COMPARING BLADE/SOIL INTERACTION MODELS IN A MATLAB PROGRAM TO MEASUREMENTS OF FORCES TO PUSH NARROW RODS THROUGH SAND AND SIMULANT MATERIALS FOR DESIGN OF EXTRATERRESTRIAL SOIL HANDLING MACHINES, R. H. King[1], P. J. van Susante[2], and M. A. Gefreh[3], [1]EG Division, CSM, 279 Brown Hall, Golden, CO 80401, rking@mines.edu, [2]EG Division, CSM, Golden, CO 80401, [3]Sierra Nevada Corporation Space Systems 8130 Shaffer Parkway Littleton, CO 80127.

B	width of blade
H_0	height of blade
R	radius of curvature of blade
θ	angle of curvature of blade
δ	angle of soil–metal friction
A_d	adhesional factor of soil–metal
γ_0	density of cut soil
C_0	cohesion of cut soil
φ_0	angle of accumulation of cut soil
m_1g	weight of soil pile (fgde) moving on the ground
m_2g	weight of cut soil (abdgf) sliding up on the surface of blade
m_3g	weight of soil wedge (bcdnmk)
α	angle of cutting blade
D	depth of cutting blade
γ	density of uncut soil
C	cohesion of uncut soil
φ	angle of internal friction
F_{f1}	frictional force between soil pile (fgde) and ground
F_{c1}	cohesional force between soil pile (fgde) and ground
P_{f2}	frictional force between blade and cut soil (abdgf)
P_{ad}	adhesional force between blade and cut soil (abdgf)
P_{f1}	frictional force between soil pile (fgdc) and cut soil (abdgf)
P_{c1}	cohesional force between soil pile (fgde) and cut soil (abdgf)
G	force acting normal to the face (bcd) and (nmk) of soil wedge
SF_2	frictional force on the sides (bcd) and (nmk) of soil wedge
CF_2	cohesional force on the sides (bcd) and (nmk) of soil wedge
CF_1	cohesional force on the rupture plane
SF_1	frictional force on the rupture plane
Q	normal force on the rupture plane
F_{ad}	adhesional force between the soil and cutting edge of blade
β	angle that the rupture makes with the horizontal
W	force acting normal to the face (bdkn) of soil wedge
P	force acting on the cutting edge of blade

Operations on the moon, Mars, or asteroids could require telerobotic, autonomous, or manned machines to excavate soil or regolith. Cost-effective extraterrestrial applications require excavation equipment to have minimal mass, low power, small size, and operate unattended in low gravity and at extreme temperatures for at least six month durations. Designing reliable soil handing machines requires estimating the stresses and strains caused by the forces experienced during excavation. The design goals and criteria for terrestrial equipment are considerably different; consequently, the extraterrestrial application requires new approaches. The new designs require precise knowledge of excavation forces. Extraterrestrial outpost development requires excavation for landing and launch sites, roads, trenches, foundations, radiation and thermal shielding, etc Consequently, blades could be a prominent tool. There are several computational models available to predict forces from blade tools interacting with soil: Balovnev [1], Gill and Vanden Berg [2], Luth and Wismer [3], McKeys [4], Osman [5], Qinsen and Shuren [6], Swick and Perumpral [7], and Zeng et al [8] Figure 1 shows a model example from Qinsen and Shuren [6], however, it is not clear which if any, can predict excavation forces precisely enough. This paper describes a MATLAB program that automates the calculation of force estimated from a suite of blade/soil interaction models over a range of soil properties and blade geometries.

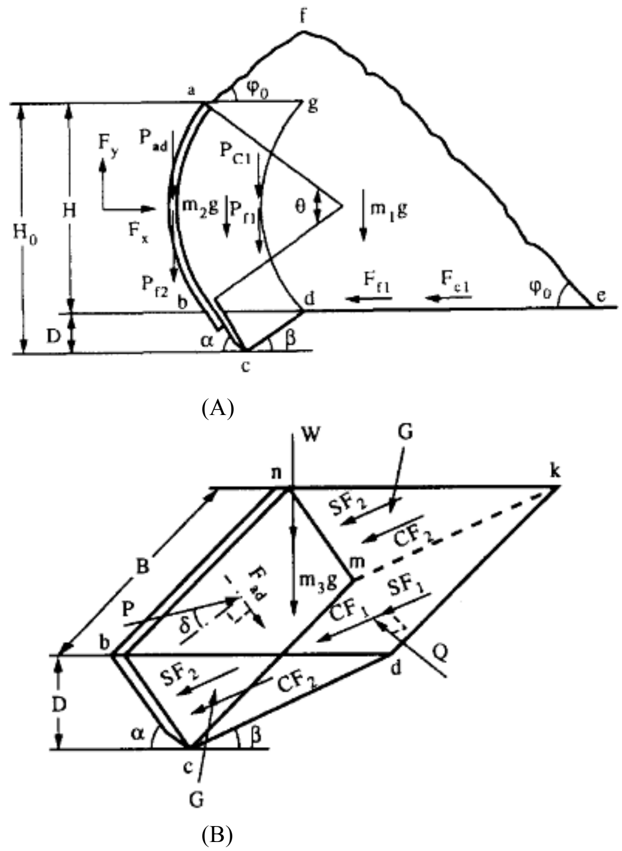

Figure 1. Qinsen and Shuren blade excavation force model geometry and forces, (A) pushing cut soil and (B) cutting below the surface [13]. Note that B ≡ w, D ≡ d, C ≡ c, β ≡ ρ, and α ≡ β in the Table 1 notation.

The program user must provide values for the soil and tool interface variables listed in Table 1. Table 1 also contains the values used in this study. All of the values are read by the program, but not all of the values are not used in every model.

Table 3. Values of computational model variables and constants

Description	Symbol	Ottawa	JSC-1A	Unit
coefficient of passive earth pressure	K_0	0.573	0.573	
cohesion	c	1.4	1.7	kPa
cohesion after cutting	c_0	0.7	1.0	kPa
cutting depth	d	0.0-0.08	0.0-0.08	m
earth acceleration of gravity	g	9.81	9.81	m/s^2
external angle of friction	δ	17	23	°
Gill's cut resistance	K	1	1	N/m
horizontal acceleration	ah	0	0	m/s^2
internal friction angle	φ	30	37	°
Internal friction angle after cutting	φ_0	30	37	°
shear plane failure angle	ρ	35	29	°
soil bulk density	γ	1.0	1.7	g/cm^3
soil bulk density after cutting	γ_1	0.7	1.4	g/cm^3
soil-tool adhesion	Ca	39	39	Pa
Soil-tool normal force	N_0	1000	1000	N
surcharge pressure	q	25.4	43.18	kg/m^2
tool angle of curvature	θ	0.001	0.001	°
tool edge angle	α	0	0	°
tool edge thickness	eb	0	0	m
tool height	H	d + 0.1	d+0.125	m
tool horizontal acceleration	ah	0	0	m/s^2
tool length	L	H	H	m
tool mass	Wb	0.4	0.4	kg
tool radius of curvature	R	10000	10000	m
tool rake angle	β	89	89	°
tool side length	Ls	H	H	m
tool side width	s	w	w	m
tool velocity	v	0.0033	0.0033	m/s
tool width	w	0.0127	0.0127	m
tool vertical acceleration	av	0	0	m/s^2

The paper also presents laboratory measurements of the forces to push narrow (2.5-cm wide) square and round rods through Ottawa sand and JSC-1A lunar simulant at different cut depths with the CSM excavation force test bed shown in Figure 2.

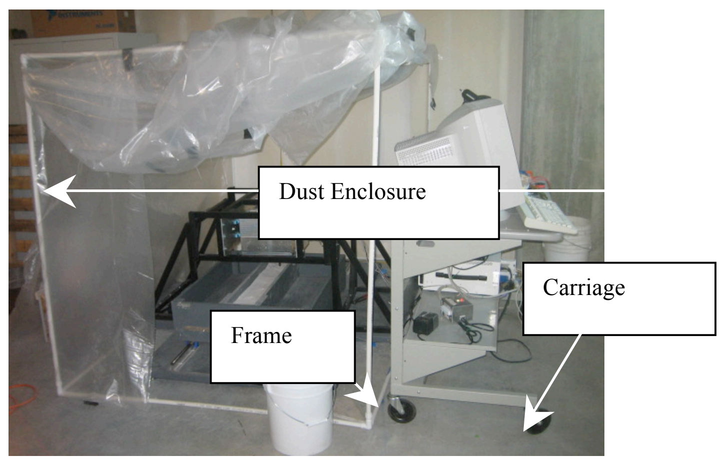

Figure 2. Soil excavation force measurement apparatus

The paper compares the measurement results with the forces predicted by eight computational models shown in Figure 3.

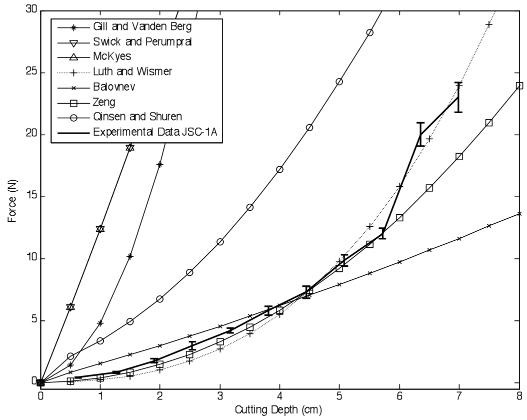

Fig. 3. Measured and computed forces in JSC-1A lunar simulant.

The Zeng, Luth and Wismer, and the Qinsen and Suren model estimates were the best fit to the measurement data. Both measurements and models showed that depth of cut has a dramatic effect on the soil-tool interaction forces. Consequently, extraterrestrial missions should use a series of shallow cuts to reduce equipment size and power requirements.

References: [1] Balovnev VI. New methods for calculating resistance to cutting of soil. Amerind Publishing (Translation), P. Datta translator and Rosvuzizdat, New Delhi, Available from National Technical Information Service, Springfield, VA 22161, 1983 and 1963, respectively.

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