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Numerical analysis on tractive performance of off-road wheel steering on sand using discrete element method

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Abstract

This paper presents a numerical analysis on steering performance including tractive parameters and lug effects. To explore the difference between the turning and straight conditions of steering, a numerical sand model for steering is designed and appropriately established by the discrete element method on the basis of triaxial tests. From the point of mean values and variation, steering traction tests are conducted to analyze the tractive parameters including sinkage, torque and drawbar pull and the lug effects resulting from type, intersection and central angle. Analysis indicates that steering motion has less influence on the sinkage and torque. When the slip ratio exceeds 20%, the steering drawbar pull becomes increasingly smaller than in the straight condition, and the increase of steering radius contributes to a decline in mean values and a rise in variation. The lug effect of central angle is less influenced by the steering motion, but the lug intersection is able to significantly increase the steering drawbar pull along with the variation reduced. However, the lug inclination reduces the steering drawbar pull along with the variation raised in different degrees.

Keywords: Steering; Off-road wheel; Tractive parameter; Lug effects; Discrete element method

1. Introduction

As the demand for resources increases, humans gradually expand mining areas to environments covered with sandy soil, such as near seacoasts, deserts and perhaps even other planets (Zhang et al., 2015). As important equipment during resource exploration, exploitation and transportation, off-road vehicles equipped with lugged wheels demand sufficient tractive performance under various operating conditions, which mainly results from the interaction between the off-road wheels and sandy soil. Therefore, the study of off-road wheels in terramechanics has attracted more attention from researchers in recent years (Asnani et al., 2009). The widely used method to research the tractive performance of a single wheel is the soil bin test, which was proposed by Bekker MG and advanced in theory by Bekker (1960), Janosi and Eiler (1968), Wong and Reece (1967), Wong and Huang (2006). However, limited to the size and cost of this equipment, soil bins are always shaped in a rectangle to simulate the straight driving condition of an off-road wheel. In reality, under complex operating environments, an off-road wheel will experience not only the common straight or sloped terrain but also curved trajectories with various steering radiuses. As a result, it is not sufficient to focus only on straight driving or climbing conditions limited by the rectangular soil bin in Brooks et al. (2006), Ding et al. (2011), Iizuka et al. (2014), Senatore et al. (2013).

There must be certain differences in the tractive performance between the straight and steering driving conditions. Steering research in terramechanics mainly focuses on multi-axle systems (Besselink, 2004; Watanabe et al.,

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2007; Edlund et al., 2012), steering theory (Itoh et al., 1995; Kozëowski and Pazderski, 2004; Genya et al., 2007) and skid steering (Maclaurin, 2011; Gao et al., 2013; Flippo and Miller, 2014). There are also a few steering studies on the absolute tractive performance including drawbar pull or torque applied on a single wheel on the basis of the soil bin test. Carnegie Mellon University (Shamah et al., 1998) designed a soil bin shaped in a regular polygon for circular traction on sands, but this equipment could not flexibly change the steering radius of a tested wheel, also the size and steering radius of the tested wheel were smaller than those of a normal vehicle. Raheman H studied the performance of off-road wheels in both the longitudinal and lateral direction of the steering trajectory by soil bin testing (Raheman and Singh, 2004). However, limited by the size of the soil bin, the maximum steering angle of the tested wheel was 50°, which could not reflect the entire process of steering motion very well. In order to analyze the real-world tractive performance of off-road wheels in cases with various steering radiuses and angles, researchers must conduct tests with an actual vehicle. For example, Liu et al. (2009) and Hajiahmad et al. (2014) analyzed the sinkage of actual off-road vehicles under the influence of steering radius and different terrains. It can be seen, relative to the lunar vehicle in model tests, that the steering research of an off-road wheel of a large size demands either large-scale soil bin equipment varying in steering radiuses in the laboratory or the measurement of an actual vehicle outside, which both require much more material and financial resources than the traditional soil bin test. Under this circumstance, a numerical simulation equipped with high flexibility and efficiency together with low cost becomes the optimal choice.

Currently in terramechanics, the widely used methods for numerical simulation on tractive performance are the finite element method (FEM) and the discrete element method (DEM). The FEM was introduced into terramechanics by Perumpral et al. (1971) and gradually advanced by Fervers (2004), Hambleton and Drescher (2008), Xia (2011). Nonetheless, FEM usually hypothesizes the sand terrain as a continuous medium based on the theories of Bekker (1969), Ingobert (1995), Koichiro et al. (2006). Consequently, it has been indicated that FEM is not very suitable for the incompact terrain like sand, which is always deep rutted in a discontinuous state (Momozu et al., 2002). In contrast, the DEM proposed by Cundall and Strack (1971) no longer simulates the sand as a continuous model but separates it into a mass of independent particles to represent the friction and extrusion effect of real sand. In recent years, the DEM in terramechanics has been increasingly developed and applied in practice by global researchers (Taheri et al., 2015; Li et al., 2015). Above all, the DEM, which could easily simulate different steering motions with various radiuses and be particularly suitable for sand simulation, is the best choice for research in this paper.

There are few researches applying DEM to simulate the steering motion of off-road wheels. Hence, on the basis of DEM theory, this paper first establishes a numerical sand model for traction tests with the help of PFC3D 4.0 software (ITACSA, 2008). Then, to determine the tractive performance, including tractive parameters and lug effects, numerical tests are carried out under different steering conditions. Finally, compared with the previous study under the normally straight condition (Du et al., 2016), the influences on steering tractive performance are analyzed in detail. In general, this paper could provide a reference for further study on steering simulations using the DEM in the future.

2. Conditions of numerical steering tests

2.1. Condition of tested sands for steering

Undeveloped seafront is commonly covered with large areas of extensive sand and gravel, the moisture contents of which decrease with an increase in distance from the coastline. In most cases, under the effect of moisture, the mechanical properties of wet sand decline in different degrees, likely further reducing the trafficability of the sand. Resulting from this extremely poor tractive performance of wheeled vehicles on wet sand, the transportation routes, stations and operating zones nearshore are usually located in the regions of sand with low moisture or other terrains which are appropriate for traction.

On the basis of the background information studied in this article, the dry sand distributed on the backshore of a natural beach in Daya Bay, Xiachong, Huizhou, Guangdong, China (22.8°N and 114.6°E) is sampled for the tests on its mechanical properties in order to simulate the typical straight and steering condition of off-road wheels operating on the backshore zone far away from the coastline. Fig. 1 shows the major tests for mechanical parameters of the tested sand in this paper. The tested sand can be divided into well-graded sand (SW) through sieve analysis according to the United Soil Classification System (ASTM D2487-11), and the moisture content is measured after constantly drying for 8 h under 110 °C. On that basis, the porosity is calculated with the help of pycnometers, where the pores of sand will be filled with water. The triaxial compression tests in this paper are conducted by a static stain-controlling instrument with auto-manual system, as shown in Fig. 1, in which the air is first compressed into the instrument and then transformed to the water confining pressure around the soil sample in the triaxial compressing room, while the vertical counter-pressure is gradually produced by the fixed beam under the lifting effect of the platform. Through a test, to obtain triaxial compressing parameters, the confining pressure, axial pressure, axial strain and volume stain of the soil sample will be recorded by sensors and analyzed by the software on the basis of the theory of soil mechanics. Deduced from the tests above, the physical parameters of the sand sample are listed in Table 1, which