COMPARISON OF LANCE BLADE FORCE MEASUREMENTS WITH ANALYTICAL MODEL RESULTS

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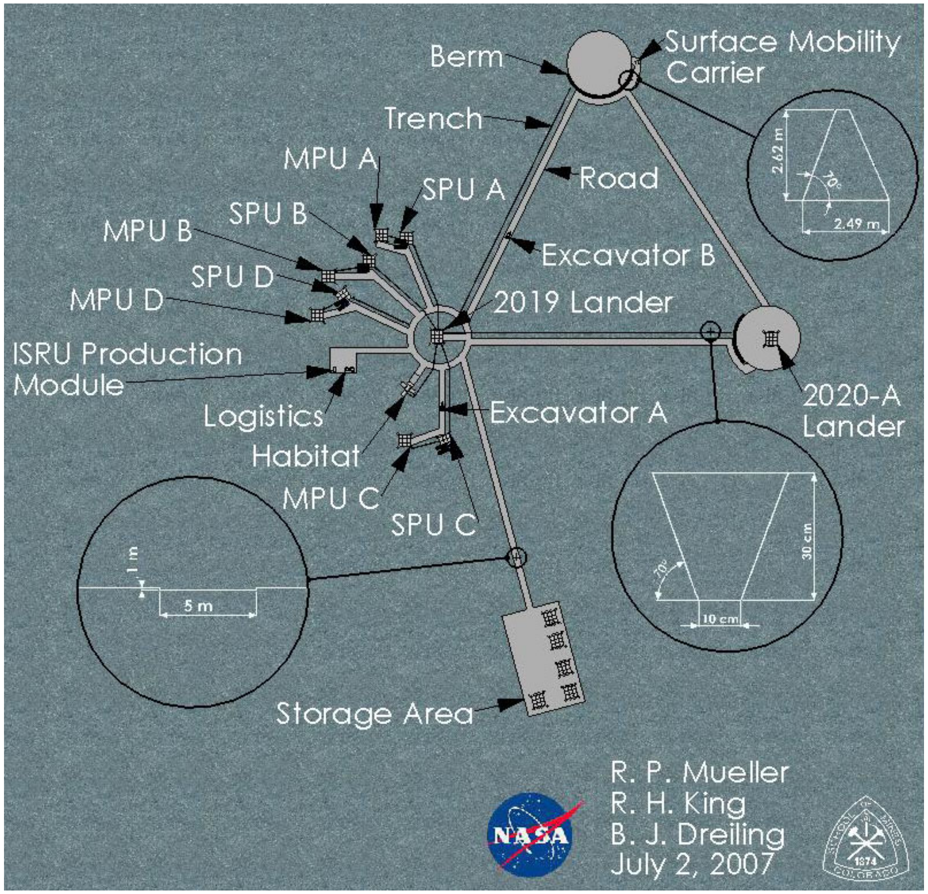
The NASA Lunar Architecture Team (LAT) lunar outpost architecture proposal to be implemented in a series of missions that begin in 2019 and continue at 6 month intervals into 2027.

roads
landing pads
berms
trenches
foundations



2023-B Lunar Outpost Site Plan Concept

Cooke D. Exploration strategy and architecture. In: NASA 2nd Exploration Conference, Houston; 2006.

A major portion of lunar outpost excavation can be done with a blade tool

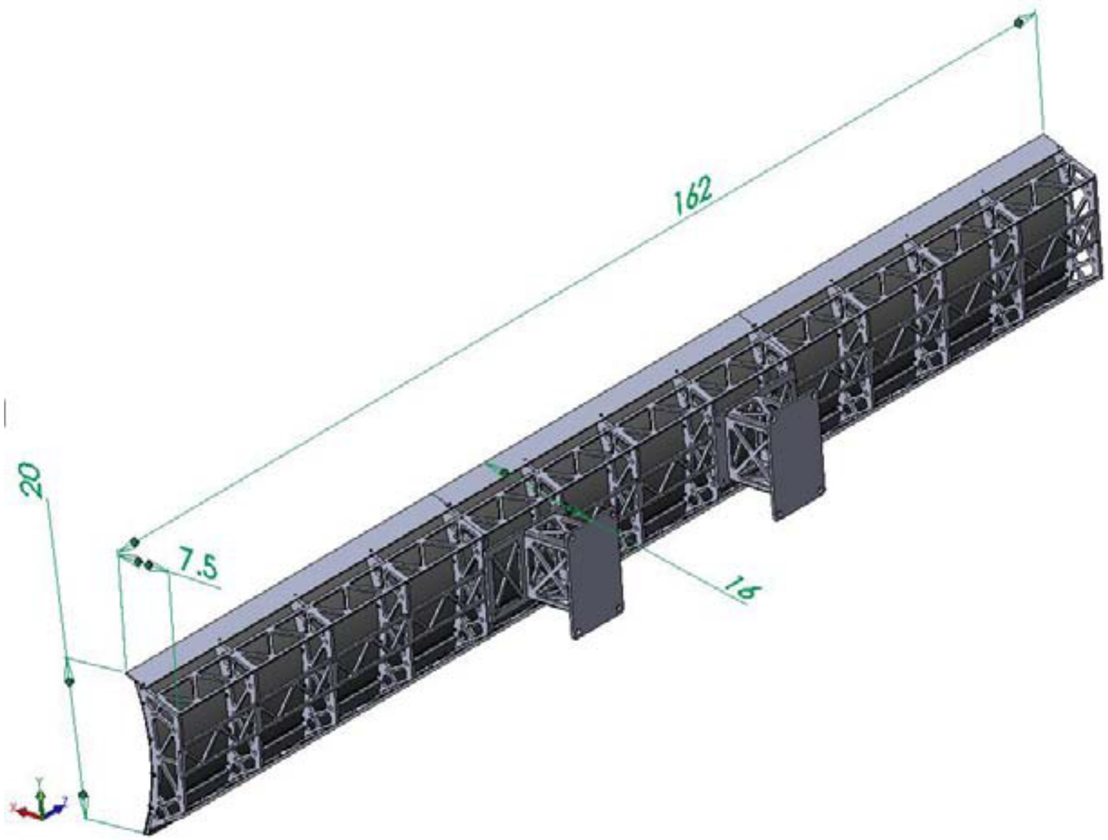
Concept 2023-B Lunar Outpost Excavation Requirements Summary (MT)

	2019-2023
Cable Trenches	112,931
Roads	525,000
Landing Pad	1,177,500
Berms	565,452
Foundations	15,300
Hab/Shield Trench	715,336
Hab/Shield Roof	267,520
O2 ISRU	500,000
Ice ISRU	100,000
Total Regolith (MT)	3,878
Total Ice Regolith (MT)	100

Assumes Hydrogen reduction processing and habitat structures shielded by regolith

Mueller RP, King RH. Trade study of excavation tools and equipment for lunar outpost development and ISRU, AIP Conf. Proc. 2008;969:237-244.

The LANCE blade was developed by NASA KSC to study lunar site preparation activities like clearing of rocks, leveling, dozing, grading, and berm construction.

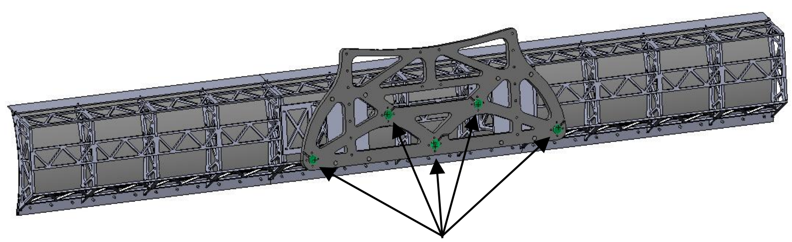


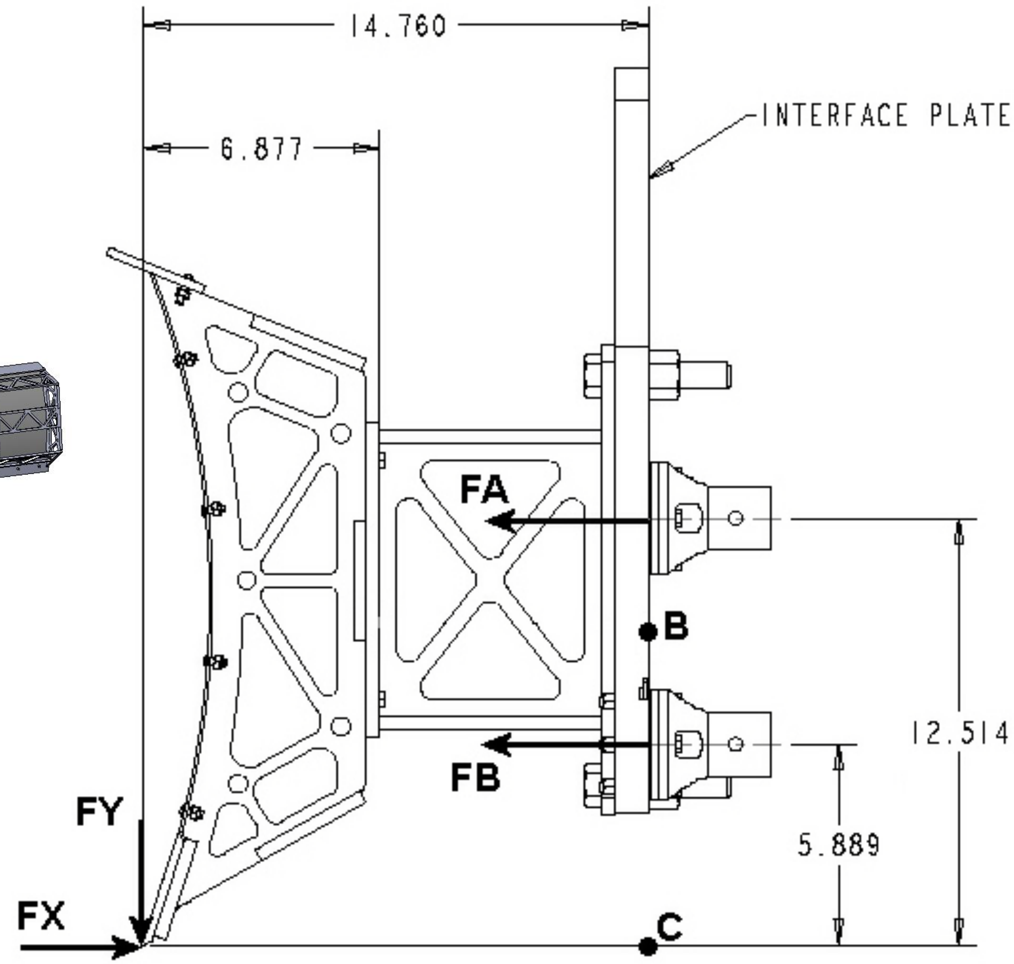
Dimensions in inches

Mueller, R. P, Wilkinson A., Gallo C., Nick A., Schuler J., King R., Lightweight Bulldozer Attachment for Construction and Excavation on the Lunar Surface, AIAA Space 2009 Meeting, Pasadena CA Sep 2009.

The LANCE Blade was mounted on the Chariot platform and tested in GRC-1 lunar simulant at NASA JSC

5 button load cells were sandwiched between the interface plate and its five attachment points. Laser distance meters attached to outrigger mounts measured blade depth. An outward pointing laser distance meter measured velocity.

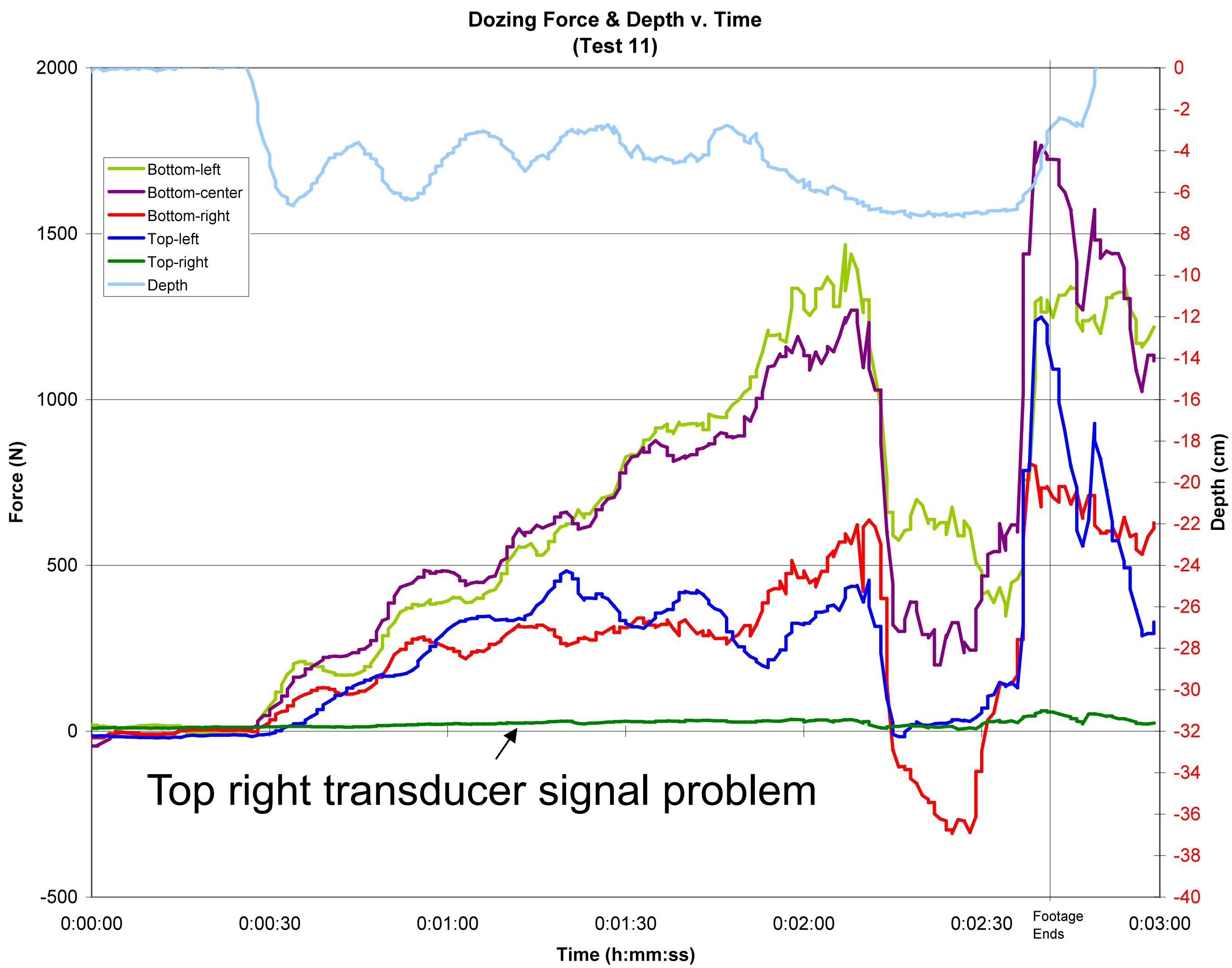




Video images, synchronized with the measurements, show surcharge volume increase.

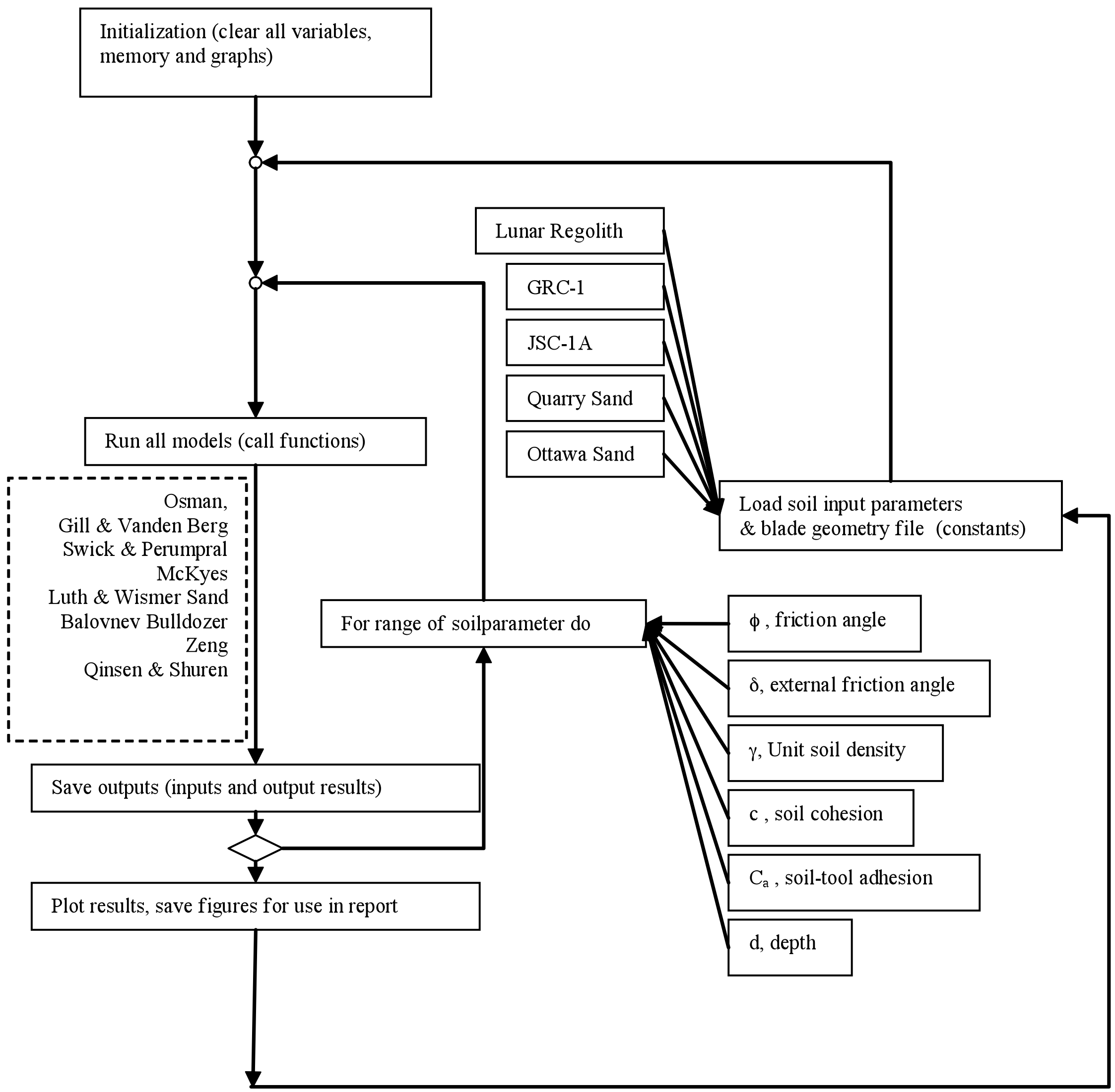
Test 11

A NI field point DAQ and LabVIEW VI acquired data continuously

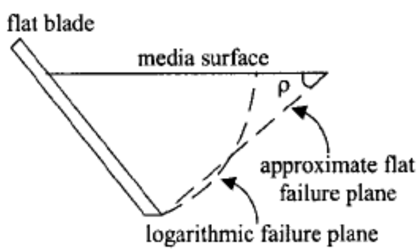


MATLAB program to explore effect of variable values and compare model predictions with LANCE data

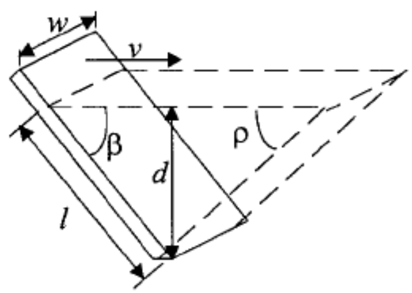
8 models for 5 soils with 6 varying soil properties produced 8x5x6 =240 sets of results



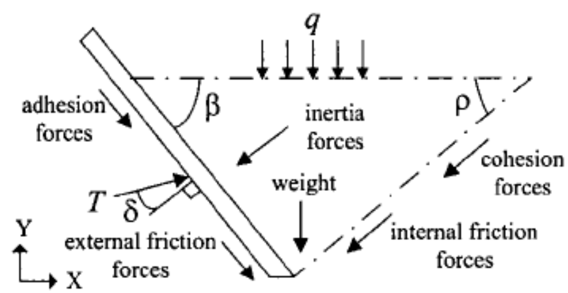
Fundamentals of Analytical Excavation Force Models



Failure surface



Cut geometry



Forces

 Blouin S, Hemami A, Lipsett M. Review of resistive force models for earthmoving processes. J Aerospace Eng 2001;14(3):102–11.

Balovnev Model

- wide blade
- based on the theory of the limiting equilibrium of soils
- assumes cut depth is less than width
- assumes full surcharge pile
- measurements in dry sand, sandy loam and loam. Theoretical values were 3-9% higher than the measured results

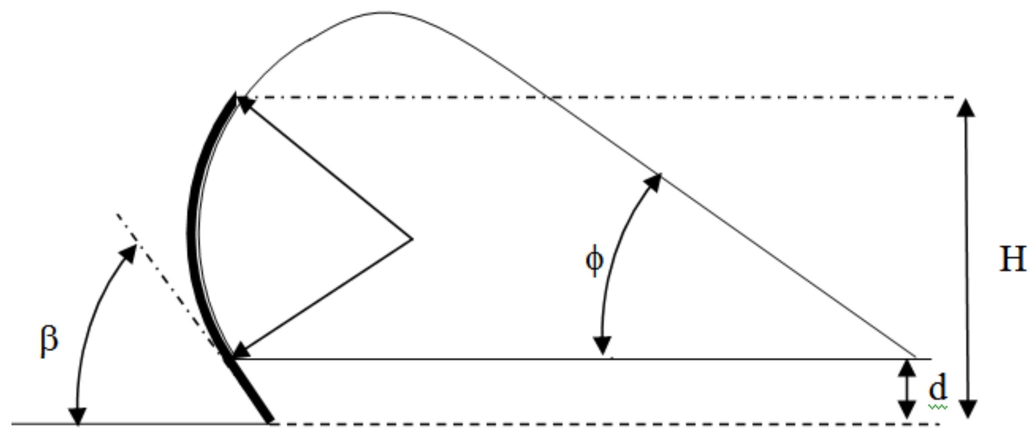
$$H_{balovnev-bulldozer} = \left(1+\cot(\beta)\tan(\delta)\right)A_1 wd\left[\frac{\gamma g d}{2} + c\cot(\phi) + \frac{\gamma_1 g\tan(\phi)(\cos(\phi))^2 H^2}{dK_\psi} + \gamma_1 g H\right] + \frac{\gamma_1 g w H^2 (\cos(\phi))^2}{2}$$

$$\text{Where } A_1 = \frac{\left(1-\sin(\phi)\cos(2\beta)\right)}{1-\sin(\phi)}$$

$$\text{and } K_\psi = \frac{\left(\tan(\beta)+\tan(\frac{\pi}{4}-\frac{\phi}{2})\right)}{\tan(\beta)\tan(\frac{\pi}{4}-\frac{\phi}{2})}$$

$$T_{balovnev-bulldozer} = H_{balovnev-bulldozer}\csc(\beta+\delta)$$

$$V_{balovnev-bulldozer} = H_{balovnev-bulldozer}\cot(\beta+\delta)$$



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

Gill and Vanden Berg Model

- agriculture emphasis
- no surcharge
- straight failure surface
- includes terms for:
  - inertia of the soil,
  - soil-soil cohesion
  - soil mass

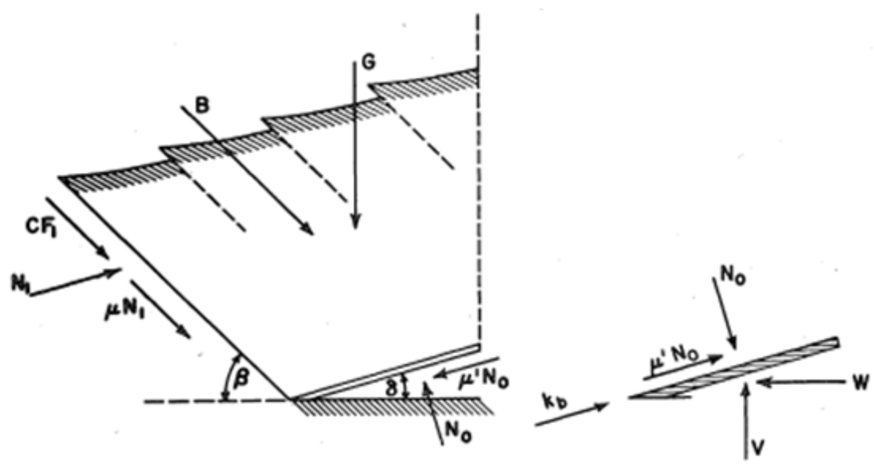
$$H_{gvdb-b} = N_0 \sin(\beta) + \delta N_\phi \cos(\beta) + Kw$$

$$H_{gvdb-b} = \left(\frac{wd(\sin(\beta) + \delta\cos(\beta))(\sin(\rho) + \phi\cos(\rho))}{\sin((\rho+\beta)(1-\phi\delta)) + \cos((\beta+\rho)(\phi-\delta))} \right) *$$

$$\left[\begin{array}{l} \left(g\gamma \frac{\sin(\beta+\rho)}{\sin(\rho)} \right) \left(l + \left(\frac{d\cos(\beta+\rho)}{2\sin(\rho)} \right) + \left(\frac{d\sin(\beta+\rho)\tan(\beta)}{2\sin(\rho)} \right) \right) + \\ \left(\frac{c}{(\sin(\rho) + (\phi\cos(\rho)))\sin(\rho)} \right) + \left(\frac{\gamma v^2 \sin(\beta)}{(\sin(\beta+\rho))(\sin(\rho) + \phi\cos(\rho))} \right) \end{array} \right] + Kw$$

$$T_{gvdb-b} = H_{gvdb=b} \csc(\beta + \delta)$$

$$V_{gvdb-b} = H_{gvdb=b} \cot(\beta + \delta)$$



Blouin S, Hemami A, Lipsett M. Review of resistive force models for earthmoving processes. J Aerospace Eng 2001;14(3):102–11.

Gill WR, Vanden Berg GE. Soil Dynamics in Tillage and Traction. Agriculture handbook no. 316. Agricultural Research Service US Dept of Agriculture; 1968.

Luth and Wismer Sand Model

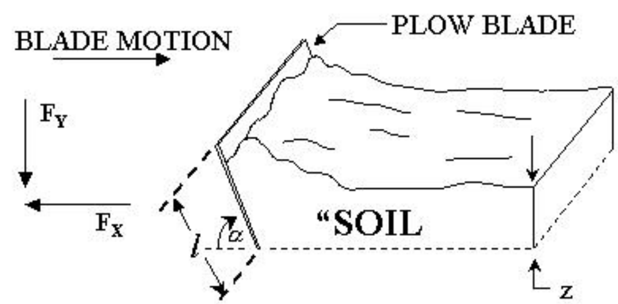
- narrow tillage tools
- based on dimensional analysis of empirical data
- no surcharge
- Separate model for clay
- measurements in sand with 30, 45, 60, 90 and 105° rake angles
- horizontal force: 48.9-N std. error, force range: 03.3 – 1334.5 N (13%)
- vertical force: 26.7-N std. error, force range: -711.7 to 556.03 N (13%)
- Used by Moore et al for Viking scoop analysis

$$H_{l\&w-sand} = \beta^{1.73}\left(\frac{d}{L\sin\alpha}\right)^{0.77}\left(1.05\left(\frac{d}{w}\right)^{1.1} + 1.26\left(\frac{v^2}{gL}\right) + 3.91\right)\gamma w d^{0.5} L^{1.5}$$

$$V_{l\&w-sand} = \left[1.93 - (\beta - 0.714)^2\right]\left(\frac{d}{L\sin\beta}\right)^{0.777}\left(1.31\left(\frac{d}{w}\right)^{0.966} + 1.43\left(\frac{v^2}{gL}\right) + 5.6\right)\gamma w d^{0.5} L^{1.5}$$

$$T_{l\&w-sand} = \sqrt{\left((H_{l\&w-sand})^2 + (V_{l\&w-sand})^2\right)}$$

ρ = DENSITY OF "SOIL"
g = ACCELERATION OF GRAVITY
b = WIDTH OF BLADE
l = HEIGHT OF BLADE
z = OPERATING DEPTH
α = BLADE ANGLE (RADIANS)
V = VELOCITY
C = COHESION



Luth HJ, Wismer RD. Performance of plane soil cutting blades in sand. Trans ASAE 1971; 255–9.

Moore Henry J, Hutton Robert E, Scott Ronald F, Spitzer Cary R and Shorthill Richard W. Surface Materials of the Viking landing Sites. J Geophysical Research 1977; 82:4497-4523.

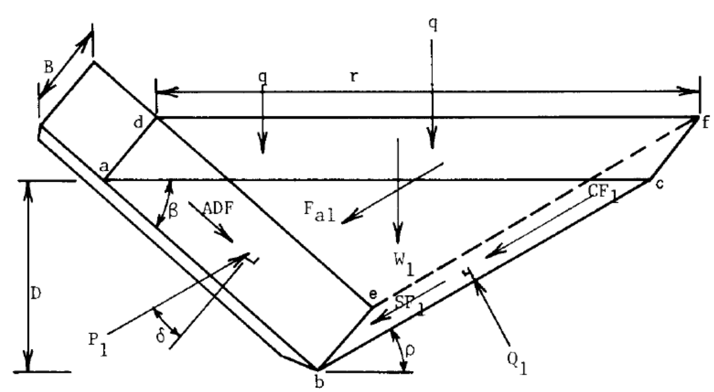
Mckyes Model

- based on Reese
- narrow tillage tools
- includes:
  - soil-tool adhesion,
  - mass,
  - inertia,
  - Surcharge
  - cohesion terms
- same results as S&P
- center and side wedges
- tested in sand and sandy loam with 1.25-25 cm blade widths, 0.25-5 width to depth ratios, from 35-63° soil failure angles, 30-90° rake angles. 14-inch blade field test matched well with predictions for rake angles of 45-60°, but 20% error at 90°.

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

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

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



McKyes E. Soil cutting and tillage. Developments in agricultural engineering, vol. 7. Amsterdam: Elsevier; 1985.

Osman Model

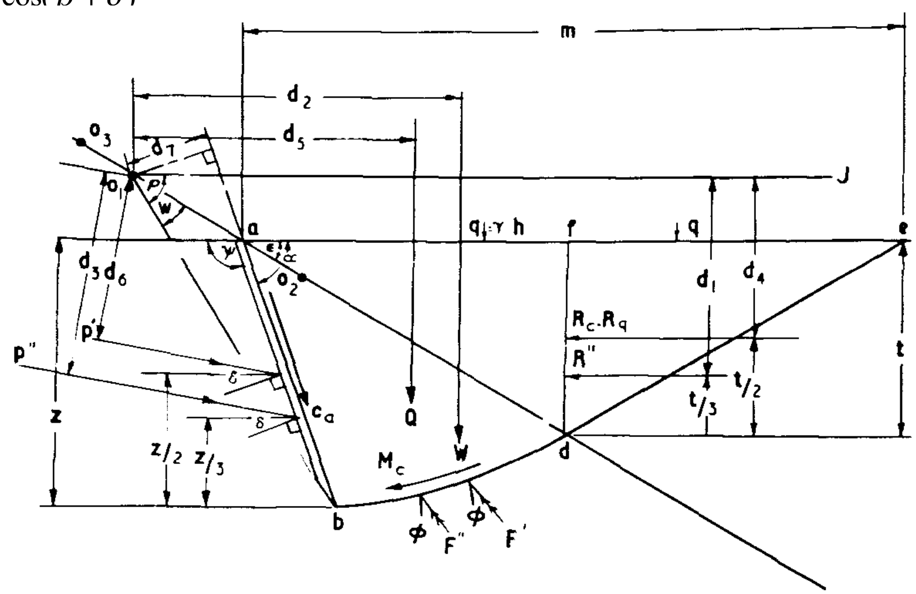
- wide blade
- surcharge is a uniform distributed pressure
- based on passive earth pressure theory
- failure surface is composed of equiangular spiral + a straight surface requiring a local minimization of $dP/d\lambda$
- measurements on 24"x4"blades, of 30, 50, 70, 90 and 105° rake angles, in sand, clay, and mixture.

$$T_{osman} = w\left[\frac{[(\frac{1}{2}g\gamma t^2(\tan(45+\frac{\phi}{2}))^2 d_1) + ((\frac{r_0{}^2}{4\tan(\phi)}g\gamma(e^{2w\tan(\phi)}-1))d_2) + ((gqt(\tan(45+\frac{\phi}{2}))^2)d_4)]}{d_3}\right] +$$

$$w\left[\frac{[((\frac{c}{2\tan(\phi)}(r_1{}^2 - r_0{}^2)) + ((2ct\sqrt{(\tan(45+\frac{\phi}{2}))^2}\,)d_4) + (x_a q g d_5) + (C_a l d_7)]}{d_6}\right]$$

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

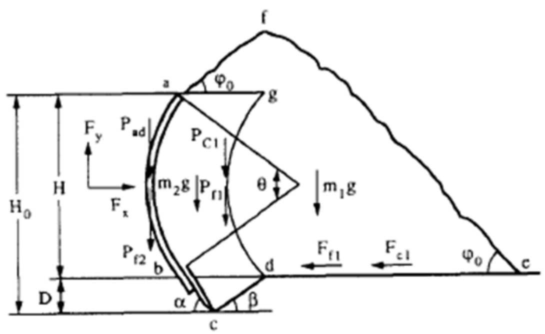
$$V_{osman} = T_{osman}\cos(\beta+\delta)$$

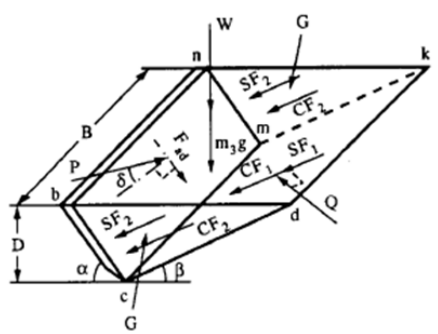


Osman M. The mechanics of soil cutting blades. J Agric Eng Res 1964; 9(4):313–28.

Qinsen and Shuren Model

- wide blade
- Model is composed of a surcharge component and a cutting component
- measurements on 389, 468 and 600-mm blade widths, 20 to 30-mm cut depths, 105 to 170-mm blade heights, of 74 to 116-mm curvature radii, and 45° rake angle in sandy clay (loess).





$$P = w \sin(\beta + \delta) - Fad \cos(\alpha + \beta + \phi) + 2 S_{F2}$$

minimize $dP/d\beta$

$$Fx = P \sin(\alpha + \delta) + F_{f1} + F_{c1}$$

$$Fy = P \cos(\alpha + \delta) - P_{f2} - P_{ad}$$

$$F_{tot} = \sqrt{F_x^2 + F_y^2}$$

surcharge component

$$F_{c1} = c_0 w(H + 2d\tan(\phi_0))\cot(\phi_0)$$

$$m_{1g} = 0.5\gamma_0 w(H + 2d\tan(\phi_0))^2 \cot(\phi_0)$$

$$F_{f1} = m_{1g}\tan(\phi)$$

$$P_{f1} = (F_{f1} + F_{c1})\tan(\phi)$$

$$P_{f2} = (F_{f1} + F_{c1})\tan(\delta)$$

$$m_{2g} = \gamma_0 wH2d$$

$$P_{c1} = c_0 wR\theta$$

$$P_{ad} = C_a wR\theta$$

cutting component

$$G = \frac{1}{3}\gamma d(1 - \sin(\phi))\frac{1}{2}d^2(\cot(\alpha) + \cot(\beta))$$

$$m_{3g} = \frac{1}{2}\gamma wd^2(\cot(\alpha) + \cot(\beta))$$

$$C_{F1} = \frac{cwd}{\sin(\beta)}$$

$$C_{F2} = \frac{1}{2}cd^2(\cot(\alpha) + \cot(\beta))$$

$$S_{F2} = G\tan(\phi)$$

$$S_{F1} = Q\tan(\phi)$$

$$F_{ad} = \frac{ad * wd}{\sin(\alpha)}$$

Qinsen Y Shuren S. A soil-tool interaction model for bulldozer blades. J Terramech 1994; 31(2):55–65.

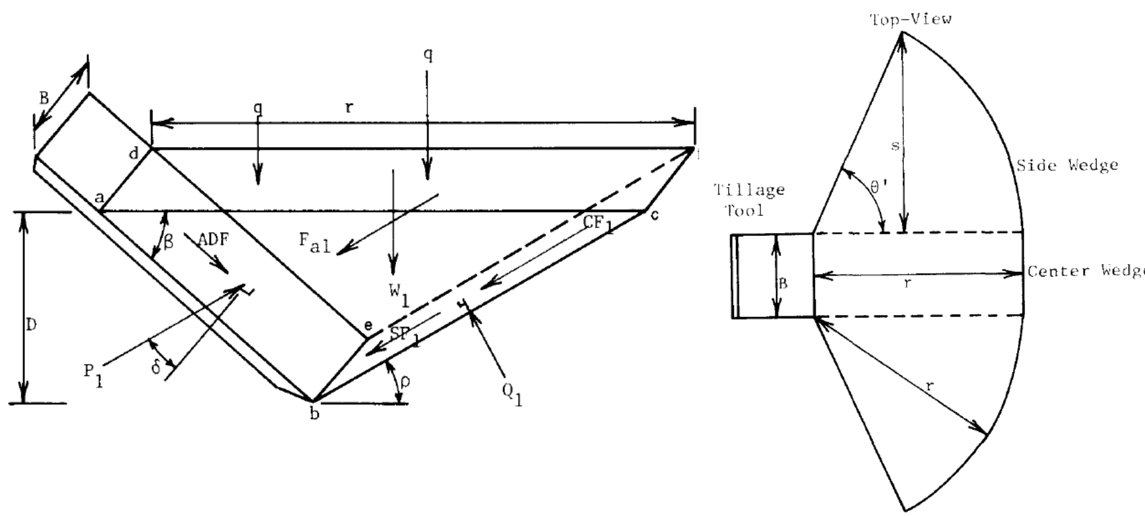
Swick and Perumpral Model

- narrow tillage tools
- includes:
  - soil-tool adhesion,
  - mass,
  - inertia,
  - surcharge
  - cohesion terms
- same results as McKyes
- center and side wedges
- tested in soil-clay mix with 2.5, 5.1, 7.6 and 10.2-cm tool widths; of 5.1, 10.2 and 15.2-cm tool depths; of 60, 75 and 90° rake angles, and 5.4, 33.1, 67.1 and 120-cm/s tool-speeds

$$T_{sw\&p} = \left(\frac{wd}{\sin(\beta+\phi+\rho+\delta)}\right)\left[\begin{array}{l}\left(\frac{-C_a\cos(\beta+\phi+\rho)}{\sin(\beta)}\right)+\left(\frac{g\gamma d}{2}(\cot(\beta)+\cot(\rho))(\sin(\phi+\rho))\right) \\ +\left(gq(\cot(\beta)+\cot(\rho))\sin(\phi+\rho)\right)+\left(\frac{c\cos(\phi)}{\sin(\rho)}\right)+ \\ \left(\frac{\gamma v^2\sin(\beta)\cos(\phi)}{\sin(\beta+\rho)}\right)\end{array}\right]$$

$$H_{sw\&p} = T_{sw\&p}\sin(\beta+\delta)$$

$$V_{sw\&p} = T_{sw\&p}\cos(\beta+\delta)$$



Swick WC, Perumpral JV. A model for predicting soil–tool interaction. J Terramech 1988;25(1):43–56.

Zeng Model

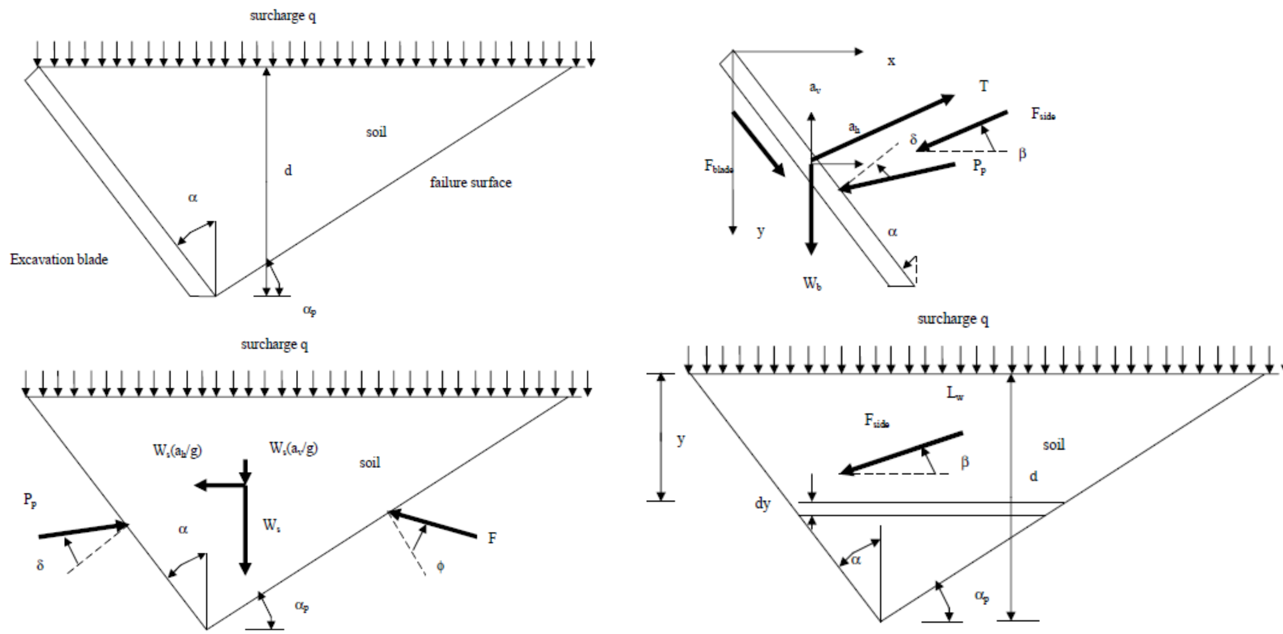
Includes:
- dynamic earth pressure,
- side friction,
- surcharge,
- blade friction,
- weight of the blade,
- blade acceleration

$$T_{zeng} = \sqrt{\left((H_{zeng})^2 + (V_{zeng})^2\right)}$$

$$H_{zeng} = -wF_{blade}\sin(90-\beta) + wP_p\cos(90-\beta-\delta) + F_{side}\cos(\phi+\delta) + (W_b)a_h$$

$$V_{zeng} = wF_{blade}\cos(90-\beta) + W_b + wP_p\sin(90-\beta-\delta) + F_{side}\sin(\phi+\delta) + (W_b)a_v$$

$$P_p = 0.5K_{PE}(1+\frac{a_v}{g})\gamma g d^2 L + 2cdL\sqrt{K_{PE}} + K_{PE}qgdL$$



Zeng X, Burnoski L, Agui JH, Wilkinson A. Calculation of excavation force for isru on lunar surface. In: 45th AIAA Aerospace Science Meeting and Exhibit, American Institute of Astronautics and Aeronautics;2007.

Comparison of included variables across models

Common to all models: rake angle (*β*), soil density (*γ*), and tool width (*w*)

Common except L&W: Cohesion (*c*), internal friction angle (*φ*), external friction angle (*δ*)

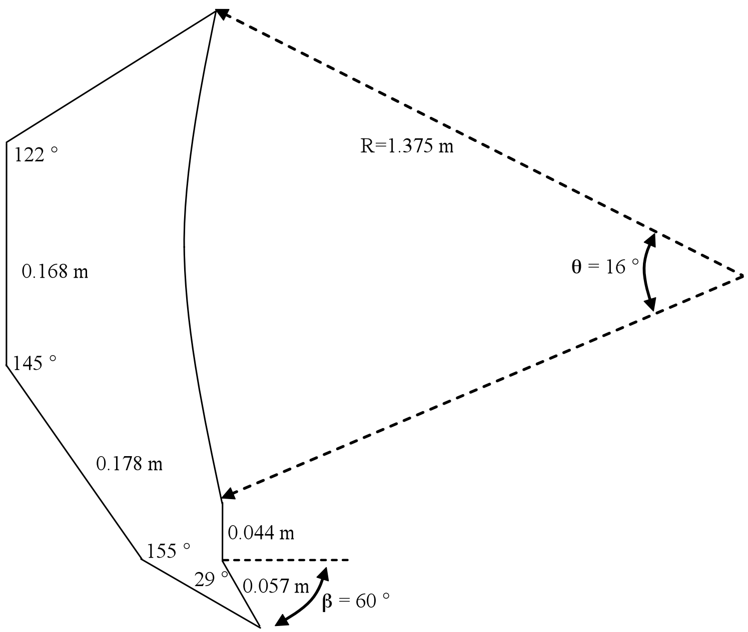
description	unit	variable	Osman	Gill & vdBerg / Blouin	swick & perumpral	McKyes	L&W sand	Balovnev bulldozer	Zeng	Qinsen & Shuren
horizontal acceleration	m/s2	a_h							x	
vertical acceleration	m/s2	a_v							x	
rake angle from horizontal	degrees	β	x	x	x	x	x	x	x	x
length of blade beneath soil surface	m	bladelength	x							
cohesion	kN/m2	c	x	x	x	x		x	x	x
cohesion after cutting	kN/m2	c_0								x
soil-tool adhesion	kN/m2	C_a	x		x	x				x
cutting depth	m	d		x	x	x	x	x	x	x
interface angle of friction	degrees	δ	x	x	x	x		x	x	x
acceleration of gravity	m/s2	g	x	x	x	x	x	x	x	
soil unit density	kg/m3	γ	x	x	x	x	x	x	x	x
soil unit density after cutting	kg/m3	γ_1						x		x
coefficient of passive earth pressure		K_0							x	
tool length	m	L		x			x			x
friction angle after cutting	degrees	ϕ_0								x
internal angle of friction	degrees	ϕ	x	x	x	x		x	x	x
surcharge	kg/m2	q	x		x	x			x	x
blade radius of curvature	m	R								x
angle of failure plane from horizontal	degrees	ρ		x	x	x				x
part of circle, curved blade	degrees	θ								x
tool height above soil surface	m	toolheight						x		
blade forward speed	m/s	v		x	x	x	x			
blade width	m	w	x	x	x	x	x	x	x	x
blade mass	kg	W_b							x	

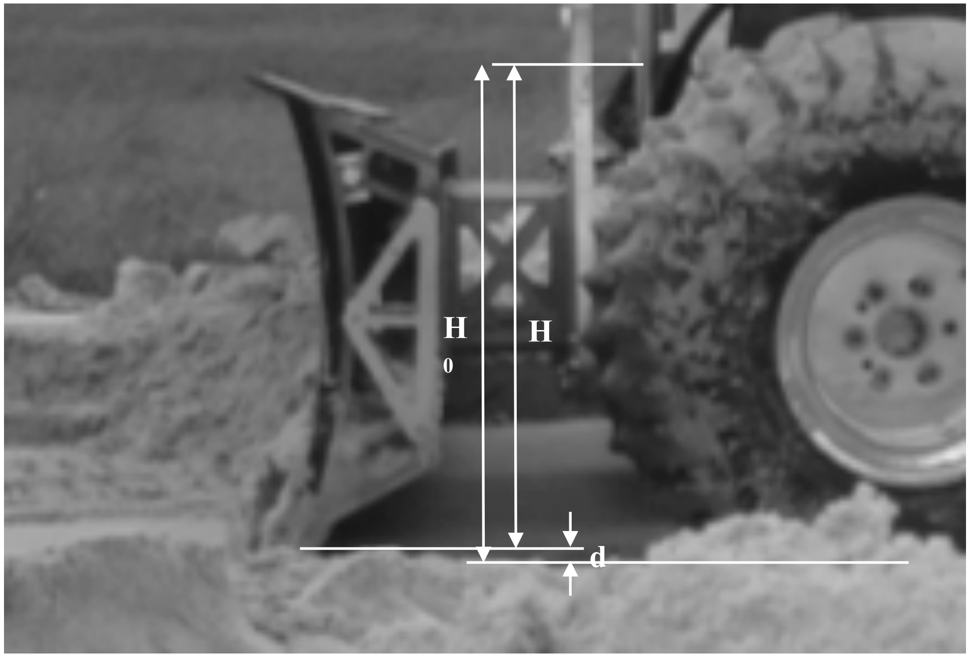
There are a variety of simulants and some geotechnical properties are not known with high degree of confidence so the program evaluates forces over a range of values for each property

	Int friction angle			Ext friction angle			Bulk Density			Cohesion			Adhesion		
	ϕ (deg)			δ (deg)			γ (g/cm^3)			c (kPa)			c_a (kPa)		
	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

Carrier III WD, Olhoeft GR, Mendell W. Physical properties of the lunar surface., Chapter 9, The Lunar Sourcebook, Heiken, Vaniman, and French, Eds. NY: Cambridge University Press; 1991.
King RH, van Susante P. Geotechnical properties of the JSC1-A lunar simulant. Paper 5-6, Planetary and Terrestrial Mining Symposium, June 10-13, Sudbury, Ont; 2007
McKay David S, Carter James L, Boles Walter W, Allen Carlton C, Allton Judith H. JSC-1: A new lunar soil simulant. In: Engineering, Construction, and Operations in Space IV, ASCE; 1994: 857-866.
Zeng X, et al. Geotechnical properties of JSC-1A lunar soil simulant. J Aerospace Engineering, 2010; 23(2):111-116

The LANCE blade geometry



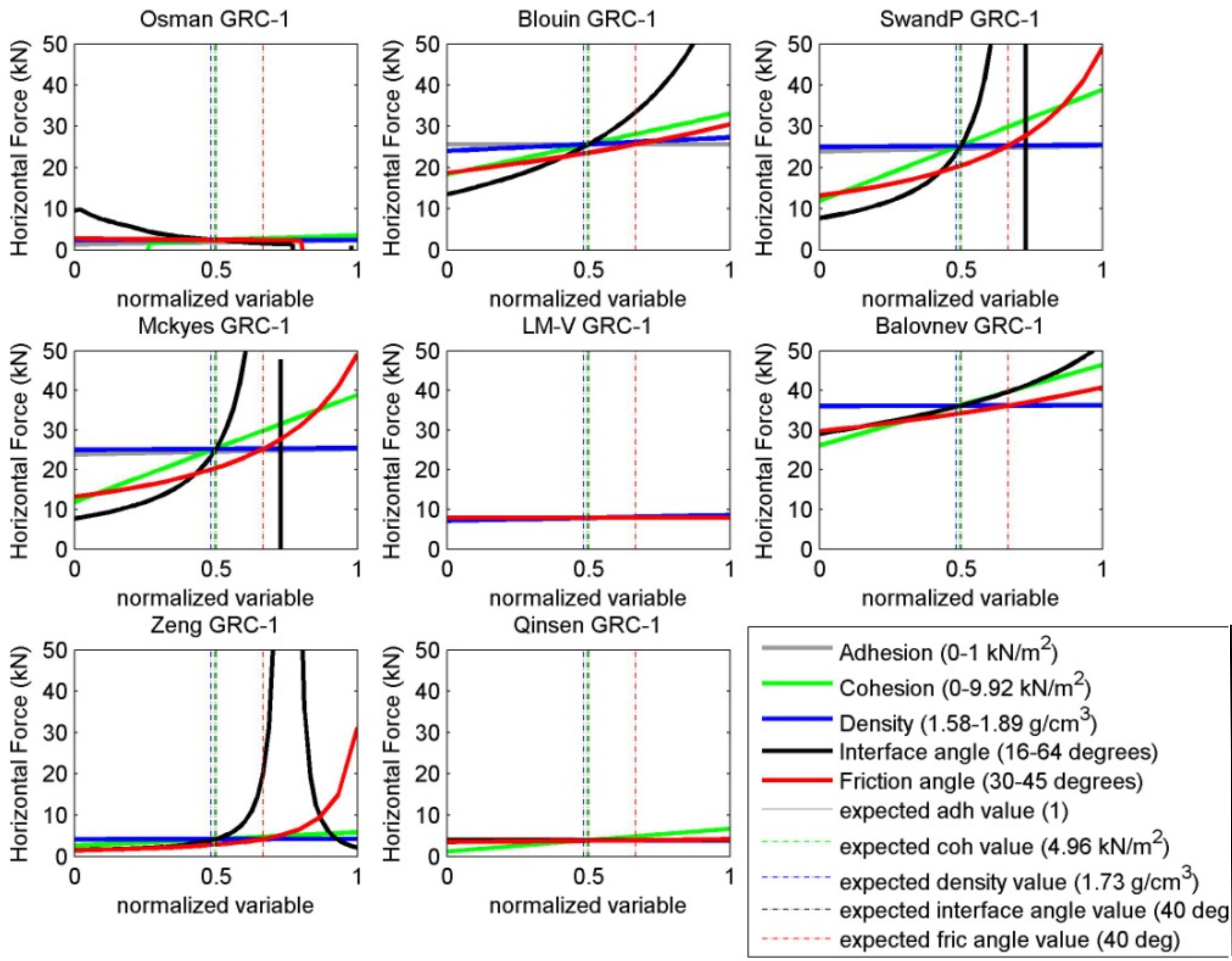


Example values for one scenario

name	value	description
gmoon	1.63	moon gravity (m/s^2)
gearth	9.81	earth gravity (m/s^2)
W	4.1148	toolwidth (m)
L	0.51054	% tool length (m)
toolheight	0.5	tool height above top of soil cutting level (m)
D	0.077	tool depth (m)
Ls	0.51054	side length (m)
S	0.005	side thickness (m)
Eb	0.0127	edge thickness (m)
V	0.2	tool speed (m/s)
alphaBdeg	29	blunt edge angle (degrees)
deltadeg	40	external friction angle (tool-soil) (degrees)
betadeg	60	rake angle (degrees)
rhodeg	30	shear plane failure angle (degrees)
phideg	40	internal angle of friction (soil-soil) (degrees)
BURIED	0	1=true (buried) , 0=false (not buried)
C	4950	cohesion (N/m^2)
gamma	1730	bulk density (kg/m^3)
gamma1	1500	bulk density of broken soil (kg/m^3)
Q	200	surcharge mass (kg/m^2)
Ca	1000	soil-tool adhesion (N/m^2
N0	1000	soil-tool normal force (N)
K	1000	Gill's cut resistance (N/m)
Ah	0	horizontal blade acceleration
Av	0	vertical blade acceleration
K0	0.573	coefficient of passive earth pressure
massblade	1000	mass of the blade in kg
R	54.15*2.54/100	radius of curvature of blade (m)
theta	17	angle of curvature of blade (degrees)
C0	0	cohesion of cut soil
Phi0	35	angle of accumulation of cut soil

Graphs of a subset of results: each graph represents horizontal force predicted by one of the models

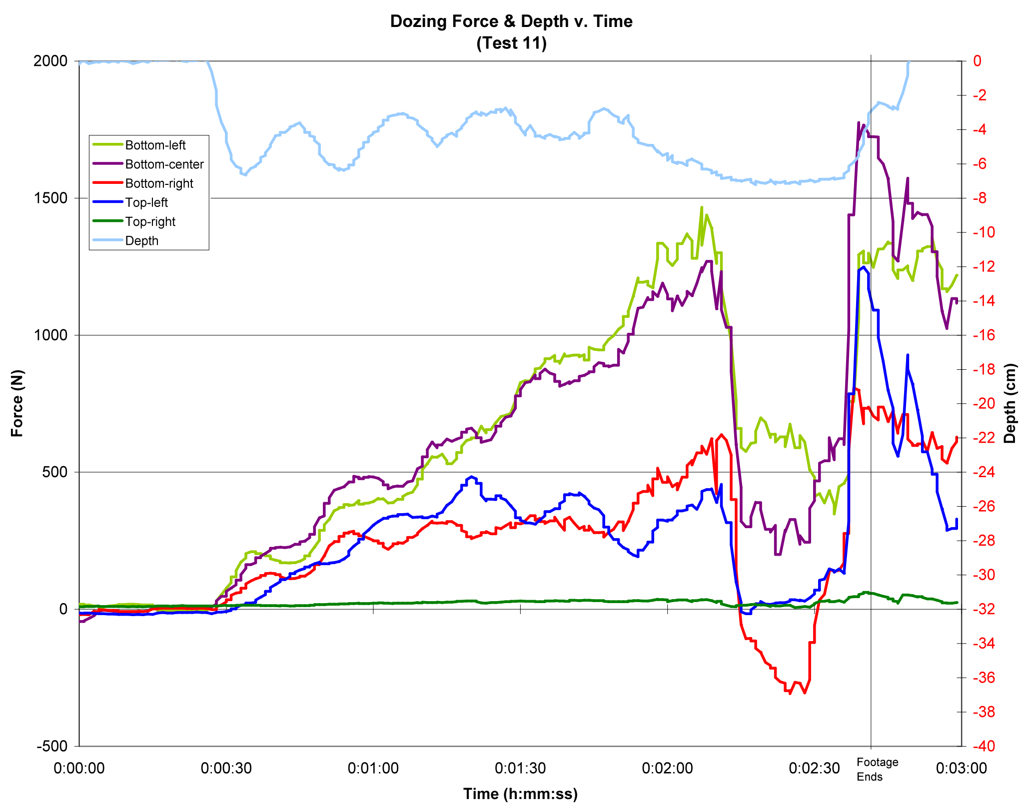
Example: ϕ varied from 30 to 45° while the other variables remained constant at expected values: δ = 40°, γ = 1.73 g/cm3, c = 4.96 kPa, and ca = 1 kPa.

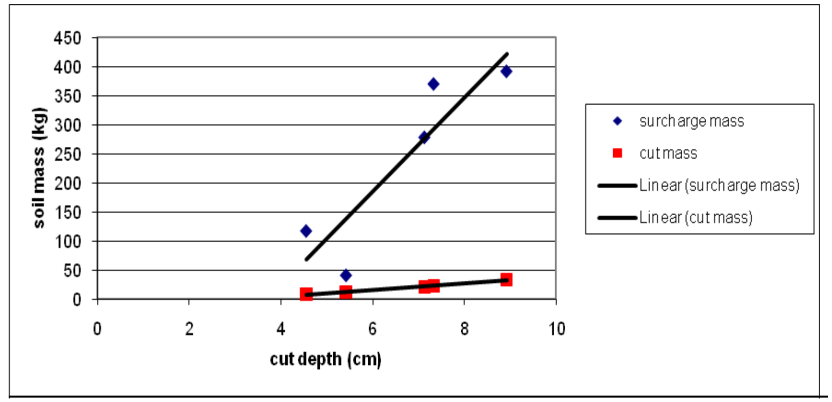


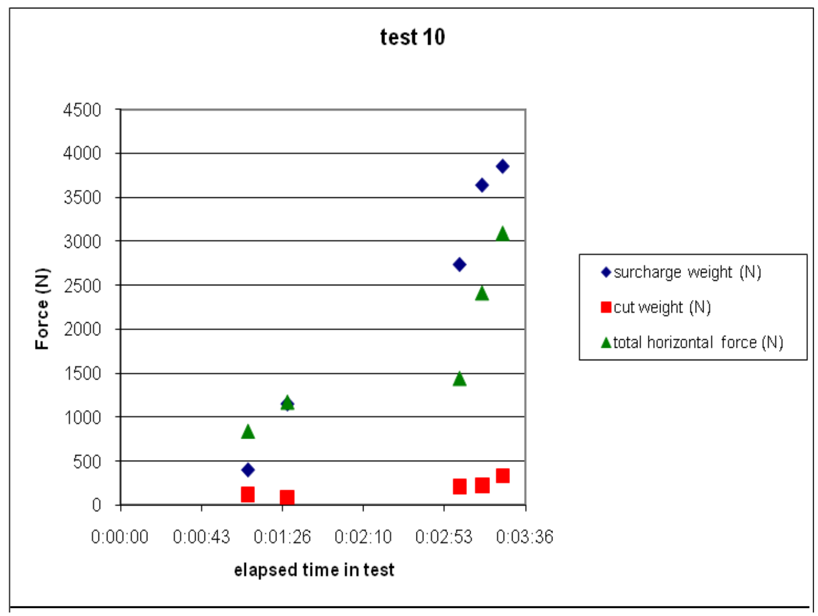
The maximum depths of cut from the Chariot 22.241 kN (5000-lbf) tractive effort in different materials as predicted by different models

	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
Ottawa sand	25.4	21.7	35	35	22.5	>>30	38	>>30
Quarry sand	20.5	9	12	12	18	15.5	24	>>30

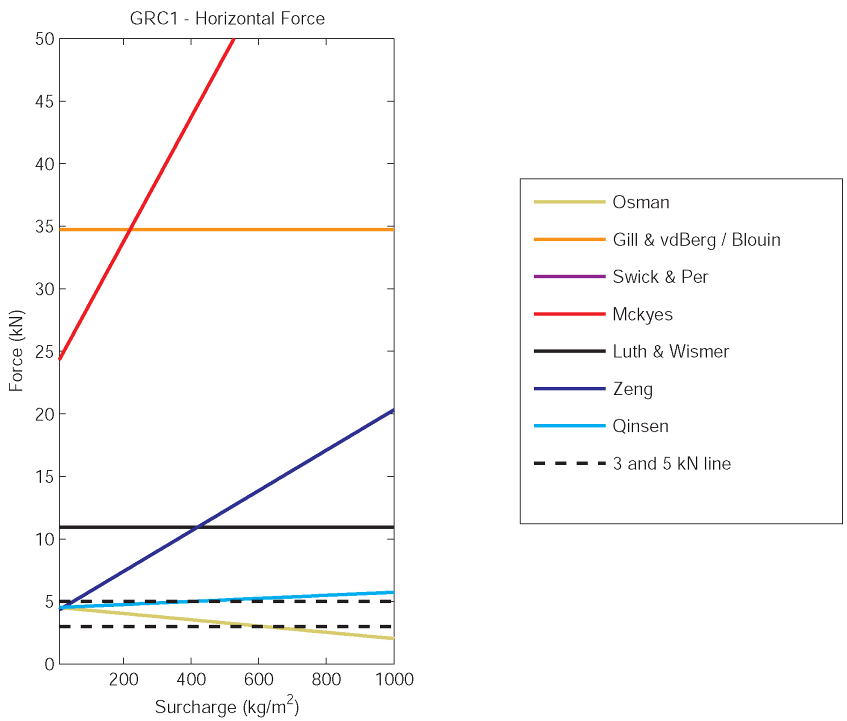
Data showed that surcharge increase has a significant influence on horizontal force.

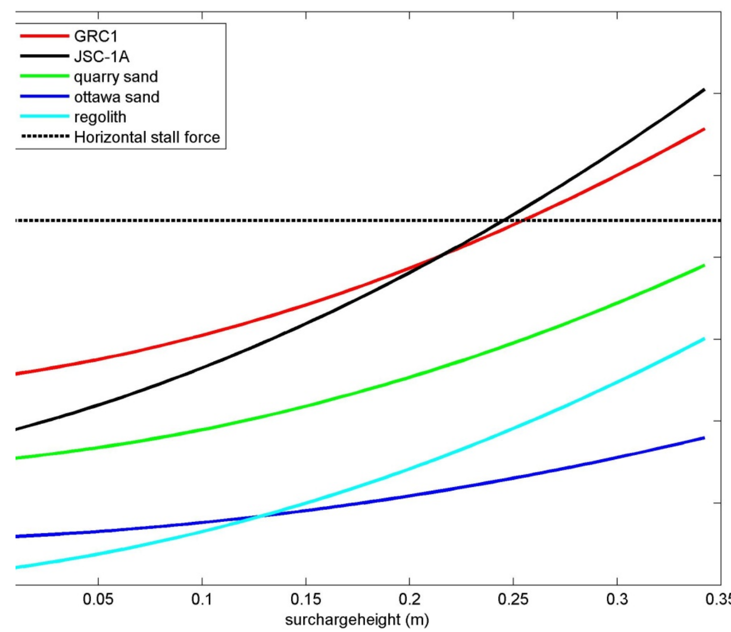






Horizontal force increases with surcharge in some models





McKyes, Osman, Qinsen & Shuren, and Zeng have separate terms for surcharge

Balovnev requires the blade height to increase to calculate effect of surcharge increase

Models fell within 3 groups based on ability to fit LANCE data.

Criteria / Models	Surcharge included in model	Model behavior over range of soil properties	Other observations	Ranking for bulldozer model consideration
Qinsen & Shuren	Yes	Best fit with chariot data		High
Balovnev	Yes	Good fit, including surcharge		High
Zeng	Yes	Asymptotic behavior occurs, but good fit otherwise		High
Osman	Yes	Unstable behavior, but good values when stable	Difficult to automate algorithm for complex geometric math problem	Medium
Swick & P	Yes	Asymptotic behavior occurs		Medium
McKyes	Yes	Asymptotic behavior occurs		Medium
L&W sand	No	Not dependent on important parameters		low
Gill & vdB / Blouin	No	No surcharge		Low

Recommendations

1. Better knowledge of the geotechnical properties of extraterrestrial bodies of interest.
2. An improved and broader suite of simulants that better mimic the geotechnical properties of extraterrestrial bodies.
3. Geotechnical property values of simulants from multiple qualified, standard laboratories including values for additional properties needed for FEA and DEM
4. Laboratory-controlled force data sets for comparing models
5. Controlled force data sets over a range of blade sizes
6. Extend the current models to distributed force/pressure models for FEA of stress and displacement in blades
7. Distributed force/pressure data sets over a range of blade sizes in controlled conditions
8. Force and simulant property measurements in vacuum, low G, and low temperature