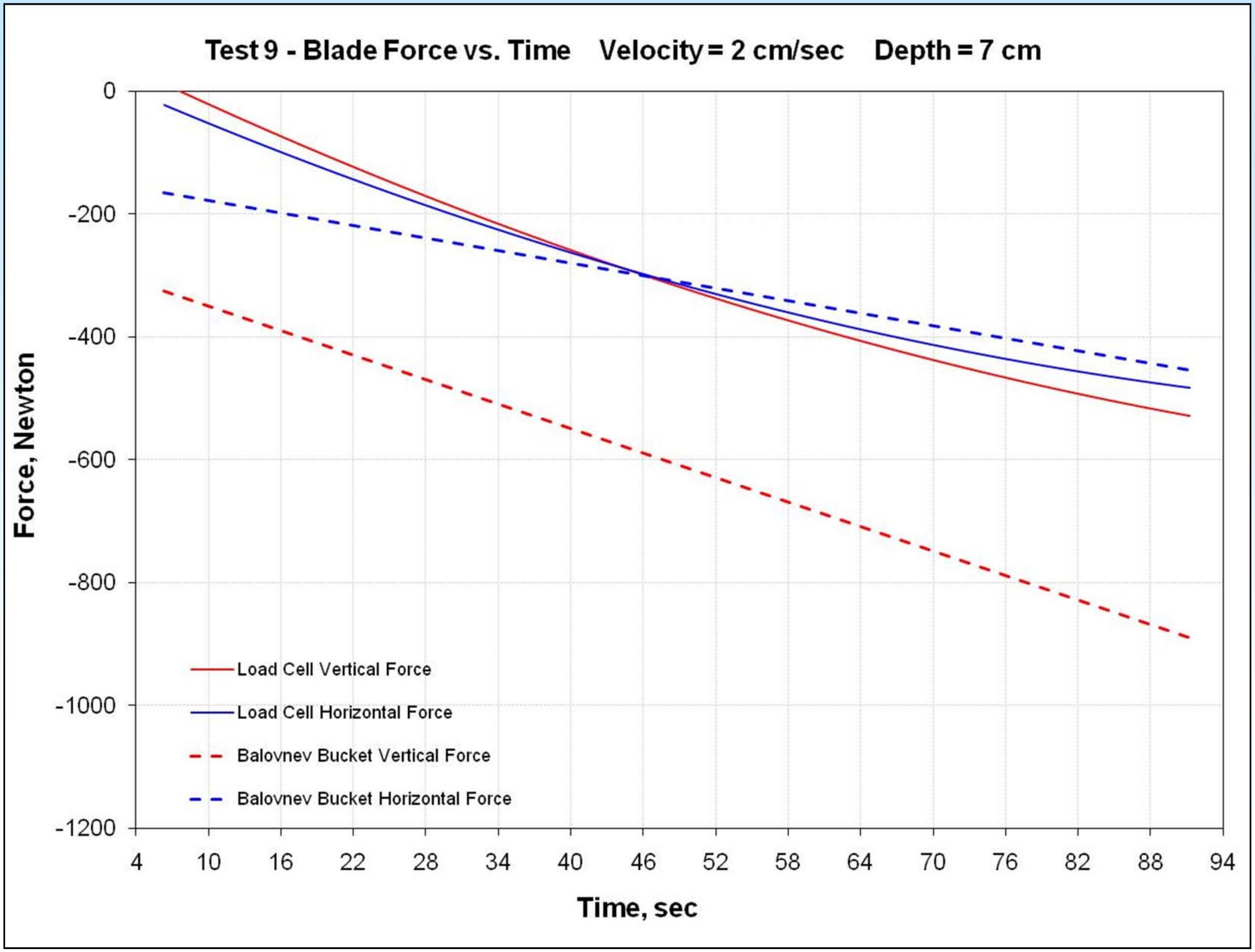
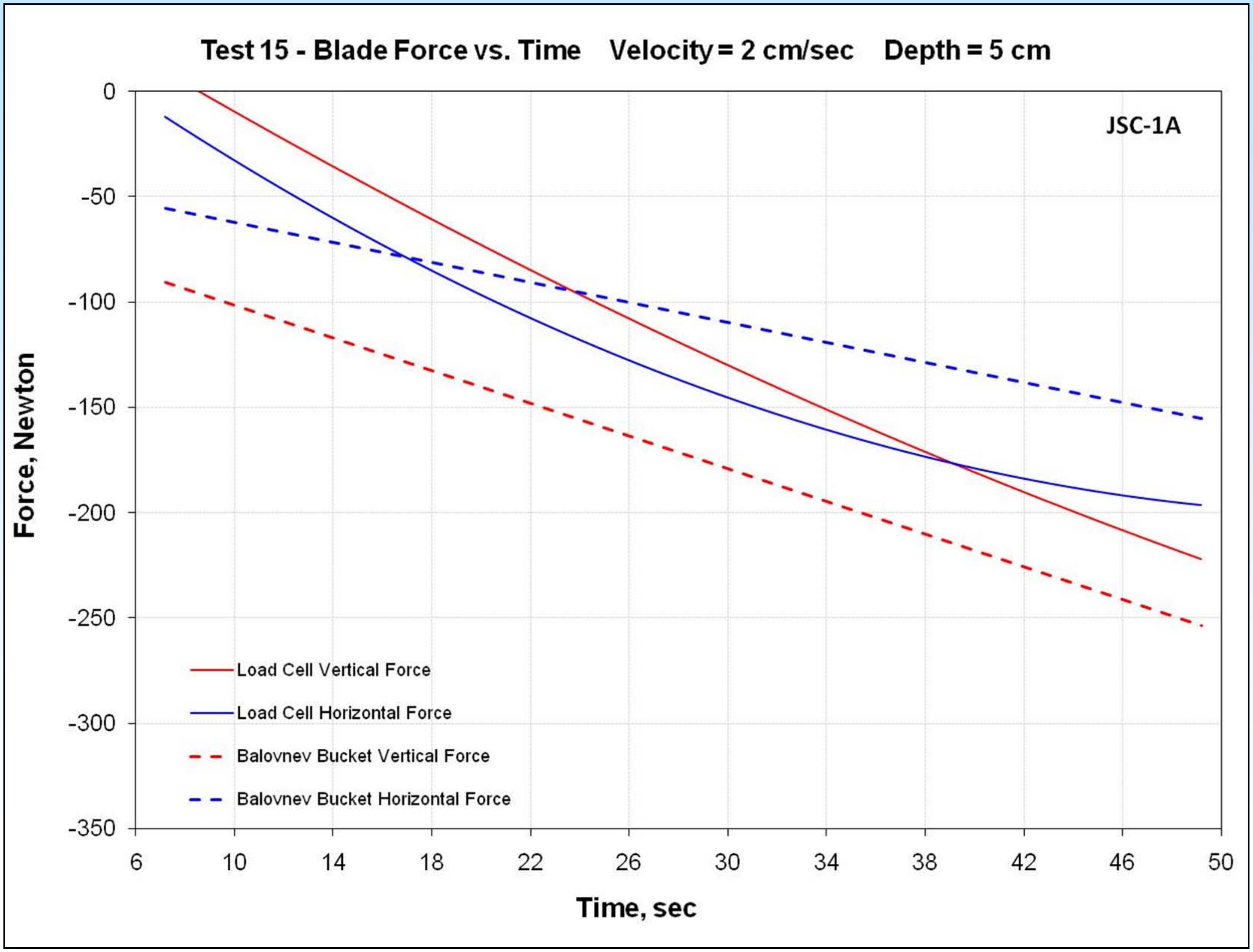
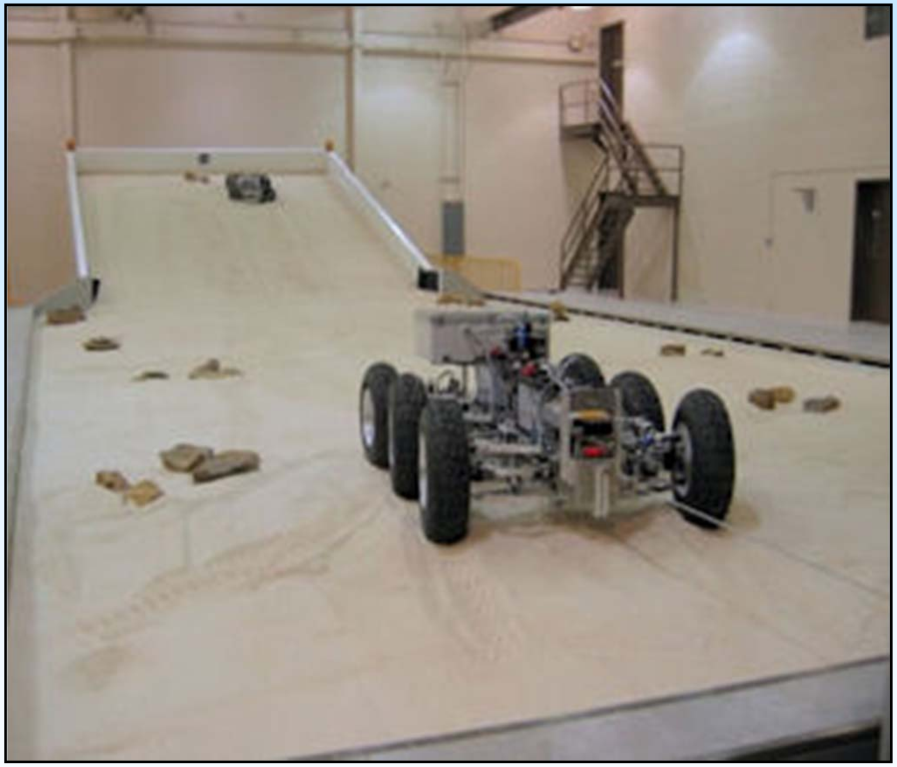


White Bin Bucket Test Results



Simulated Lunar Operations (SLOPE) Test Facility

- The purpose of the SLOPE facility is to conduct traction and excavation testing of vehicle and component concepts to be used on the lunar surface
- Filled with GRC-1 sand mix which is a mixture of sands to mimic the lunar regolith particle size distribution
- Bin Size: 12 m length x 6 m width x 0.3 m depth

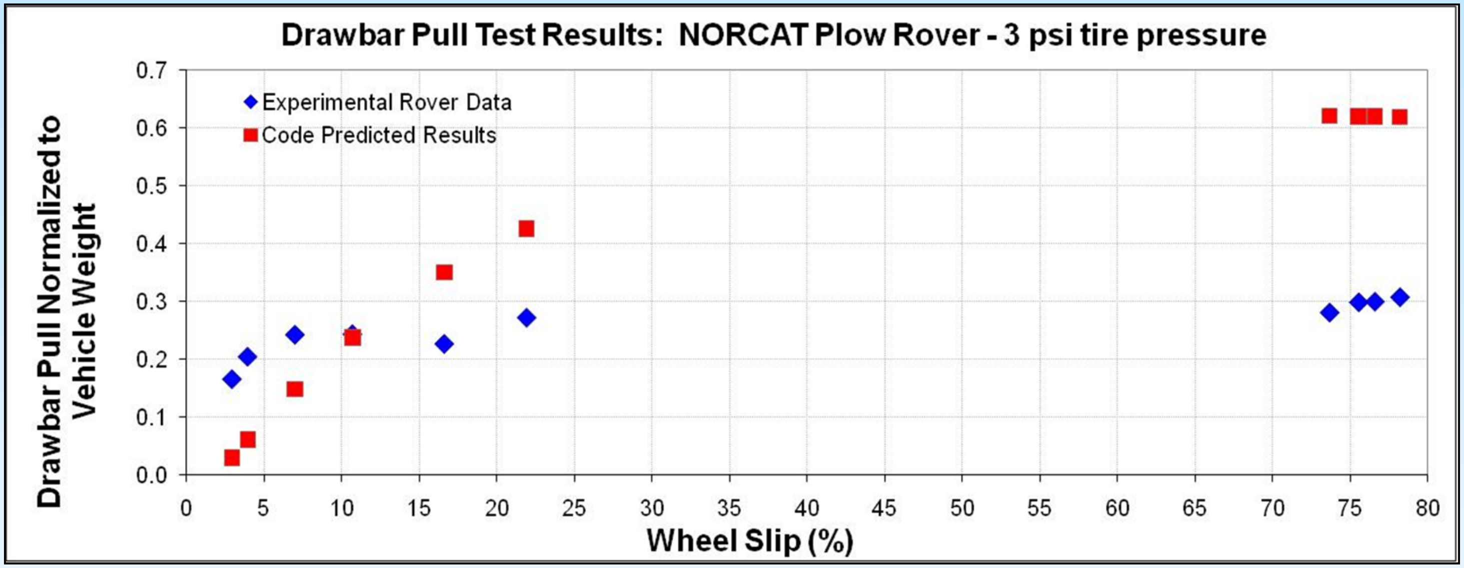


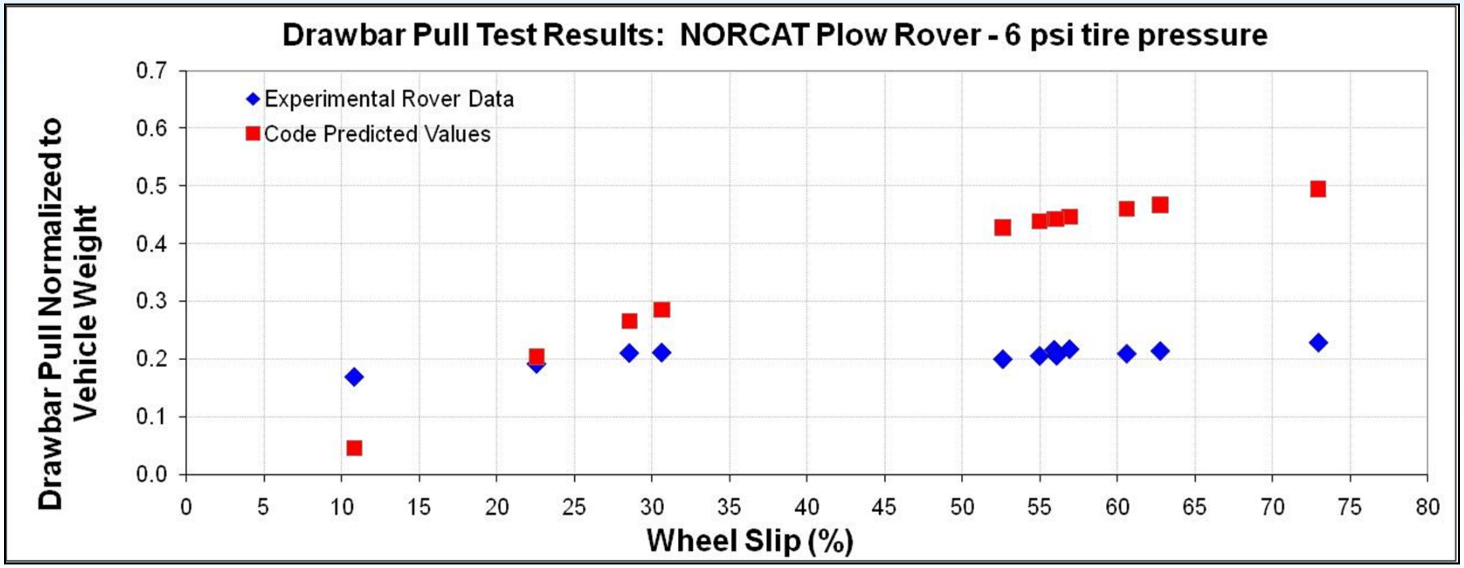
- Soil is prepared by digging with shovels the entire length and width to loosen the soil and then leveling with a metal plate
- Drawbar pull and excavation tests were performed in this facility

Drawbar Pull Test Description and Results

- Two drawbar pull runs were made at tire pressures of 3 psi and 6 psi
- A cable was attached to the back of the rover to apply an increasing resistive force while the rover was driven forward in the soil
- The pull force was increased until the wheels started slipping and the rover stopped moving
- The force at the point of wheel slippage is the drawbar pull force
- Force, rover velocity and wheel slip were determined at specified increments during the test
- The Excavation System Model was used to calculate the theoretical drawbar pull at each increment using the rover and soil parameters
- The plot on the following page compares the normalized drawbar pull vs. percent wheel slip for both tests

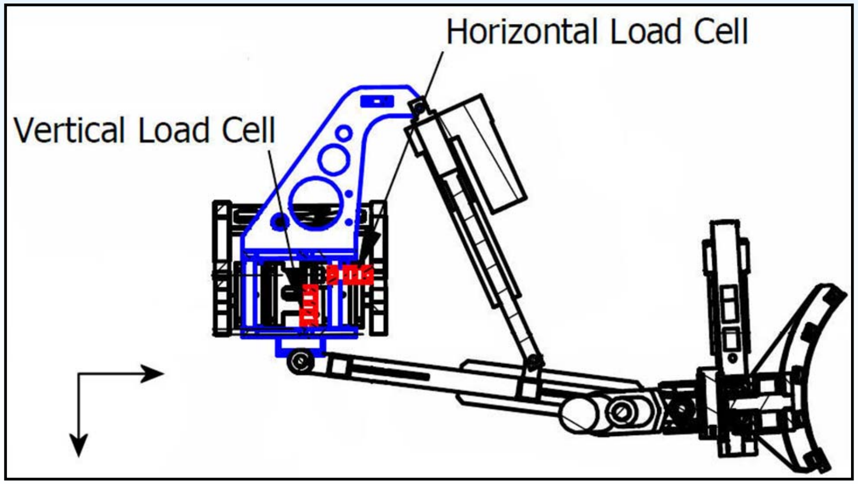
Drawbar Pull Test Results





NORCAT Plow Rover Test Description

- Plow rover driven in the SLOPE facility at 6 psi tire pressure
- Load cells mounted above the plow lower rear pivot point measured forces while plowing at predetermined velocities and cut depths
- For each data point, the rover was driven a known distance or until the wheels would spin
- The average plow depth and average rover velocity over the duration of the test were used as input for the code predictions



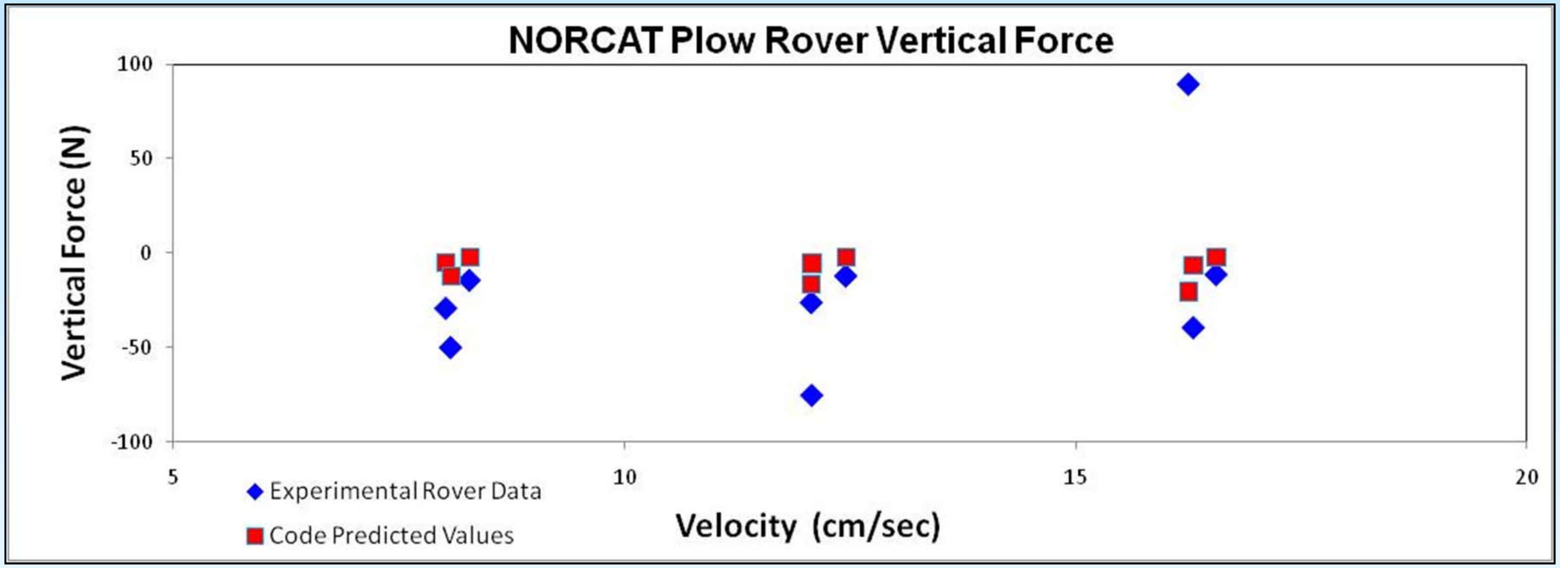
NORCAT Plow Rover Results in SLOPE

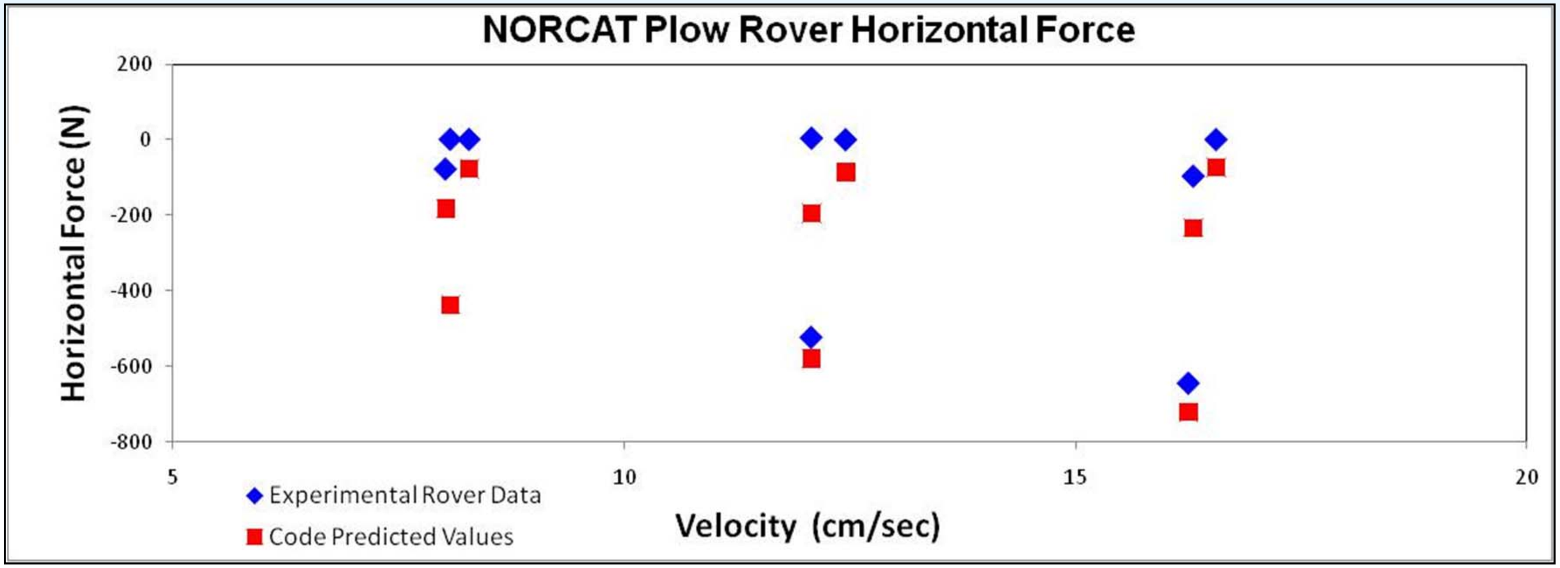
Plow Parameters		
plow width	1.724	meter
plow length	0.000	meter
plow height	0.314	meter
rake angle	68.0	degree
plow radius	0.254	meter
blunt edge angle	68.0	degree
side plate thickness	0.000	meter
blunt edge thickness	0.006	meter
Soil Properties		
moon gravity	9.81	m / sec^2
regolith spec mass	1625	kg/m^3
internal friction angle	31.50	N/m^2
cohesion	0.00	degree
external friction angle	23.63	degree

Test Parameters		Experimental Data		Predicted Forces	
Vertical Cut Depth cm	Wheel Velocity cm/sec	Vertical Force Newton	Horizontal Force Newton	Vertical Force Newton	Horizontal Force Newton
2.6	8.3	-14	2	-2	-77
2.8	12.5	-12	1	-2	-86
2.8	16.6	-11	1	-2	-74
4.6	8.0	-29	-77	-5	-182
4.4	12.1	-75	5	-6	-195
4.9	16.3	-39	-96	-7	-233
7.3	8.1	-50	2	-12	-437
8.7	12.1	-26	-523	-16	-579
9.9	16.3	90	-645	-20	-721

- Target cut depths were 3, 5 and 7 cm
- Target rover velocities were 10, 15 and 20 cm/sec

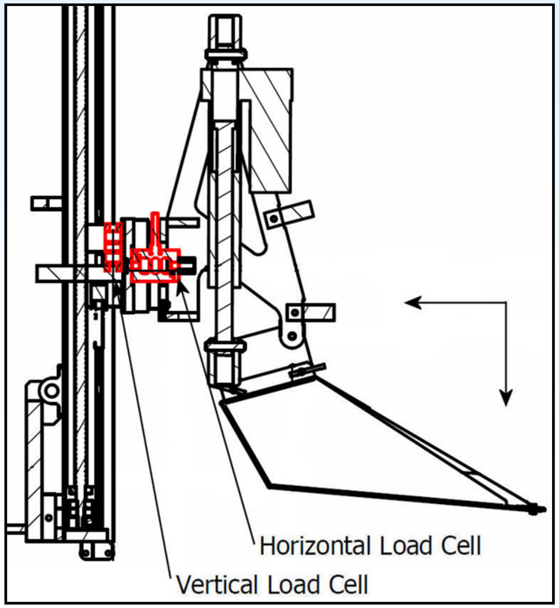
NORCAT Plow Rover Results in SLOPE





NORCAT Bucket Rover Test Description

- Bucket rover driven in SLOPE facility at 3 psi tire pressure
- Load cells mounted behind the bucket support hardware measured forces while excavating at set velocities and cut depths
- Measured bucket forces were low for all tests regardless of rake angle, cut depth or velocity when compared to the predicted forces
- Load cells for this test were assumed to be reading inaccurately



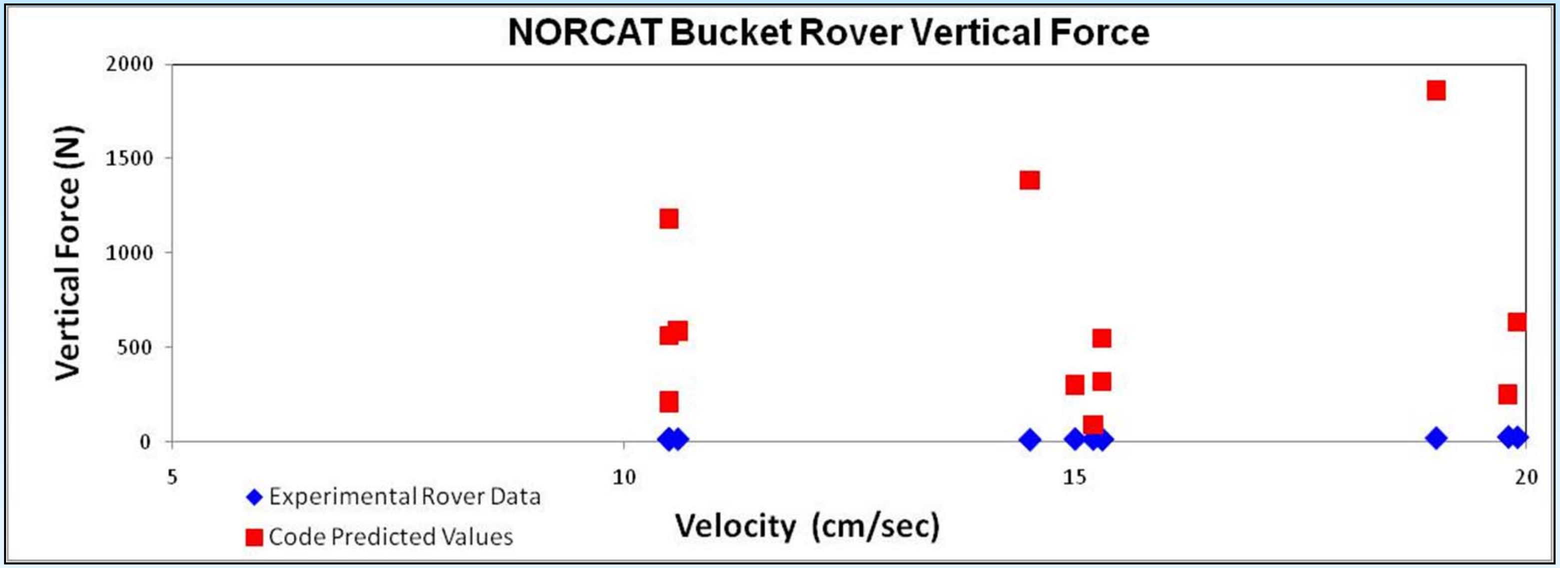
NORCAT Bucket Rover Results in SLOPE

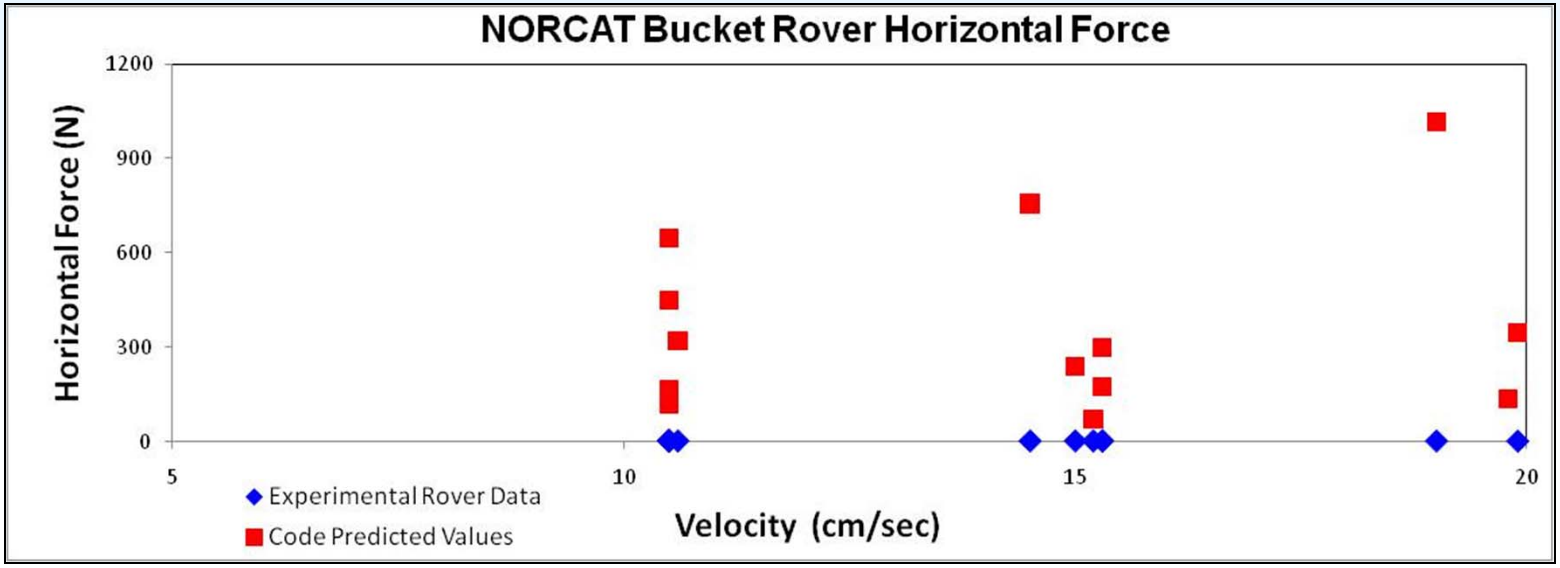
Bucket Parameters		
bucket width	0.511	meter
bucket length	0.450	meter
bucket height	0.200	meter
side plate thickness	0.003	meter
blunt edge thickness	0.006	meter
Soil Properties		
moon gravity	9.81	m / sec^2
regolith spec mass	1625	kg/m^3
internal friction angle	31.50	N/m^2
cohesion	0.00	degree
external friction angle	23.63	degree

Test Parameters			Experimental Data		Predicted Forces	
Vertical Cut Depth cm	Wheel Velocity cm/sec	Rake Angle degrees	Vertical Force Newton	Horizontal Force Newton	Vertical Force Newton	Horizontal Force Newton
2.4	10.5	5	17	2	221	121
3.3	15.3	5	14	1	320	175
3.4	19.8	5	27	-2	251	137
5.1	10.6	5	16	1	589	321
4.9	15.3	5	16	1	549	300
5.1	19.9	5	26	0	635	347
7.3	10.5	5	16	2	1182	645
7.7	14.5	5	12	1	1384	755
9.4	19.0	5	21	1	1861	1016
3.1	15.2	15	16	1	90	72
5.2	15.0	15	16	1	301	240
4.7	10.5	15	15	3	208	167
7.6	10.5	15	15	1	561	448

- Target cut depths were 3, 5 and 7 cm
- Target rover velocities were 10, 15 and 20 cm/sec

NORCAT Bucket Rover Results in SLOPE





Conclusions

- Duplicate White Bin tests showed repeatability in load cell forces.
- Balovnev bucket equations appear to overestimate forces at low rake angles and higher cut depths as determined from the White Bin bucket testing which may result in hardware that is too heavy.
- Drawbar pull experimental results were close to the theoretical values although the code predicted higher forces as slip increased.
- The plow rover testing resulted in forces that were near predicted values. Some forces matched well while others were further apart.
- The bucket rover testing possibly had load cells that were not measuring forces correctly. Out of 26 load cell forces, 23 were less than 6% of the code predicted values.
- Overall the testing was successful. Excavation forces were near the predicted values (after ignoring potentially inaccurate data). Therefore it can be concluded that the methodology in the code reasonably predicts forces obtained from the experimental methods.

Recommendations and Future Work

- Testing in the White Bin at greater rake angles. This will verify the theory that the Balovnev equations over predict blade forces at low rake angles.
- Testing of different buckets in the White Bin to compare results to the Norcat bucket testing results.
- Additional bucket testing in JSC-1A lunar soil simulant.
- Testing of other vehicles in SLOPE for traction and excavation.