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Development and numerical validation of an improved prediction model for wheel-soil interaction under multiple operating conditions

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ABSTRACT

This paper presents the establishment and validation of an improved model predicting tractive parameters of a lugged wheel under multiple operating conditions. During the basic straight driving wheel-soil interaction, the common-used equivalent radius theory and the bulldozing theory are combined to calculate the lug effects referring the traditional theories of soil stress distribution, while the bulldozing effect is reconsidered according to the work conservation. On the basis of the further prediction under multiple conditions including the inclination in three degrees of freedom and the turning driving, the numerical model using the discrete element method under each operating condition is separately established. Under such circumstances, the validation and analysis are conducted differing in sizes and driving parameters of the wheel. It is indicated that the improved model displays the better reasonability and precision in predicting lug effects of a heavy off-road wheel. This model is mostly accurate and sensitive to the variation of parameters under straight and inclining driving conditions, but demands further correction during low slipping of the turning condition. Generally, the improved model in this paper focuses on the prediction of drawbar pull and driving torque, but lacks precision in the tendency of sinkage.

1. Introduction

As important equipments during resource exploration and transportation, off-road vehicles equipped with different kinds of lugged wheels usually present outstanding tractive performance under various operation conditions, which mainly benefits from the wheel-soil interaction. Concentrating on the different performances produced by various soils and lugged wheels, the early study on wheel-soil interaction conducted by Bekker (1960b) contributed to the foundation of a cross-discipline subject called terramechanics. As the development of terramechanics in recent years, three major analysis means including the laboratory experiment, the theoretical model and the burgeoning numerical simulation separately play important roles.

The earliest means to quantitatively analyze the wheel-soil interaction is soil-bin experiment, which was put forward by Bekker (1960b). On the surface of the sampled soil during an experiment, the scaled wheel model is driven by an engine in the constant driving and rotating velocity, while the tractive parameters including drawbar pull, driving torque and sinkage will be steadily measured, so the soil-bin experiment is widely considered as the most convinced method. However, limited to the size and cost of the instrument, the soil-bin is commonly shaped in rectangle and only experimented for the wheel-soil interaction under the straight driving condition (Brooks et al., 2006; Ding et al., 2011; Iizuka et al., 2014; Senatore et al., 2013). Hence to include multiple operating conditions like climbing and turning, several different experiments were conducted. Carnegie Mellon University (Shamah et al., 1998) designed a regular polygonal soil-bin for turning driving analysis, but the instrument could not flexibly change the turning radius, also the size and the turning radius of the scaled wheel were smaller than the normal. Raheman and Singh (2004) studied an actual single wheel along a curved turning trajectory, but limited to the size of the soil-bin, the turning angle of the tested wheel was 50° to the max. Besides, to analyze the wheel-soil interaction under inclining driving conditions, Chofu Aerospace Center (Wakabayashi and Matsumoto, 2006) designed a soil-bin instrument which could change the longitudinal inclination angle, while Tohoku University (Inotsume et al., 2012) manufactured an instrument with the transverse inclining control system. Hence it can be seen, the experimental analysis on the wheel-soil interaction under different driving conditions demands multiple functional or large-scale soil-bin instruments along with sufficient sampled soil, so the soil-bin experiment is difficult to be generalized in spite of its accuracy and reliability.

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Nomenclature

i	slip ratio of wheel
i_{eq}	equivalent slip ratio
i_c	slip ratio at center of lug force
r	wheel radius (m)
r_{eq}	equivalent wheel radius (m)
r_c	center of lug bulldozing force (m)
R	turning radius (m)
b	width of wheel (m)
b_{lug}	width of lug (m)
h_{lug}	height of lug (m)
h_{eq}	equivalent height of lug (m)
λ	equivalent coefficient of lug
γ	angle between adjacent lugs (°)
c_1, c_2, c_3	fitting coefficients in Wong's model
c	Internal cohesion of soil (Pa)
φ	Internal friction of soil (°)
k_c	Bekker's cohesive modulus (N/m^{n+1})
k_φ	Bekker's frictional modulus (N/m^{n+2})
n	Bekker's sinkage exponent of soil
n_{lug}	lug number in the wheel-soil interaction region
K	Janosi's shearing modulus of soil (m)
K_p	fluid coefficient of soil
ρ	Natural density of soil (kg/m^3)
F_{lug}	vertical bulldozing force of lug (N)
F_{DP}	drawbar pull of lugged wheel (N)
F_{DP}^{s}	drawbar pull under transverse inclining condition (N)
F_{DP}^{s0}	drawbar pull under longitudinal inclining condition (N)
F_{DP}^{s3}	drawbar pull under horizontal inclining and turning condition (N)
F_R	resistance force of soil (N)
F_S	drawbar pull of smooth wheel (N)
F_L	extra drawbar pull from lugs (N)
F_M	extra resistance force (N)
F_{M1}	extra resistance force from wheel broadside (N)
F_{M2}	extra resistance force from lug broadside (N)
F_F	extra adhesion force (N)
F_{F1}	extra adhesion force from wheel broadside (N)
F_{F2}	extra adhesion force from lug broadside (N)
z	total sinkage of wheel (m)
z_1	static sinkage (m)
z_2	slipping sinkage (m)
z_3	lug rutting sinkage (m)
Δz	equivalent soil sinkage in Rankine's theory (m)
θ	variable interaction angle (°)
θ_0	interaction angle considering dynamic sinkage (°)
θ_1	entrance angle of front region (°)
θ_2	leaving angle of rear region (°)
θ_m	location of maximum radial stress (°)
θ_f	variable angle in front region (°)
θ_r	variable angle in rear region (°)
$\theta_{lug}{}^k$	location angle of lug (°)
σ	radial stress of soil (Pa)
σ_1	radial stress in front region (Pa)
σ_2	radial stress in rear region (Pa)
σ_1'	extra pushing stress of wheel broadside (Pa)
σ_2'	extra pushing stress of lug broadside (Pa)
σ_{lug}	stress at the bottom of lug (Pa)
σ'_{lug}	stress at the top of lug (Pa)
τ	shearing stress (Pa)
τ_1	shearing stress in front region (Pa)
τ_2	shearing stress in front region (Pa)
τ_1'	extra shearing stress of wheel broadside (Pa)
τ_2'	extra shearing stress of lug broadside (Pa)
W	vertical load of lugged wheel (N)
Ws	vertical force of smooth wheel (N)
W_L	extra vertical force from lugs (N)
U_L	work produced by lug (N·m)
M	torque of lugged wheel (N·m)
M_s	torque under transverse inclining condition (N·m)
M_{s0}	torque under longitudinal inclining condition (N·m)
M_{s3}	torque under horizontal inclining and turning condition (N·m)
M_R	torque produced by resistance force of soil (N·m)
M_S	torque of smooth wheel (N·m)
M_L	extra torque from lugs (N·m)
M_M	extra resistance torque (N·m)
M_{M1}	extra resistance torque from wheel broadside (N·m)
M_{M2}	extra resistance torque from lug broadside (N·m)
M_F	extra adhesion torque (N·m)
M_{F1}	extra adhesion torque from wheel broadside (N·m)
M_{F2}	extra adhesion torque from lug broadside (N·m)
z_{s0}	sinkage under longitudinal inclining condition (m)
z_{s1}	sinkage under terrain transverse inclining condition (m)
z_{s2}	sinkage under wheel transverse inclining condition (m)
z_{s3}	sinkage under horizontal inclining and turning condition (m)
ω_0	rotating speed of wheel

Less depending on experimental instruments, the theoretical model has advantages in rapidity, consumption and the visualized analysis on major factors. The theoretical model of wheel-soil interaction deserves to be founded on the basic stress-strain relationship of soil under the wheel's pressure. Nowadays, the most widely accepted and applied soil stress-strain relationship is the Bekker's normal stress-sinkage model (Bekker, 1960b) and the shearing stress-strain model simplified by Janosi and Eiler (1968), as Bekker's original shearing model is quite complex in measuring and calculating the parameters. On that basis, Bekker established the primary wheel-soil interaction model in a mechanical way (Bekker, 1960a), which was widely referred by following researches. Meanwhile the original model also had some disadvantages. First of all, Wong JY and Reece AR pointed that only radial stress before the peak well satisfies the Bekker's sinkage model according to their experiential results, so they provided the comprehensive stress distribution along the wheel-soil interaction surface (Wong and Reece, 1967). Then, the sinkage calculated by Bekker's model of lugged wheel is usually proved smaller than the experiential results (Ishigami et al., 2007), hence several researches proposed the dynamic correction by theoretical analysis (Jiang et al., 2013; Lyasko, 2010; Ding et al., 2010) or mathematical fitting in linear (Ding et al., 2014), exponential (Jin et al., 2013) and polynomial functions (Huang et al., 2015). Moreover, the lug effects derived from Bekker's model, which are based on Rankine's passive soil pressure theory, also exceed the normal level especially under a heavy load, hence the equivalent radius method is put forward and substituted for explaining the extra performance of lugged wheels (Ding et al., 2009). Last but not least, the existing theories on wheel-soil interaction mostly establish a planar model which ignores the additional adhesion or resistance along the wheel broadside and other inclining or turning driving conditions in a three-dimensional environment.

To validate the accuracy of theoretical models, numerical simulation is usually conducted if without the conditions of soil-bin experiment. The discrete element method (DEM), which was put