



Modeling the effects of surcharge accumulation on terrestrial and planetary wide-blade soil–tillage tool interactions

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ABSTRACT

Several experimental results in the literature demonstrate that tillage and excavation forces increase dramatically as soil accumulates ahead of a cutting blade, however these effects are not always modeled; when they are added to classical models, they are included as a surcharge force without consideration of the soil properties of the piled soil, other than mass. This work introduces a modified McKyes excavation cutting model, that takes into account the friction angle and cohesion of the piled soil when computing the failure plane of a cut. Simulation results show that this new model replicates the decreasing failure plane angles, as a cut proceeds, observed in experimental and Discrete Element Model (DEM) results in the literature. Simulations at 1g and 1/6g gravity, with various levels of cohesion, show that excavation forces due to soil accumulation are especially sensitive to cohesion in planetary excavation. These results elaborate on prior work in the literature showing that cohesion plays an important role when soil accumulation is not considered. Modeling such aspects of excavation without resorting to computationally-intensive DEM is especially useful in autonomous terrestrial excavators that must model and plan cutting in real-time or in planetary excavators where computing power is limited.

1. Introduction

The modeling of soil–tool interactions is important for successful excavation and tilling tasks both terrestrially as well as in planetary missions. On Earth, mining, agriculture, and construction are subject to increasing optimization and automation, whereas in space challenging new tasks like in situ resource utilization (ISRU) will require efficient tools tailored to extreme conditions as well as intelligent planning and control algorithms. The canonical modeling problem for such tasks is the cutting problem, in which an angled tool (e.g. bucket or blade) is moved horizontally through the soil (Hettiaratchi et al., 1966; Blouin et al., 2001; Shmulevich et al., 2007) and forces are predicted based on parameters of both the tool and the soil. This problem is directly relevant to tillage and scraping in terrestrial applications, as well as planetary excavation on the Moon or Mars.

Scrapers, described directly by the soil cutting problem, are very commonly proposed for planetary excavation and ISRU. Example prototypes include NASA's Cratos (Caruso et al., 2008), an open bowl scraper with a central bucket between its tracks, as well as NASA's Chariot with LANCE bulldozer blade (King et al., 2010). Juno rovers (Theiss et al., 2010) have been equipped with a load-haul-dump bucket, though the fact that cut depth is the only controllable degree of freedom (DOF) makes it effectively a discrete scraper. NASA's Centaur 2 has been equipped with a full 2-DOF front-loader bucket, but experiments

have exclusively involved horizontal cutting at set depths and cutting angles (Johnson et al., 2012). It is noteworthy that even configurations capable of more complex excavation have only been used as scrapers in the planetary excavation literature to date.

Modeling of soil cutting typically takes the form of either classical terramechanical models, discussed further below, or discrete element method (DEM) models (Shmulevich, 2010; Tsuji et al., 2012). DEM has risen in prominence and use as it has demonstrated success in capturing complex aspects of excavation and as the availability of computing resources has grown. DEM is an inherently computationally intensive approach, as it models soil interactions on a particle-by-particle basis. There is still an important place for classical terramechanical models, though, that thanks to generalizations greatly simplify the required computations. Such rapidly computable models are especially useful in planetary excavators where computing power is limited or in autonomous terrestrial excavators that must model and plan cutting in real-time.

With classical terramechanical modeling of the soil cutting problem thus motivated, this paper proceeds as follows: Section 1.1 provides an overview of classical cutting models and highlights a major shortcoming of such models as presently used, namely the lack of proper surcharge modeling; Section 2 then develops a modified classical model that explicitly accounts for surcharge in order to address this shortcoming, as confirmed with computed examples in Section 3; Section 4

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demonstrates how this new approach can be used to better understand and predict the effects of reduced gravity (i.e. planetary environments) on excavation forces, and conclusions are then summarized in Section 5.

1.1. Background literature

The mechanics of excavation are typically modeled based on the principles of passive earth pressure, adapted from the design of retaining walls. Hettiaratchi et al. (1966) present the following as the fundamental equation of earthmoving mechanics:

$$P_{Ex} = N_f \gamma g d^2 + N_c c d + N_q q d + N_a C_a d \quad (1)$$

where P_{Ex} is excavation resistance force per unit width, and the four terms of the summation represent (in order) forces due to frictional shearing (i.e. gravity), cohesion, surcharge, and soil–tool adhesion. Inertial forces are explicitly ignored, as low cutting speed is assumed. The N_i are non-dimensional coefficients pertaining to each of the four sources of force, respectively. Gravitational acceleration is denoted g , γ is soil dry bulk density, d is cut depth, c is cohesion, q is surcharge pressure, and C_a is soil–tool adhesion. The equation is for cutting with a flat plate. As this is a two-dimensional formulation, a first order estimate of excavation resistance force for a cut of finite width can be made by multiplying by said width, w :

$$F_{Ex} = w P_{Ex} \quad (2)$$

A wide variety of models have been investigated for their potential applicability to planetary excavation (Willman, 1994; Wilkinson and DeGennaro, 2007; King et al., 2010; Gallo et al., 2010). However, at their root, they are all just variations of the fundamental equation (1) (with the possible exception of Luth and Wismer (1971), a purely empirical model). Models vary in which force terms they do and don't include. Several models omit tool–soil adhesion and/or surcharge forces. Some include inertial forces, which Reece explicitly omitted. Table 1 lists the array of models and shows which force terms they include. Additionally, the models vary in their definitions of the N_i coefficients.

Gravity and cohesion forces. Excavation shears soil, and a soil's shear strength is governed by its internal friction angle and cohesion. These shear strength contributions are modeled for excavation resistance by gravity and cohesion terms, respectively. All the models listed in Table 1 include at least some form of these two terms, implying that their contribution to total excavation resistance is of primary importance. In fact, Wilkinson and DeGennaro (2007) show that for the Swick model (Swick and Perumpral, 1988), a model that includes all

five typical terms, the gravity term (referred to as the depth term in their paper) and/or cohesion are the dominant contributions to total excavation resistance force over a very broad range of operating conditions.

Adhesion and inertial forces. Compared to gravity and cohesion, adhesion and inertial forces tend to have minimal contribution to excavation resistance force. Hettiaratchi et al. (1966) note that the N_a coefficient (for adhesion) is small compared to the other N_i and that soil–tool adhesion is almost always smaller than cohesion; they neglect inertial forces outright, arguing that cutting speeds are typically low. Table 1 shows that adhesion and inertial terms are the two most often omitted from excavation resistance force models.

Surcharge forces due to soil accumulation. Accumulated soil increases the resistance faced by subsequent soil being cut or collected. As a cut proceeds and soil accumulates, excavation forces thus rise. This rise in excavation force is clearly demonstrated in the experiments conducted by Agui and Wilkinson (2010) as well as those by King et al. (2010). Excavation forces in their experiments increase several times over throughout a cut, meaning the forces due to soil accumulation rise to the point where they dwarf the other contributions (i.e., from initial friction and cohesion shearing). Accurate excavation force modeling thus cannot neglect this major, even primary, contribution.

One direct effect of soil accumulation on excavation force is an increase in surcharge (q in Eq. (1)), i.e. weight pressing down on the soil currently being cut. Another, less direct, effect is that the soil failure surface changes. Experiments by Shmulevich et al. (2007) show that failure planes get shallower as a cut proceeds and soil accumulates at the front of the cutting blade. The weakest failure surface may not pass through the accumulated pile of soil, so as more soil accumulates the failure plane may shift forward, avoiding the pile. Inspecting the experimental photographs published by Shmulevich suggests this is indeed the case, at least in some particular circumstances. These two effects have been considered separately in prior literature, but have not been combined comprehensively to date. Shmulevich et al. (2007) as well as by Kobayashi et al. (2006) model increasing surcharge with cut length, as shown below, but assume the subsurface failure plane remains constant. Qinsen and Shuren (1994) account for accumulated soil directly and include its effect on the failure plane; however, they model forces already at steady state once soil accumulation has reached maximum extent, not during the accumulation phase itself. Their model is also tailored specifically to curved bulldozer blades, making it more geometrically complex than is necessary for the general case.

Shmulevich et al. (2007) model changing surcharge with cut length in the form:

$$q \propto \gamma g x \quad (3)$$

where x is cut advance distance (and γ is soil dry bulk density). Kobayashi et al. (2006), making different assumptions about the shape of the accumulating pile, propose $q \propto \gamma g \sqrt{x d}$ where d is cut depth. In both cases, surcharge increases with cut advance distance, linearly in the former and as the square root in the latter. As discussed above, in both these cases the surcharge force is assumed to be only due to the additional weight causing increased frictional shearing.

To be consistent with all the experimental results discussed above, a model needs to capture both the increasing excavation force and decreasing soil failure angle as a function of cut length.

2. Development of modified classical cutting model

The development of a new soil cutting model is undertaken here, based on a modification of the popular McKyes model (McKyes and Ali, 1977). This base model is selected based on its “simplicity and common use” (Shmulevich et al., 2007; Onwualu and Watts, 1998). It assumes a simplified failure surface, using a plane rather than a log-spiral shaped surface; it has been shown that this is a reasonable approximation in practical situations (McKyes and Ali, 1977).

Table 1

Models vary in which force terms they include, but gravity and cohesion are always considered.

Model	Gravity	Cohesion	Surcharge	Adhesion	Inertia
Reece	✓	✓	✓	✓	
Osman	✓	✓	✓	✓	
Gill	✓	✓			✓
Luth and Wismer	✓	~ ^a			~ ^a
Godwin	✓	✓	✓	✓	
Balovnev ^b	✓	✓	✓		
McKyes	✓	✓	✓		
Swick	✓	✓	✓	✓	✓
Qinsen	✓	✓	✓ ^c	✓	
Willman	✓	✓			
Zeng	✓	✓	✓		~ ^d

^a In Luth and Wismer, cohesion and inertia terms are multiplied by gravity terms, rather than added to them.

^b Balovnev includes additional terms to account for sidewalls and a blunt cutting edge.

^c Qinsen models a curved bulldozer blade, and explicitly models surcharge due to accumulated soil.

^d Zeng treats acceleration directly, rather than inertia.

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