**FINITE ELEMENT METHOD TO CALCULATE FORCES AND STRESSES ON BLADES EXCAVATING LUNAR SIMULANTS**. P. J. van Susante[1], R. H. King[2], [1]EG Division, CSM, 269 Brown Hall, Golden, CO 80401, paulvans@mines.edu, [2]EG Division, CSM, Golden, CO 80401.

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**Introduction:** Operations on the moon, Mars, or asteroids could require telerobotic, autonomous, or manned machines to excavate soil or regolith. Designing reliable soil handing machines requires estimating the stresses and strains caused by the forces experienced during excavation. Blades could be a prominent tool for lunar, Martian, or asteroid soil handling. Analytical models that are available in the literature are limited to estimates of total force and simple geometries as well as simple constitutive models to describe the material behavior. Finite Element Analysis (FEA) allows for the calculation of total forces, force and stress distributions on the blade, using virtually any geometry. In addition, a variation with time is possible. A FEA model was generated simulating a bulldozer blade operating in lunar simulant. Results will be presented comparing FEA model results to analytical models as well as data gathered with NASA's Chariot rover outfitted with the LANCE blade as shown in Figure 1.

Figure 1: LANCE blade attached to the LER pushing GRC-1 lunar simulant

**Analytical models:** Many analytical models exist to calculate excavation forces using a tine or a blade. The most well known models include those by Balovnev [1], Osman [2], Reece [3], Luth and Wismer [4], McKyes [5], Swick and Perumpral [6], Qinsen and Shuren [7], Zeng et al. [8] and Each model is slightly different from the others. Some have a different failure surface, some have different parameter definitions and some include surcharge whereas others do not. An example of a general blade excavation geometry can be seen in Figure 2 where L is the length of the blade in the soil, d is the depth of cut, $\beta$ is the cutting angle, $\rho$ is the angle of the failure surface in the soil and q is the amount of surcharge applied.

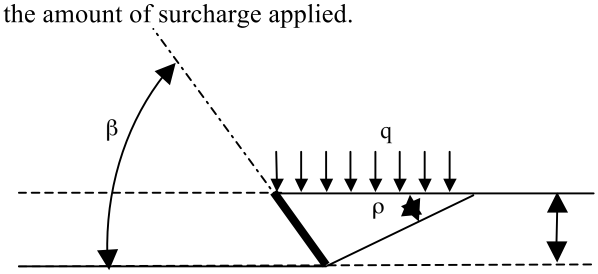


Figure 2: general blade excavation geometry

These analytical models calculate a steady state maximum horizontal and vertical excavation force for the defined geometry. For design of planetary excavation tools more information is needed to optimize the design of the blade and excavators to limit the mass of the total excavation system.

**FEA:** FEA is applied to find forces and stress distributions on the blade while excavating. Different blade geometries also can be tested. Both the analytical models and the FEA models require input in the form of geometry parameters and material properties of the soil. It is important to realize that soil is a material that has great variation and in-situ has a range of values for its mechanical properties. In the available literature, a significant range of values was reported for the major soil mechanics properties such as friction angle, cohesion, bulk density, external friction angle and adhesion. FEA requires the definition of a constitutive model describing the material behavior under various conditions. Because lunar regolith and lunar simulants are a dry granular material, the Drucker Prager extended constitutive model was used with the following inputs to model JSC-1A:

$\gamma$=1800 kg/m$^3$
DP angle of friction= 55.6 degrees
DP Flowstress ratio (K) = 0.79
DP Dilation Angle = 15 degrees
E=36 MPa
$\nu$=0.3

The Drucker-Prager extended model requires the definition of material hardening/softening for the plastic range. The values which were determined from triaxial tests can be found in Table 1. A commercially available FEA software package named ABAQUS was chosen to perform the simulations. First some 2D models were setup to test different approaches to the problem.

Table 1: JSC-1A hardening values for input in the Abaqus extended DP model

| hardening profile | |
|---|---|
| yield stress (kPa) | absolute plastic strain |
| 25 | 0 |
| 70 | 0.027 |
| 150 | 0.028 |

Figure 3 shows the different bodies that interact to model a blade cutting soil and pushing already cut soil. After a final model setup was chosen, a full scale 3D FEA model of one side of the blade was setup due to symmetry, as shown in Figure 4.

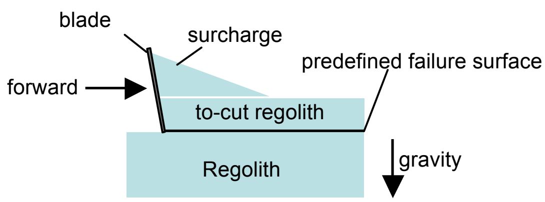


Figure 3: Basic FEA model setup showing the different bodies that interact.

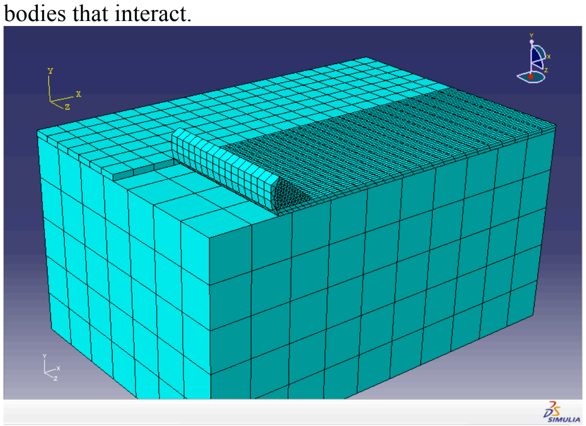

Figure 4: Full scale 3D half model due to symmetry

**Results:** Using the full scale model stress distributions occuring in the blade and soil can be seen in Figure 5. The maximum stress occurs close to the edge of the blade. The horizontal force on the blade calculated with this FEA model is plotted in Figure 6 where it is compared to Chariot data and analytical model results. The Chariot data has different surcharges for the three different depths and thus the trend is odd. However, the FEA results, the data and several of the analytical models are in the same ballpark.

**References:**[1] Balovnev V.I. (1963) New methods for calculating resistance to cutting of soil. Amerind Publishing (Translation),Available from National Technical Information Service, Springfield, VA 22161, 1983 and 1963, respectively. 39180-6199, 1992.

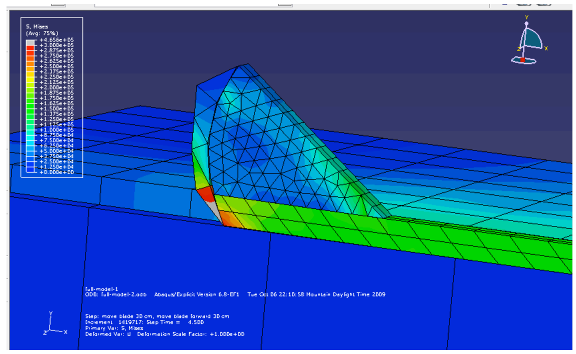

Figure 5: stress distribution on a cross section of the blade and soil close to the edge of the blade.

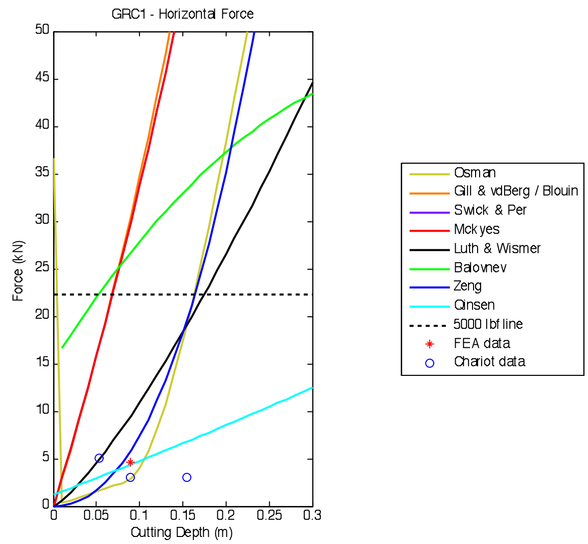


Figure 6: Horizontal forces measured with the Chariot while bulldozing GRC-1, analytical and FEA model results.

[2] Osman, M. S. (1964). “The mechanics of soil cutting blades.” *J. Agric. Eng. Res.*, 9(4), 313–328. [3] Reece, A. R. (1965). “The fundamental equation of earth-moving mechanics.” *Symp. on Earth-moving machinery, Proc., Instn. Of Mech. Engrs.*, 179(3F), London, UK., 16–22. [4] Luth, H. J., and Wismer, R. D. (1971). “Performance of plane soil cutting blades in sand.” *Trans ASAE*, 14, 255 – 262. [5] McKyes, E. (1985). *Soil cutting and tillage*, Elsevier, New York, NY. [6] Swick, W. C., and Perumpral, J. V. (1988). “A model for predicting soil/tool interaction.” *J. Terramechanics*, 25(1), 43–56. [7] Qinsen, Y. and Shuren, (1994) S., A soil-tool interaction model for bulldozer blades. J. Terramechanics, Vol. 32, issue 2 [8] Zeng, X., He, C., Oravec, H., Wilkinson, A., Agui, J., and Asnani, V. (2008). “Geotechnical Properties of JSC-1A Lunar Soil Simulant.” NASA Glenn Research Center Report, Cleveland, OH.