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Review

Overview of soil-machine interaction studies in soil bins

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ABSTRACT

This paper presents a review of soil-machine interaction studies in soil bin test facilities; it provides an insight on the historical background, concepts, past and present studies and future research direction. Soil-machine interaction studies seek to provide scientific knowledge on how tillage tools and traction devices interact with the terrain over which they work or move. Variables usually investigated include; force required to pull or push the tillage tool, vertical and lateral forces on tools, soil failure patterns, soil particles displacement, force generated at the interface of the wheel and the soil, wheel sinkage, rolling resistance, wheel contact area estimation, and soil stress at different depths. Soil bin facility is a model laboratory for tillage and traction experiments. The main components include the soil bin that models the ground; mobile tool carrier that models tool/implement frame; soil engaging tool/device for modeling tillage tools or traction elements; power source and the drive system that model the prime mover; soil conditioning equipment for preparation of the soil before experiments; motion control system for controlling the moving components along the rails of the soil bin; measurement/data acquisition and analysis system for real time measurement, analysis and display of variables during experiments; a lifting system for hoisting of heavy components. Simulations with Finite Element and Discrete Element Methods together with experimental analyses in the field or the soil bin are applied by many researchers in studying soil-machine interaction. Results of this kind of study are useful for design, modeling, prediction, performance evaluation and optimization of different kinds of off-road vehicles, earth moving machines, tractors, tillage tools/implements, traction elements, wheeled mobile robots and autonomous traction vehicles.

1. Background

The development of soil engaging tools and machines for soil tillage and traction started without any scientific knowledge of how the tools and traction elements interact with the soil while working the soil. This caused inefficiencies as the tools and machines were used under different operating conditions, environment and power sources. George Kuehne was the first researcher who initiated studies in a soil bin in the year 1914 in Berlin, Germany (Ademosun, 2014). However, Mark L. Nichols and John W. Randolph were the first (Gill, 1990) to conceive the idea and to develop a full-sized soil bin laboratory between 1920 and 1933, where controlled experiments could be carried out to study the relationship between tillage tools, traction equipment and the soil. The National Soil Dynamics Laboratory in Auburn Alabama, USA was the world's first full-size laboratory. The soil bin consisted of powered, rail mounted tillage tool carriage working in soils isolated from external influences. Soil-machine interaction studies over the years, especially in the soil bin have provided insight to the operation mechanism and hence the design of traction elements and tillage tools on different soils under varying soil conditions. Such traction equipment ranges from different kinds of off-road vehicles, earth moving machines to wheeled mobile robots used for military, agriculture, search and rescue, mining, terrestrial explorations, forestry, etc. Equipment manufacturers have utilized the results of soil-machine interaction studies in the soil bin to improve the design and efficiency of tillage implements, such as plows, harrows, planters and cultivators, and traction and transport machines, such as tractors, combines, and trailers. Studies in the soil bin have revolved around providing better understanding of soil failure patterns with different sizes and designs of tillage tools under varying conditions of both the soil and the machine, earth moving and transport, soil working and amendment, forces required to fail the soil, power requirements of tillage tool carriers or prime movers, optimizing traction efficiency for effective vehicle mobility and more recently autonomous navigation of wheeled mobile robots. Studies and research in this subject have undergone many interesting stages worth reviewing and taking note of, in order to provide current understanding of the trends

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in this discipline and to point out future directions. This paper is therefore an attempt to provide an overview of soil-machine interaction studies, particularly in the soil bin, which will be a concise reference for all researchers and groups interested in the development of traditional and modern traction and tillage equipment.

2. The concept of soil-machine interaction and terramechanics

Soil-machine interaction which has now become known as terramechanics is a field of research that deals with terrain-vehicle mechanics for off-road vehicles and soil engaging machinery. Specifically it is the study of how the wheel of the vehicle or the tool of the machinery interacts with the material of the terrain surface which is mostly soil. This leads to the general classification of soil-machine interaction into two broad areas of either traction or tillage studies. Traction is defined as the capability of the vehicle's wheel or other tractive elements to develop sufficient thrust force to overcome all types of vehicle resisting forces and hence keep the vehicle in constant motion in the direction of the force (Young et al., 1984). The study of vehicle traction mechanics provides insight and understanding of the scientific and mathematical relationships involved in the interaction of traction devices and the terrain; and this knowledge is useful for rational design, selection, operation, performance prediction, evaluation, modeling and design optimization of machine systems. On the other hand, tillage is the mechanical manipulation of the soil for different specific purposes such as seedbed preparation for crop production in agriculture, earth-moving in civil engineering, ditch-forming in military operation, hole-digging in forestry, tunnel-making in seabed operation, trenching in underwater pipe laying, etc. Tillage tools are mechanical devices that are used to apply forces to the soil to simultaneously cause several desired effects such as cutting, inversion, pulverization, movement of the soil or mixing. Techniques for evaluating soil-tool interaction and different phases in the development of a soil-tillage tool mechanics are illustrated in Figs. 1 and 2. The purpose of studying mechanics of tillage tools is to provide a way for describing the application of forces to the soil and for describing the soil's reaction to the forces. Such mechanics provide methods by which the effects of the interaction can be predicted and controlled either through improved design of tools or improved techniques of operation (Gill and VandenBerg, 1968). The proper design and selection of soil-engaging tools to achieve desired soil tilth depends largely on the mechanical behavior of the soils (Rajaram and Erbach, 1998). Soil failure patterns play an important role in obtaining a better understanding of the mechanical behavior of soils under varied soil and tool conditions. The variation in soil failure patterns can be attributed to the variations of mechanical behavior of the soil (Al-kheer et al., 2011). Soil failure patterns can include collapse, fracturing (brittle), chip forming, and flow (Salokhe, 1986; Rajaram and Gee-Clough, 1988; Sharma, 1990). These failure patterns may vary with soil and tool parameters (Elijah and Weber, 1971; Godwin and Spoor, 1977; Stafford, 1981; Makanga et al., 1996).

3. Past and current trends in soil-machine interaction studies

From the time of Dr. M. G. Bekker and A. R. Reece who are considered notable pioneers of soil-machine interaction studies, intensive research efforts were geared towards obtaining better understanding of the nature of the interaction of traction elements and tillage tools. Tractive performance of tractors and other off-road vehicles has been a challenging problem till date in the design, performance evaluation/prediction and very recently in automation and control of earthmoving machines and wheeled mobile robots moving in uneven and deformable terrains. Soil-machine interaction studies have been carried out theoretically based on mechanics or by experimental methods in soil bins or full scale field tests. Usually, the soil and machine parameters in soil bins are controlled. Thus, soil-machine interaction studies are pivotal for design and development, optimization, automation and control of different types of off-road vehicles, earthmoving machines and wheeled mobile robots; and also for appropriate matching of implements with power sources and the selection of optimum operating conditions in agricultural mechanization for food production. Soil–tool interaction involves two aspects: on one hand are the forces developed at the interface of the soil and the tool such as draught, side and vertical forces; on the other hand is the displacement of soil particles also known as soil disturbance (Conte et al., 2011; Chen et al., 2013). To gain a balanced understanding of soil–tool interaction requires both field and laboratory experiments under controlled conditions such as that in soil bins at different soil physical conditions and operating conditions of the tool (Mouazen et al., 1999).

According to (Mak et al., 2012) both analytical and numerical methods have been used to model soil–tool interactions with the aim of improving the design of soil engaging tools. The Universal Earthmoving Equation (UEE) which was developed from the theory of passive earth pressure is one example of analytical methods which has been used by many researchers (Hettiaratchi and Reece, 1967; McKyes and Ali, 1977; Godwin and Spoor, 1977). Earthmoving is a term originally associated with construction equipment such as scrapers, bulldozers, pay loaders etc. Later, the term became extended to agricultural machines involved in soil manipulation such as tillage, planting and harvesting tools. Analytical models for soil tool interaction are sometimes limited because not all the variables involved are captured. However in the recent time, Finite Element Method/Analysis (FEM/FEA) as a numerical method has been widely used to analyze soil-tool interaction problems (Upadhyaya et al., 2002; Mootaz et al., 2004; Hemmat et al., 2012; Bentaher et al., 2013). This method takes care of both material and geometric nonlinearities which characterize most soil–machine interaction problems. FEM assumes that continuum mechanics apply (Upadhyaya et al., 2002). Discrete Element Method (DEM) is also one of the newest numerical methods for soil-tool interaction modeling and simulation (Mak et al., 2012).

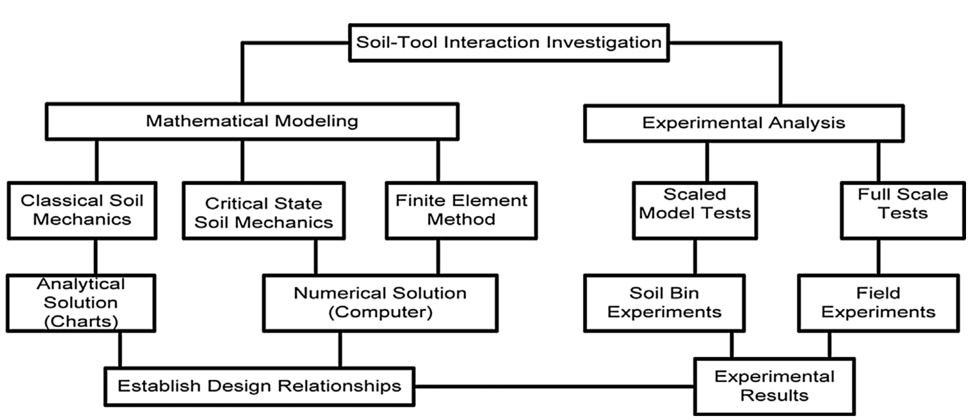

Fig. 1. Techniques for Evaluating Soil-Tool Interaction (Onwualu, 1991).