CAREER: Modeling Soil-Machine Interaction for Advances in Civil Construction and Terrestrial Robotics

This Faculty Early Career Development Program (CAREER) award will investigate the physical processes through which machines interact with soils, and develop theoretical models that will underpin the design of future, autonomous devices used for construction, mining, agriculture, and mobility. Humans move, manipulate, and interact with soil on a massive scale for civil construction, mining, and agriculture using machines that have been designed and built primarily through trial and error, without fundamental knowledge of how soils respond under different loading conditions. Advances in mechatronics and robotics can revolutionize the design of these machines. Since existing techniques for simulation and design are largely for devices operating on hard surfaces, a major impediment to answering this question and others is the lack of methods to predict how machines operate on deformable terrain. This project will collect data and launch an integrated research and educational program dedicated specifically to Soil-Machine Interaction (SMI), one that ultimately will examine a wide variety of machine configurations and soil types. The broader impacts of this project will shape an emerging, interdisciplinary field by stimulating technological advances in the devices used for construction, mining, agriculture, and mobility. Through integrated educational aims, the project will also attract, excite and educate a diverse group of future civil engineers through inclusive outreach and educational activities that engage learners of all ages, from early childhood onward.

This project will integrate experiments and theory based on fundamental soil mechanics to obtain models for predicting the evolution of forces and reactions as machines come into contact with soils to induce large, permanent (plastic) deformations. Significant novelty lies in the complete experimental characterization of force-displacement histories and deformation fields over a wide range of possible motions, considering two fundamental soil types and using the 6-axis robotic arm in the Soil-Machine Interaction Laboratory at Northwestern University for actuation. To overcome the high computational demands of existing numerical methods, the project will formulate an efficient simulation technique based on the Sequential Kinematic Method, an approach that utilizes simplified kinematics and an optimization-based solution scheme to decrease computation times significantly. Since force-displacement histories obtained experimentally or through numerical simulation are applicable only to a single motion or load path, a significant breakthrough pursued in this project is the formulation of a semi-analytical framework capable of predicting force-displacement histories under arbitrary motions and loading conditions. Educational and societal impact will be maximized through sustained outreach, training of undergraduate and graduate students, interaction with industry, and dissemination of results internationally across various platforms, including open-source software written in an architecture advised by industry collaborators. Through collaboration with the Chicago Children's Museum and Chicagoland maker fairs, the project aims to stimulate interest in engineering and SMI across a wide range of demographics.