Earthmoving through the lens of geotechnical engineering

Le terrassement à travers la lunette du génie géotechnique

James Hambleton
Department of Civil and Environmental Engineering, Northwestern University, USA, jphambleton@northwestern.edu

ABSTRACT: Earthmoving machines of varying sophistication, ranging from the simple garden spade to the hydraulic excavator, have evolved considerably over the centuries, but the scientific understanding of earthmoving processes lags considerably behind the technology. Historically much effort has been directed towards aspects of the machine, whereas relatively little attention has been given to the soil. For this reason, the problem has primarily engaged the interest of mechanical engineers. This paper provides a brief overview of the state of the art in analytical and numerical modeling, as well as some of the significant challenges that have yet to be overcome. It concludes with a description of the research program at Northwestern University, which includes analytical and numerical modeling of earthmoving processes and experiments completed using a new experimental facility. The preliminary results shown in the paper highlight key features of earthmoving processes and the potential for contributions from geotechnical engineers.

1 INTRODUCTION

Human beings move a remarkable quantity of earth for civil construction. Entering into the new millennium, Hooke (1994) estimated that humans move between 30 and 35 trillion kilograms annually worldwide for housing excavations, road building, and mineral production alone. This corresponds to 6,000 kilograms annually per capita, a figure that excludes the astronomical quantities we shift for agriculture. Recognizing that these estimates include soils as well as rocks, the focus of this paper is exclusively on soils.

Earthmoving is an area where the scientific understanding lags well behind the technology. Formulating accurate, efficient, and robust earthmoving models poses a significant challenge due mainly to the large, progressive deformations involved and the wide range of possible machine configurations and operating conditions. In general, the deformation is three-dimensional. It is also influenced by inertial effects and, when the soil is wet, rate effects from hydromechanical coupling. As a result of geometric changes to the soil configuration as well as the evolving strength and deformability of the soil, the forces or reactions depend crucially on the history of deformation. Wide variations in mechanical behavior can be observed across different soils types, which differ according to grain size and angularity, mineralogy, and moisture content.

2 EXISTING MODELS

Existing analytical methods developed to predict the forces on tools moving through soil (e.g., Hettiaratchi & Reece 1974) bear strong resemblance to the earth pressure theories applied in geotechnical engineering. In these models, the soil accumulated throughout the process of deformation is replaced with an equivalent surcharge, using a concept similar to the one proposed by Terzaghi (1943) for assessing the bearing capacity of a footing located at some depth below the ground surface. While this simplifies the solution considerably, it neglects the deformation occurring within the volume of accumulated soil.

Some attempts have been made to simulate earthmoving processes using numerical methods. These include the finite element method (FEM) (Yong and Hanna 1977), the discrete element method (DEM) (Schmulevich et al. 2007), and continuum-based meshless methods such as the material point method (MPM) (Ambati et al. 2012). These methods have advanced to the stage that they can model earthmoving processes, but their use and acceptance have been slowed by serious drawbacks. Most importantly, they are prohibitively inefficient, often requiring days to complete a single simulation. DEM provides a high degree of realism for blocky materials, but the method's effectiveness tapers dramatically as the grain size decreases due to an inability to model efficiently a large number of particles. Furthermore, model parameters are typically tuned on a case-by-case basis to simulate different soil types, reflecting the more fundamental problem of deducing bulk properties from the micromechanical properties in the simulations.

Broadly speaking, existing models tend to be reasonably accurate but prohibitively inefficient, as in the case of high fidelity numerical approaches, or highly efficient but limited in terms of their accuracy and applicability, as in the case of analytical methods. From a computational viewpoint, these models either involve too many unknowns (degrees of freedom) or too few. This implies that future developments can proceed along two different axes: (1) reducing the complexity of computationally onerous techniques such as DEM or (2) increasing the complexity of low fidelity techniques. In the next section, both possibilities are discussed.

3 FUTURE MODELS

One approach for the development of efficient computational methods is to reduce the demands of existing techniques through the use of reduced order models (ROMs) or so-called surrogate models. A ROM attempts to increase efficiency (at the cost of accuracy) by decreasing the computational complexity through a series of operations on the original numerical formulation, often using projection-based reduction. Advances have been made in reducing computational fluid dynamics simulations to models that perform almost in real-time (Amsallem and Farhat 2008), and the concept also has been successfully extended to FEM (Ryckelynck 2009) and DEM (Boukouvala et al. 2013). A surrogate model is conceptually similar to a ROM but with the basic difference that it is not ascertained directly from the original model. Rather, it is constructed from the inputs and outputs obtained from numerous simulations, most often through machine learning. This approach also displays considerable promise as a means of producing fast algorithms that effectively synthesize the behavior of computationally intensive schemes (Gorissen et al. 2009). The predictive capabilities of ROMs and surrogate models as applied to earthmoving simulations remain to be demonstrated.

A second possibility is to formulate methods that are, by their very construction, reduced in complexity compared to conventional numerical techniques. A concept explored by

Kashizadeh et al. (2014) and Hambleton et al. (2014) that draws on the kinematic method of plasticity is to approximate the true pattern of deformation by a field of deformation characterized in terms of a modest number of unknowns, and then to compute these unknowns through optimization. Fig. 1a shows the basic idea for the case of a thin, vertical blade moving laterally through sand. In this case, the surface of the soil is discretized, and a set of potential shear bands is constructed as the series of lines spanning the nodes and the tip of the tool, each of which corresponds to a different angle of inclination β. Within each increment of deformation, an optimization procedure is used to determine the optimum angle β^* that minimizes the lateral force P. Once β^* is determined, the kinematics with respect to the incremental displacement of the block, denoted by Δu_β, are evaluated for a specified incremental displacement of the tool, Δu. Finally, the deformed configuration is updated based on the optimal mode of deformation within the increment, as shown in Fig. 1a, by updating the nodal coordinates. To model the full process of deformation, the steps are repeated over a series of increments. The key advantage of this optimization-based formulation is that the forces on the blade can be resolved accurately without detailed account of the stress and strain distributions within the soil. A comparison against preliminary experimental data is shown in Fig. 2. Starting from an initial mechanism and force conisistent with Coulomb's earth pressure theory, the deformation proceeds as a sequence of periodically developing shear bands that is well predicted by the proposed model, which includes the effect of softening.

Current work at Northwestern University focuses on extending the model to other, more general types of constitutive laws (Fig. 1b), enriched kinematic mechanisms, and 3D configurations (Fig. 1c), as well as validating the proposed models using a new experimental facility housing a 6-axis robot for actuation and control.

4 CONCLUDING REMARKS

The aim of this work is to establish a scientific understanding of the physical processes by which soil is progressively moved and shaped through interaction with tools and machines. This will be realized by (1) formulating new theoretical models that will enable optimization of tool shapes and motions, and permit real-time analysis and control and (2) developing experimental techniques to measure the tool forces and soil deformation for a variety of soil types and configurations, thus providing essential data to inform and validate the new theoretical models.

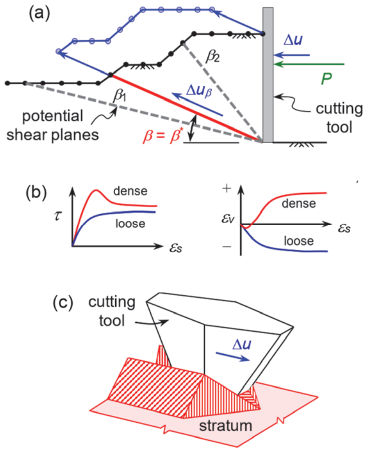

Figure 1. Simulation of fundamental earthmoving processes in soils using an optimization-based kinematic technique: (a) simple 2D problem (Hambleton et al., 2014); (b) shear stress−shear strain (τ−ε_s) and volumetric strain−shear strain (ε_v− ε_s) for soils; (c) extension to 3D kinematic techniques (adapted from Azarkhin & Devenpeck 1997).

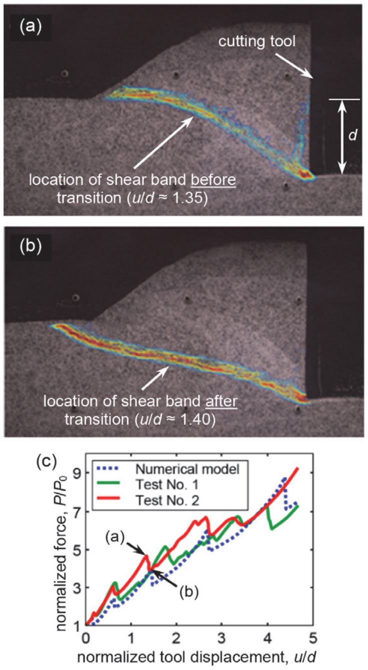

Figure 2. Patterns of deformation and force-displacement histories from preliminary 2D experiments on a vertical blade translating through sand (Kashizadeh et al. 2014, Hambleton et al. 2014): (a,b) contours of incremental shear strain inferred using digital image correlation; (c) measured and predicted force-displacement histories (P_0 = initial force).

5 ACKNOWLEDGEMENTS

Financial support provided by an ARC Discovery Early Career Research Award (DE160100328) is gratefully acknowledged.

6 REFERENCES

Ambati R., Pan X., Yuan H. and Zhang X. 2012. Application of material point methods for cutting process simulations. *Computational Materials Science*, 57, 102-110.

Amsallem D. and Farhat C. 2008. Interpolation method for adapting reduced-order models and application to aeroelasticity. *AIAA Journal*, 46(7), 1803-1813.

Azarkhin A. and Devenpeck M. 1997. *Wear*, 206(1-2), 147-155.

Boukouvala F., Gao Y., Muzzio F. and Ierapetritou M.G. 2013. Reduced-order discrete element method modeling. *Chemical Engineering Science*, 95, 12-26.

Gorissen D., Dhaene T. and De Turck F. 2009. Evolutionary model type selection for global surrogate modeling. *Journal of Machine Learning Research*, 10, 2039-2078.

Hambleton J.P., Stanier S.A., White D.J. and Sloan, S.W. 2014. Modelling ploughing and cutting processes in soils. *Australian Geomechanics*, 49(4), 147-156.

Hettiaratchi D.R.P. and Reece A.R. 1974. The calculation of passive soil resistance. *Géotechnique*, 24, 289-310.

Hooke R.LeB. 1994. On the efficacy of humans as geomorphic agents. *GSA Today*, 4(9), 217, 224-225.

Kashizadeh E., Hambleton J.P. and Stanier S.A. 2014. A numerical approach for modelling the ploughing process in sands. *Proc. 14th Int. Conf. of IACMAG*, Kyoto, Japan, Sept. 22-25, pp. 159-164.

Ryckelynck D. 2009. Hyper-reduction of mechanical models involving internal variables. *International Journal for Numerical Methods in Engineering*, 77, 75-89.

Schmulevich I., Asaf Z. and Rubinstein, D. 2007. Interaction between soil and a wide cutting blade using the discrete element method. *Soil and Tillage Research*, 97(1), 37-50.

Terzaghi K. 1943. *Theoretical Soil Mechanics*. New York, Wiley.

Yong R.N. and Hanna A. W. 1977. Finite element analysis of plane soil cutting. *Journal of Terramechanics*, 14(3), 103-125.