ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Journal of Terramechanics xxx (2017) xxx–xxx

Journal of Terramechanics

www.elsevier.com/locate/jterra

Analysis of Mars Exploration Rover wheel mobility processes and the limitations of classical terramechanics models using discrete element method simulations

Jerome B. Johnson [a,*], Paul X. Duvoy [a], Anton V. Kulchitsky [a], Colin Creager [b], Jeffery Moore [c]

[a] University of Alaska Fairbanks, Institute of Northern Engineering, P.O. Box 755910, Fairbanks, AK 99775-5910, USA
[b] NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH 44135, USA
[c] NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035-1000, USA

Received 6 April 2017; received in revised form 4 August 2017; accepted 2 September 2017

Abstract

A previous three-dimensional discrete element method (DEM) model of Mars Exploration Rovers (MERs) wheel mobility demonstrated agreement with test data for wheel drawbar pull and sinkage for wheel slips from 0.0 to 0.7. Here, results from the previous model are compared with wheel mobility data for non-MER wheels that cover the range of wheel slip from 0.0 to 1.0. Wheel slips near 1.0 are of interest for assessing rover mobility hazards. DEM MER wheel model predictions show close agreement with weight-normalized wheel drawbar pull data from 0.0 to 0.99 wheel slip and show a similar trend for wheel sinkage. The nonlinear increase in MER wheel drawbar pull and sinkage for wheel slips greater that 0.7 is caused by development of a tailings pile behind the wheel as it digs into the regolith.

Classical terramechanics wheel mobility equations used in the ARTEMIS MER mobility model are inaccurate above wheel slips of 0.6 as they do not account for the regolith tailings pile behind the wheel. To improve ARTEMIS accuracy at wheel slips greater that 0.6 a lookup table of drawbar pull, wheel torque, and sinkage derived from DEM mobility simulations can be substituted for terramechanics equation calculations.

Keywords: Mars Exploration Rovers; Discrete element method; Model validation; High wheel slip mobility; Wheel mobility testing; Terramechanics; ARTEMIS

1. Introduction

In 2004 the Mars Exploration Rovers (MERs) began an extensive exploration of Martian terrain enabled by their mobility. The rovers experienced few mobility problems during their traverses with some notable exceptions where they became embedded in the Martian regolith when their wheel slippage approached 100% (Squyres et al., 2004a, 2004b; Arvidson et al., 2011). The Curiosity rover has experienced similar high wheel slip mobility problems on Mars. Experience gained during efforts to extract Spirit rover and interest in overcoming mobility challenges caused by high wheel slip motivated development of the ARTEMIS rover-terrain interaction model using classical terramechanics equations (Zhou et al., 2014).

ARTEMIS is able to represent rover mobility for wheel slip up to about 0.6, but has difficulty when wheel slips increase further (Arvidson et al., 2017). The ARTEMIS model has difficulty simulating high wheel slip mobility

* Corresponding author.
E-mail address: jerome.b.johnson@alaska.edu (J.B. Johnson).

https://doi.org/10.1016/j.jterra.2017.09.002
0022-4898/

Please cite this article in press as: Johnson, JB et al., Analysis of Mars Exploration Rover wheel mobility processes and the limitations of classical terramechanics models using discrete element method simulations, J Terramechanics (2017), https://doi.org/10.1016/j.jterra.2017.09.002

due to assumptions about wheel-regolith interactions that break down for high slip conditions, as we discuss later in this paper. To improve the ARTEMIS model's ability to simulate MER mobility under conditions of high wheel slip Johnson et al. (2015) examined MER rover wheel mobility performance using the Coupi three dimensional (3-D) discrete element method (DEM) model. The Johnson et al. (2015) model results are used as the basis of the analysis described in this paper and the reader is referred to that paper for details.

An advantage of DEM models is that once initial conditions, control functions, particle parameters and contact physics between regolith particles and the wheel are determined they remain valid over the full range of wheel slip conditions. Johnson et al. (2015) demonstrated that the DEM wheel mobility model well represented available measured steady-state sinkage and drawbar pull (DP) from the Massachusetts Institute of Technology (MIT) tests with wheel slips up to 0.7. Wheel driving slip is defined as

$$i = 1 - \frac{v}{r\omega} \quad when\ v < r\omega \tag{1}$$

where v is the wheel forward speed (m/s), the product $r\omega(m/s)$ is the rotational speed of the wheel, r (m) is the radius of the wheel, and ω is the angular speed of the wheel (rad/s). When wheel slip equals 0.0 the vehicle is moving forward at the same speed as the wheel rotation speed and when wheel slip equals 1.0 the wheel is spinning in place. Steady-state refers to the condition where wheel sinkage and DP remain constant as the wheel continues moving forward with a constant wheel slip.

Above wheel slips of 0.7 to around 0.9 the DEM model predicts that wheel sinkage and DP continue to increase under steady-state conditions. At some wheel slip greater than 0.9 wheel sinkage and DP become time dependent, increasing with time as well as wheel slip. Under these conditions, the wheel continues sinking until the rover either high centers, producing a wheel slip of 1.0, or the amount of energy required to drive the wheel to maintain forward progress becomes more than the rover can supply and it becomes bogged.

Wheel sinkage and DP data to assess how well the DEM model represented MER high wheel mobility performance were not available at the time of the Johnson et al. (2015) study for wheel slips greater than 0.7. Of particular interest is understanding the DEM model prediction that wheel sinkage and DP are a function of time at wheel slips greater than 0.9; this had not been previously been observed or investigated. Recently, wheel mobility performance data for wheel slips from 0.0 to 1.0 obtained during mobility testing on two different wheel designs at the NASA Glenn Research Center (GRC) became available (Creager, 2009). While GRC's wheel mobility data is not for a MER wheel the data indicate that different wheel types can have similar mobility performance as predicted by the DEM MER wheel mobility model.

In this paper we use the GRC wheel mobility data to assess the DEM MER wheel mobility model predictions of wheel sinkage and DP at wheel slips greater than 0.7. The Johnson et al. (2015) DEM model results are then used to examine MER wheel mobility processes over the full range of wheel slip from 0.0 to 1.0 and to describe how DEM model predictions of wheel DP, torque and sinkage can be used by ARTEMIS to improve mobility predictions for high wheel slip conditions. We also discuss the reasons why traditional terramechanics equations breakdown under high wheel slip conditions.

2. Comparison of measured and DEM simulation wheel sinkage and DP for wheel slips from 0.0 to 0.99

Creager (2009) conducted a series of mobility tests at GRC to examine wheel DP for two different rigid wheels for wheel slips from 0.0 to 1.0 (Table 1 and Figs. 1 and 2). Wheel test 1 was done in the GRC SLOPE laboratory using 405 mm radius and 180 mm width rigid wheels (Fig. 1a), with grip tape added to the wheel circumference to increase friction with regolith particles (NASA GRC, 2009). For test 1, the wheels were mounted on a four-wheel drive vehicle (Fig. 1b) with a cable attached to apply a DP force that was increased in steps after each 0.5 m of vehicle travel. The wheel slip and DP force were averaged over each step once steady-state conditions were reached. When a steady-state region was not apparent from the data (at high wheel slip) the last 15 s of data, or the best judgment of test personnel, was used to estimate DP. The SLOPE regolith bin was filled to a depth of about 0.76 m, resulting in little or no boundary effects during testing; a test was usually stopped when the wheel hub touched the regolith surface.

Wheel test 2 was done using a 255 mm radius and 180 mm width rigid wheel with added grip tape (Fig. 2a) in the GRC single-wheel TREC test bed (Fig. 2b) (NASA GRC, 2014). Wheel motion was slip controlled with the translation speed of the wheel varied to achieve different wheel slips. The wheel was driven one full revolution per slip condition with DP, wheel sinkage, and wheel slip averaged over each test run once steady-state was achieved. Steady-state was not likely achieved at very high slip (0.99) (Creager, personal communication, February 17, 2016).

The DP to wheel weight ratio (DPWR) as a function of wheel slip for the MIT and GRC wheel mobility tests compared with DEM simulations of the MER wheel over the range of wheel slips from 0 to 0.99 in Fig. 3. The DPWR is a reasonable way to represent the pulling power of wheels of different geometry and weight operating in similar regolith conditions since traction is limited by regolith strength, which is affected by vehicle weight. As is shown in Fig. 3, DPWR measurements for the MER, GRC wheel 1, and GRC wheel 2 have the same form as each other and the DEM MER wheel simulation results. Of particular interest is the rapid increase in DPWR above wheel slips