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Further study of the method of approach to testing the performance of extraterrestrial rovers/rover wheels on earth

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Abstract

The current practice for experimentally evaluating the performance of extraterrestrial rovers/rover wheels is to conduct tests on earth on a soil simulant, appropriate to the regolith on the extraterrestrial body of interest. In the tests, the normal load (force) applied by the rover/rover wheel to the soil simulant is set identical to that expected on the extraterrestrial surface, taking into account its acceleration due to gravity. It should be pointed out, however, that the soil simulant used in the tests is subject to earth gravity, while the regolith on the extraterrestrial surface is subject to a different gravity. Thus, it is uncertain whether the performance of the rover/rover wheel obtained from tests on earth represents that on the extraterrestrial surface. This issue has been explored previously. A method has been proposed for conducting tests of the rover/rover wheel on earth with identical mass to that on the extraterrestrial surface, instead of with identical normal load used in the current practice [1]. This paper provides further evidence to substantiate the merits of the proposed method, based on a detailed analysis of the test data obtained under various gravity conditions, produced in an aircraft undergoing parabolic flight manoeuvres [8]. In the study, the effect of slip on wheel sinkage has been evaluated. It is found that gravity has little effect on the slip and sinkage relationship of the rover wheel under self-propelled conditions.

Keywords: Compaction resistance; Extraterrestrial rovers; Gravity effects; Mobility; Parabolic flight manoeuvres; Rover wheels; Sinkage; Slip–sinkage; Soil simulant; Testing

1. Introduction

In the development of extraterrestrial rovers/rover wheels, it is desirable to test their performance under the same gravity as that on the extraterrestrial body where they are to be deployed. However, it is challenging to do so in a terrestrial laboratory or test facility. The current practice is to conduct tests on earth on a soil simulant, with the normal load on the rover/rover wheel identical to that expected on the extraterrestrial surface, taking into account its acceleration due to gravity. This practice has been adopted by space research centres, laboratories and agencies in many countries over the past few decades. For instance, various wheel candidates for the lunar roving vehicle for the Apollo missions of the U.S. National Aeronautics and Space Administration (NASA) were tested with normal loads on the wheels identical to those expected on the lunar surface with gravity equal to 1/6 of that on the earth surface [1,2]. As noted previously, the soil simulant used in the tests is subject to earth gravity, while the regolith on the extraterrestrial surface is subject to a different gravity. It is uncertain, therefore, that the performance of the rover/rover wheel obtained from tests conducted on earth would represent that on the extraterrestrial surface [1,3].

The issue of predicting the performance of rover wheels on extraterrestrial surfaces based on test results obtained on earth has been previously explored [1]. A method of approach to testing the performance of rovers/rover wheels

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Nomenclature

b	smaller dimension of contact patch
c	cohesion of soil
D	diameter of a wheel
g	acceleration due to earth gravity (9.81 m/s^2)
g_e	acceleration due to gravity on earth surface
g_{ex}	acceleration due to gravity on extraterrestrial surface
K_c, K_ϕ	pressure–sinkage parameters of the modified Reece equation
K_{ce}, $K_{\phi e}$	pressure–sinkage parameters of the modified Reece equation for soil under gravity g_e
K_{cex}, $K_{\phi ex}$	pressure–sinkage parameters of the modified Reece equation for soil under gravity g_{ex}
k'_c, k'_ϕ	pressure–sinkage parameters for the original Reece equation
m	mass carried by a wheel
n	exponent of the Reece pressure–sinkage equation
n_e	exponent of the Reece pressure–sinkage equation for soil under gravity g_e
n_{ex}	exponent of the Reece pressure–sinkage equation for soil under gravity g_{ex}
p	pressure
R_c	compaction resistance of a rigid wheel
R_{ce}	compaction resistance of a rigid wheel under gravity g_e
R_{cex}	compaction resistance of a rigid wheel under gravity g_{ex}
T_e	driving torque of a rigid wheel under gravity g_e
T_{ex}	driving torque of a rigid wheel under gravity g_{ex}
W	normal load (force) on a wheel
z	sinkage
z_e	sinkage of a rigid wheel under gravity g_e
z_{ex}	sinkage of a rigid wheel under gravity g_{ex}
γ_m	mass density of soil
ϕ	angle of internal shearing resistance of soil

on earth with identical mass to that on the extraterrestrial surface, instead of with identical normal load used in the current practice, has been proposed [1]. This method has the following merits:

A. It does not require additional equipment, such as an elaborate system with a robotic crane used in some research establishments, to reduce (or control) the normal load of the rover/rover wheel applied to the soil simulant during tests on earth.
B. The procedures for predicting the performance of rovers/rover wheels on extraterrestrial surfaces based on test results obtained on earth are greatly simplified. For instance, if the parameters characterizing the mechanical properties of the regolith on the extraterrestrial surface are the same as those of the soil simulant used in tests on earth, then it is predicted that the wheel sinkage on the extraterrestrial surface, whether on the Moon, Mars or other extraterrestrial body, would be the same as that measured on earth, even though the gravity on the extraterrestrial surface is different from that on the earth surface [1].

This paper presents additional experimental evidence to substantiate the merits of the proposed method of approach to predicting the performance of rover wheels on extraterrestrial surfaces based on test data obtained on earth. As rigid wheels are used in many extraterrestrial rovers, such as NASA's Mars Exploration Rovers, *Spirit and Opportunity*, this paper focuses on the study of the sinkage and compaction resistance of rigid rover wheels.

2. Predicting wheel sinkage on extraterrestrial surfaces based on test data obtained on earth, with identical wheel mass on both the extraterrestrial and the earth surfaces

2.1. Analysis

The basis for the proposed method of approach to predicting rigid rover wheel sinkage and compaction resistance on extraterrestrial surfaces based on test data obtained on earth has been outlined in a previous paper [1]. However, for the convenience of the reader, it is summarized below.

The Bekker approach is followed in the development of the method for predicting the performance of rigid rover wheels, as it has been widely used in the study of extraterrestrial rover mobility [1]. However, the Reece pressure–sinkage equation given below is used for predicting the sinkage and compaction resistance of rigid rover wheels, as it takes into account the effect of gravity [1,4]:

$$p = (ck'_c + \gamma_m g b k'_\phi)\left(\frac{z}{b}\right)^n = \left(\frac{ck'_c}{b^n} + \frac{\gamma_m g k'_\phi}{b^{n-1}}\right)z^n = (K_c + gK_\phi)z^n \quad (1)$$

where b is the smaller dimension of the contact patch; c is the cohesion of the terrain (regolith); g is the acceleration due to gravity; k'_c and k'_ϕ are non-dimensional pressure–sinkage parameters of the original Reece equation, whereas K_c and K_ϕ are the pressure–sinkage parameters of the modified Reece equation; n is a non-dimensional exponent; p is pressure; z is sinkage; and γ_m is the mass density of the terrain (regolith). The basic features of the Reece equation have been substantiated by experimental data obtained with homogeneous soils [4].

Using the model for rigid wheel-soil interaction proposed by Bekker [5–7] and incorporating the modified Reece pressure–sinkage equation, Eq. (1), the sinkage of a rigid wheel may be expressed by:

$$z = \left[\frac{3mg}{b(3-n)(K_c + gK_\phi)\sqrt{D}}\right]^{2/(2n+1)} \quad (2)$$

where D is the wheel diameter; m is the mass carried by the wheel; and all other parameters have been defined earlier.

The ratio of the rigid rover wheel sinkage on the extraterrestrial surface z_{ex} to that on the earth surface z_e may be expressed by [1]

$$\frac{z_{ex}}{z_e} = \frac{\left[\dfrac{3mg_{ex}}{b(3-n_{ex})(K_{cex} + g_{ex}K_{\phi ex})\sqrt{D}}\right]^{2/(2n_{ex}+1)}}{\left[\dfrac{3mg_e}{b(3-n_e)(K_{ce} + g_eK_{\phi e})\sqrt{D}}\right]^{2/(2n_e+1)}} \quad (3)$$

where n_{ex}, K_{cex} and $K_{\phi ex}$ are the pressure–sinkage parameters of the regolith on the extraterrestrial surface under gravity g_{ex}; whereas the pressure–sinkage parameters of the soil simulant under earth gravity g_e are designated as n_e, K_{ce} and $K_{\phi e}$, to differentiate them from those on the extraterrestrial surface.

If the soil simulant used in the tests on earth and the regolith on the extraterrestrial surface are dry with low cohesion (i.e., the values of K_{cex} and K_{ce} being insignificant), and $n_{ex} = n_e$ and $K_{\phi ex} = K_{\phi e}$, then Eq. (3) may be simplified to [1]

$$\frac{z_{ex}}{z_e} = 1 \quad (4)$$

Eq. (4) indicates that with identical mass carried by the wheel on both the extraterrestrial and the earth surfaces, the sinkage of the rigid rover wheel on the extraterrestrial surface with any gravity is simply equal to that measured on the earth surface. This finding is of significance as it greatly simplifies the prediction of the rigid rover wheel sinkage on the extraterrestrial surface based on that measured on earth.

It should be pointed out that while Eq. (4) is based on certain simplifying assumptions, experimental evidence presented later substantiates its effectiveness in estimating the sinkage of rigid rover wheels under various gravity conditions based on test data obtained on earth.

It should also be noted that the wheel sinkage predicted using Eq. (2) and the sinkage ratio z_{ex}/z_e predicted using Eq. (3) or (4) do not take into account the effect of slip on sinkage. The additional sinkage due to slip is commonly known as slip–sinkage. The issue of the effect of slip on the sinkage ratio z_{ex}/z_e will be discussed later in Section 2.3.

2.2. Comparison of predictions with test data

The predictions obtained using Eq. (4), with identical wheel mass on both the extraterrestrial and the earth surfaces, are evaluated with test data [8]. The tests were conducted with a rigid wheel in a soil bin on the ground and in an aircraft undergoing various parabolic flight manoeuvres to produce different gravity conditions, as shown in Fig. 1 [8]. As illustrated in the figure, various gravity conditions in the aircraft can be produced by adjusting the ascent or descent path in flight manoeuvres. The rigid wheel had a diameter and a width of 150 and 80 mm, respectively. The mass of the wheel was 10 kg. A lunar soil simulant and a particular type of sand, known as Toyoura sand, were used in the tests. The basic properties of these two types of soils with relative densities of 50% and 70% are given in Table 1 [8]. The soil was contained in a bin with length of 600 mm, width of 200 mm, and depth of 100 mm. The values of the pressure–sinkage parameters of the two soil simulants used in the tests (such as n, K_c and K_ϕ in the modified Reece equation, Eq. (1)), are not given [8].

Two sets of experiments were performed. One was carried out on the ground with loads on the wheel equal to 1/6, 1/2, 3/4, 1, and 2 of the weight W (10 kg × 9.81 m/s^2). The sinkages of the wheel measured on the ground with loads of 1/6 W, 1/2 W, 3/4 W, 1 W, and 2 W, while moving under self-propelled conditions (without drawbar load), on the lunar soil simulant (denoted by LSS in the figures) with relative densities of 50% and 70% and on Toyoura sand (denoted by Toyoura in the figures) with relative densities of 50% and 70% at various times are shown in Figs. 2a–5a, respectively. The other set of experiments was performed in the soil bin installed in an aircraft undergoing various parabolic flight manoeuvres to produce different gravity conditions. The wheel sinkages measured under gravities of 1/6g, 1/2g, 3/4g, 1g, and 2g (g = 9.81 m/s^2) on the lunar soil simulant with relative densities of 50% and 70% and on Toyoura sand with relative densities of 50% and 70% at various times are shown in Figs. 2b–5b, respectively.

As noted previously, one of the objectives of this study is to further verify experimentally the proposed method for estimating the sinkage of rigid rover wheels on extraterrestrial surfaces based on test data obtained on earth. Consequently, the focus is on analyzing the test data for determining the ratio of wheel sinkage z_{ex} measured at various gravities to that measured on the ground z_e at earth gravity under similar operating conditions (such as at the corresponding time instants from the beginning of the test shown in the figures, or under comparable wheel slips discussed in Section 2.3). Therefore, whether the test run reaches a steady-state or not is of little concern in determining the sinkage ratio z_{ex}/z_e. Furthermore, it should be mentioned that during the tests on the ground and in the aircraft, the wheel was driven by a motor that can maintain a constant rotating speed of 0.314 rad/s (3 rpm). The sinkage-time characteristics shown in the figures indicate that the inertia (dynamic) effect on test results is insignificant and negligible. The time-varying characteristics of wheel sinkage shown in the figures are likely due to the slip–sinkage effect, which will be discussed later in Section 2.3. The procedure for determining the sinkage ratio z_{ex}/z_e from test data is described below.

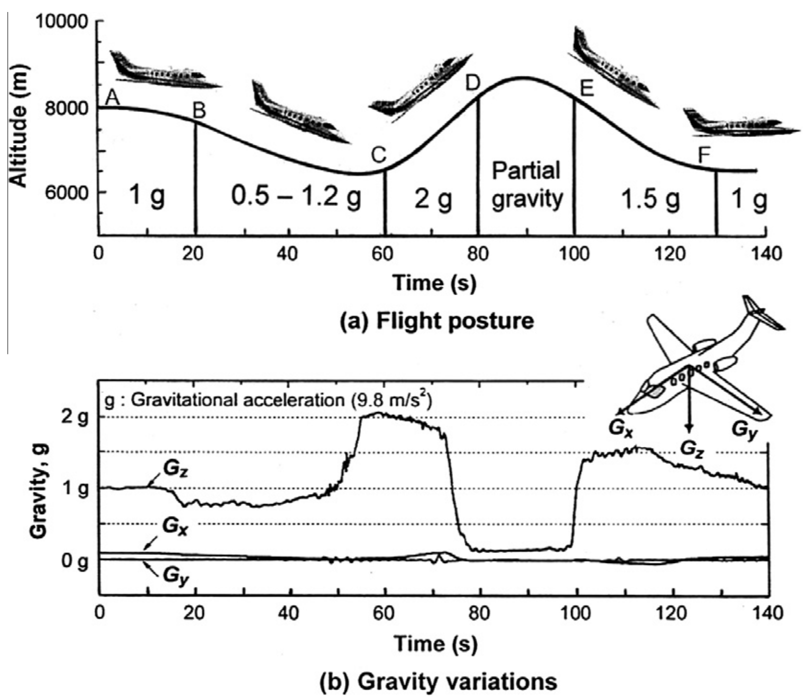

Fig. 1. Parabolic flight manoeuvres to produce various gravity conditions. *Source*: Kobayashi et al. [8].

Table 1
Bulk densities, void ratio and shear strength parameters of the lunar soil simulant and Toyoura sand at relative densities of 50% and 70% used in the tests. *Source*: Kobayashi et al. [8]

Soil	Relative density D_r (%)	Bulk density ρ (g/cm^3)	Void ratio, e	Cohesion[a] c' (kN/m^2)	Internal friction angle[a] Φ' (°)
Lunar soil simulant	50	1.71	0.72	1.07	40.1
	70	1.82	0.62	2.78	44.6
Toyoura sand	50	1.47	0.80	2.08	38.2
	70	1.54	0.73	2.66	40.7

[a] Cohesion and internal friction angle were obtained from drained triaxial compression tests.

To compare the measured wheel sinkage z_{ex}, when both the wheel and the soil simulant are subject to gravity g_{ex} in the aircraft, with the sinkage z_e of the wheel carrying identical wheel mass measured on the ground subject to earth gravity g_e, a specific procedure is followed to process the test data shown in the figures. The data shown in Fig. 2a and b for the lunar soil simulant with relative density of 50% are used as an example to illustrate the procedure involved. For instance, with the wheel carrying identical mass (i.e., 10 kg) on the ground and under gravity of $1/2g$, the sinkage ratio z_{ex}/z_e at time 5 s is calculated by the ratio of the wheel sinkage z_{ex} measured under $1/2g$ at time 5 s shown in Fig. 2b (or Table 2) to that z_e measured on the ground at wheel load of 1 W at time 5 s shown in Fig. 2a (or Table 2). It should be noted that the mass carried by the wheel (10 kg) while under various gravities in the aircraft is identical to that on the ground with wheel load of 1 W (10 kg × 9.81 m/s^2). From the data shown in Fig. 2b or Table 2, under gravity of $1/2g$ the sinkage z_{ex} at time 5 s is 9.26 mm, whereas from Fig. 2a or Table 2 with wheel load of 1 W on the ground, the sinkage z_e at time 5 s is 10.8 mm. Therefore, with identical wheel mass of 10 kg, under gravity $g_{ex} = 1/2g$ at time 5 s, the sinkage ratio $z_{ex}/z_e = 9.26/10.8 = 0.86$, as shown in the fourth row under the column of time 5 s in Table 2. In the table, the first row lists the times at which the measurements of wheel sinkage were taken. In the second row, the wheel sinkages z_{ex} under gravity $g_{ex} = 1/2g$ at various times are given, whereas in the third row, the wheel sinkages z_e under wheel load of 1 W measured on the ground under earth gravity g_e at various times are shown. In the fourth row, the values of sinkage ratio z_{ex}/z_e at various times are given. Following the same procedure, the measured values of the sinkage ratio z_{ex}/z_e under various gravities g_{ex} at different times on the lunar soil simulant with relative densities of 50% and 70% and on Toyoura sand with relative densities of 50% and 70% are presented in Table 2.

It can be seen from the table that the sinkage ratio z_{ex}/z_e under different gravities in the range of times shown varies within a relatively narrow band around one (unity). For instance, as can be seen from the last column on the right of Table 2, on the lunar soil simulant with relative density of 50%, the average value of the sinkage ratio z_{ex}/z_e varies from 1.05 to 1.09 within the gravity range from $1/2g$ to $2g$.

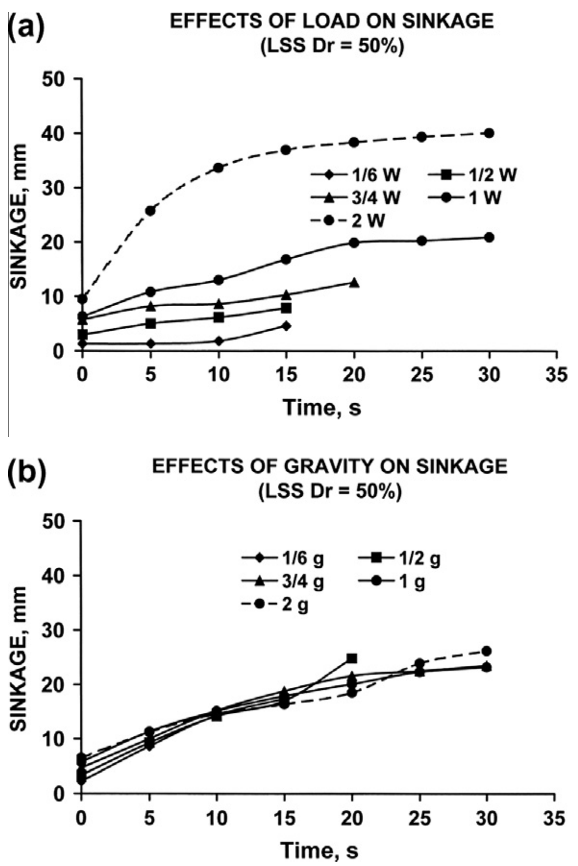

Fig. 2. (a) Sinkages under different loads measured on the ground and (b) sinkages under various gravities measured in an aircraft at various times on the lunar soil simulant with relative density of 50%.

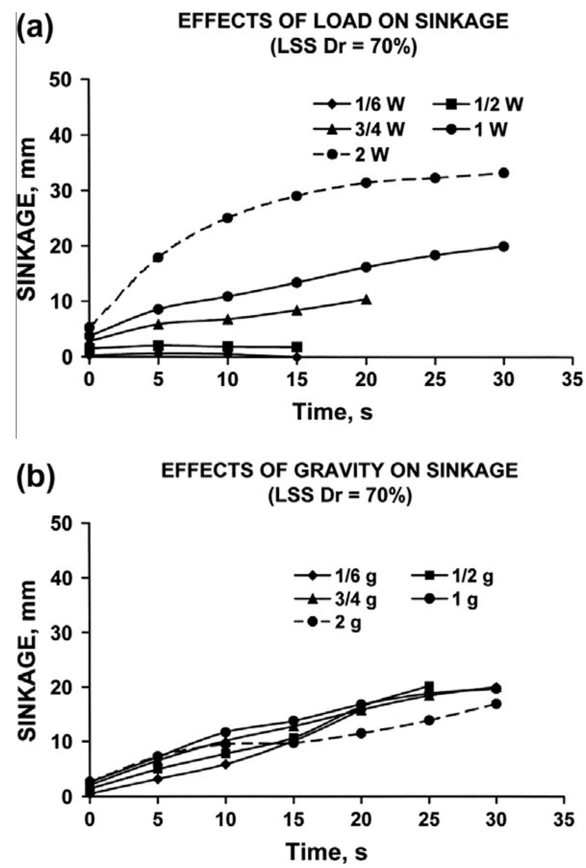

Fig. 3. (a) Sinkages under different loads measured on the ground and (b) sinkages under various gravities measured in an aircraft at various times on the lunar soil simulant with relative density of 70%.

On Toyoura sand with relative density of 70%, the average value of the sinkage ratio z_{ex}/z_e varies from 1.0 to 1.09 within the same gravity range. Thus the prediction using Eq. (4) that with identical wheel mass the wheel sinkage under various gravity conditions should be the same as that measured on earth under earth gravity is quite well borne out by the test data, at least to a first approximation.

The average values of the sinkage ratio z_{ex}/z_e under various gravity conditions over the specific range of times, on the lunar soil simulant and Toyoura sand with two relative densities, shown in the last column on the right of Table 2, are plotted against the gravity ratio g_{ex}/g_e in Fig. 6. It should be noted that the variation of the sinkage ratio z_{ex}/z_e with the gravity ratio g_{ex}/g_e predicted by Eq. (4) is represented by a horizontal line with $z_{ex}/z_e = 1$ in Fig. 6.

It should be mentioned that under normal load of 1/6 W, the wheel sinkage is small (such as that shown in Fig. 3a) and is susceptible to errors in measurements. This causes irregularities in the wheel sinkage ratio z_{ex}/z_e under gravity $g_{ex} = 1/6g$. For this reason, the values of the wheel sinkage ratio z_{ex}/z_e under gravity $g_{ex} = 1/6g$ for the lunar soil simulant and Toyoura sand with two relative densities are not shown in Fig. 6 and Table 2.

As can be seen from Fig. 2b, for instance, the curves representing the variations of wheel sinkage z_{ex} with time, measured under gravity ranging from $1/6g$ to $2g$, are close together. This indicates that gravity has insignificant effects on wheel sinkage with identical wheel mass. Furthermore, these curves are similar to that measured on the ground with wheel load 1 W (i.e., with identical mass of 10 kg) shown in Fig. 2a. This set of test data again substantiates the prediction based on Eq. (4) that with identical wheel mass on both the extraterrestrial and the earth surfaces, the sinkage z_{ex} under gravity g_{ex} should be the same as the sinkage z_e under earth gravity g_e. Similar observations may be made from Figs. 3b–5b, with the exception on Toyoura sand with relative density of 70%, where the curve for $1/6g$ is an anomaly, as shown in Fig. 5b.

In summary, despite the probable errors in measurements of wheel sinkage, particularly under low gravity or low load, and the neglect of the effect of slip on sinkage and soil cohesion in the analysis, all experimental evidence presented above appears to substantiate, at least to a first approximation, the predictions using Eq. (4) that for a rigid wheel with identical mass on the extraterrestrial and the earth surfaces, the sinkage z_{ex} on the extraterrestrial surface under gravity g_{ex} should be the same as that measured on the earth surface z_e under gravity g_e, if the regolith on the extraterrestrial surface and the soil simulant used in the tests conducted on earth have negligible cohesion and the same pressure–sinkage parameters (i.e., $n_{ex} = n_e$ and $K_{\phi ex} = K_{\phi e}$).

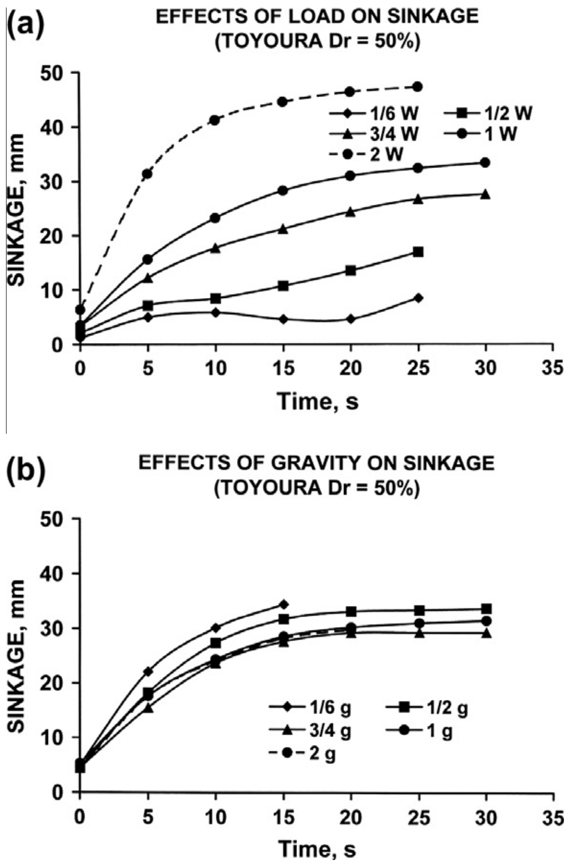

Fig. 4. (a) Sinkages under different loads measured on the ground and (b) sinkages under various gravities measured in an aircraft at various times on Toyoura sand with relative density of 50%.

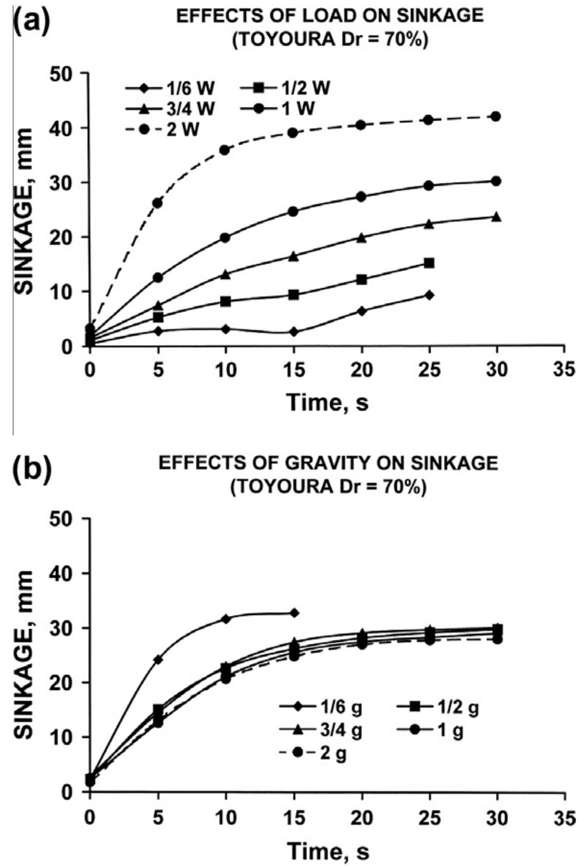

Fig. 5. (a) Sinkages under different loads measured on the ground and (b) sinkages under various gravities measured in an aircraft at various times on Toyoura sand with relative density of 70%.

2.3. Slip–sinkage and sinkage ratio z_{ex}/z_e

Slip–sinkage has been a subject of study since the early stage of development of terramechanics, and a number of methods for predicting the additional sinkage of vehicle running gear due to slip have been proposed [4,9]. So far a generally accepted method is lacking for predicting slip–sinkage in relation to terrain characteristics and design parameters and operating conditions of the wheel, including wheel slip. It is noted, however, that attempts have recently been made to simulate the slip–sinkage phenomenon using the discrete element method (DEM) [10]. In this study, a pragmatic approach, based on experimental data [8], is followed to address the issue of the effect of wheel slip on the sinkage ratio z_{ex}/z_e.

Table 3 shows the wheel slip i_{ex} measured during tests in the aircraft under various gravities and the wheel slip i_e measured on the ground with identical wheel mass, at various times on the lunar soil simulant and Toyoura sand with two different relative densities. It is noted that at the same time instant, the wheel slip i_{ex} measured under various gravities are generally comparable to that measured on the ground i_e. In other words, the slip ratio i_{ex}/i_e varies within a relatively narrow band around one (unity). As can be seen in Table 3, the average slip ratio i_{ex}/i_e under various gravities shown in the last column on the right of Table 3, varies from 0.86 to 1.17 on the lunar soil simulant and Toyoura sand with relative densities of 50% and 70%, with the exceptions at gravity of $1/2g$ on the lunar soil simulant with relative density of 50% and Toyoura sand with relative density of 70%, where the values of the slip ratio i_{ex}/i_e are 1.52 and 1.23, respectively. Fig. 7 shows the variations of slip ratio i_{ex}/i_e with gravity ratio g_{ex}/g_e on the lunar soil simulant and Toyoura sand with two relative densities. The value of the slip ratio i_{ex}/i_e being close to unity under various gravities would indicate, at least to a first approximation, that gravity may have insignificant effect on wheel slip under self-propelled conditions during the tests.

Using the data shown in Tables 2 and 3, the relationships between sinkage and slip under various gravities and on the ground with identical wheel mass can be established. The wheel sinkage z_{ex} or z_e at a given time instant and the corresponding slip i_{ex} or i_e can be identified from Table 2 and Table 3, respectively. The relationship between sinkage z_{ex} and i_{ex} and that between z_e and i_e can, therefore, be established. For instance, from the second row of Table 2, on the lunar soil simulant with relative density of 50%, under gravity of $1/2g$ at time of 5 s, the wheel sinkage z_{ex} is 9.26 mm. From the second row of Table 3, on the same soil, under gravity of $1/2g$ at time of 5 s, the wheel slip i_{ex} is 0.36. Thus, on the lunar soil simulant with relative density of 50%, under gravity of $1/2g$ at slip $i_{ex} = 0.36$, the measured

Table 2
Summary of wheel sinkage data on z_{ex}, z_e, and z_{ex}/z_e and at different times and under various gravities on the lunar soil simulant (LSS) and Toyoura sand with relative densities of 50% and 70%.

Time (s)			5	10	15	20	25	30	Average z_{ex}/z_e for a given g
LSS (Dr = 50%)	1/2g	z_{ex}, mm	9.26	14.2	17	24.8			
		z_e, mm	10.8	13	16.8	19.9			
		z_{ex}/z_e	0.86	1.09	1.01	1.25			1.05
	3/4g	z_{ex}, mm	9.99	15.2	18.8	21.6	22.5	23.5	
		z_e, mm	10.8	13	16.8	19.9	20.3	20.9	
		z_{ex}/z_e	0.93	1.17	1.12	1.09	1.11	1.12	1.09
	1g	z_{ex}, mm	11.3	15.1	17.9	20.1	22.3	23.2	
		z_e, mm	10.8	13	16.8	19.9	20.3	20.9	
		z_{ex}/z_e	1.05	1.16	1.07	1.01	1.10	1.11	1.08
	2g	z_{ex}, mm	11.2	14.6	16.4	18.5	23.9	26.2	
		z_e, mm	10.8	13	16.8	19.9	20.3	20.9	
		z_{ex}/z_e	1.04	1.12	0.98	0.93	1.18	1.25	1.08
	Average z_e/z_e for a given time		0.97	1.14	1.07	1.07	1.13	1.15	
LSS (Dr = 70%)	1/2g	z_{ex}, mm	4.95	7.78	10.7	16.4	20.2		
		z_e, mm	8.54	10.9	13.4	16.2	18.4		
		z_{ex}/z_e	0.58	0.71	0.80	1.01	1.10		0.84
	3/4g	z_{ex}, mm	6.56	10.1	12.8	15.8	18.4	20	
		z_e, mm	8.54	10.9	13.4	16.2	18.4	20	
		z_{ex}/z_e	0.77	0.93	0.96	0.98	1.0	1.0	0.94
	1g	z_{ex}, mm	7.2	11.7	13.8	16.8	18.8	19.7	
		z_e, mm	8.54	10.9	13.4	16.2	18.4	20	
		z_{ex}/z_e	0.84	1.07	1.03	1.04	1.02	0.99	1.0
	2g	z_{ex}, mm	7.31	9.5	9.75	11.5	13.9	16.9	
		z_e, mm	8.54	10.9	13.4	16.2	18.4	20	
		z_{ex}/z_e	0.86	0.87	0.73	0.71	0.76	0.85	0.80
	Average z_e/z_e for a given time		0.76	0.90	0.88	0.94	0.97	0.95	
Toyoura (Dr = 50%)	1/2g	z_{ex}, mm	18.2	27.4	31.8	33.2	33.5	33.8	
		z_e, mm	15.6	23.2	28.3	31	32.4	33.4	
		z_{ex}/z_e	1.17	1.18	1.12	1.07	1.03	1.07	1.10
	3/4g	z_{ex}, mm	15.5	23.7	27.7	29.3	29.4	29.4	
		z_e, mm	15.6	23.2	28.3	31	32.4	33.4	
		z_{ex}/z_e	0.99	1.02	0.98	0.95	0.91	0.88	0.96
	19	z_{ex}, mm	17.6	24.4	28.6	30.3	31.1	31.6	
		z_e, mm	15.6	23.2	28.3	31	32.4	33.4	
		z_{ex}/z_e	1.13	1.05	7.07	0.98	0.96	0.95	1.01
	2g	z_{ex}, mm	17.6	24.1	28.3	29.9			
		z_e, mm	15.6	23.2	28.3	31			
		z_{ex}/z_e	1.13	1.04	1.0	0.96			1.03
	Average z_e/z_e for a given time		1.11	1.07	1.03	0.99	0.97	0.95	
Toyoura (Dr = 70%)	1/2g	z_{ex}, mm	15.1	22.7	26.3	28.3	29.3	29.9	
		z_e, mm	12.5	19.8	24.6	27.3	29.3	30.1	
		z_{ex}/z_e	1.21	1.15	1.07	1.04	1.0	0.96	1.07
	3/4g	z_{ex}, mm	14.5	23	27.5	29.2	29.8	30.2	
		z_e, mm	12.5	19.8	24.6	27.3	29.3	30.1	
		z_{ex}/z_e	1.16	1.16	1.12	1.07	1.02	1.0	1.09
	1g	z_{ex}, mm	12.6	21.1	25.6	27.6	28.4	29.2	
		z_e, mm	12.5	19.8	24.6	27.3	29.3	30.1	
		z_{ex}/z_e	1.01	1.07	1.04	1.01	0.97	0.97	1.01
	2g	z_{ex}, mm	13.1	20.7	24.9	27.1	27.9	28.1	
		z_e, mm	12.5	19.8	24.6	27.3	29.3	30.1	
		z_{ex}/z_e	1.05	1.05	1.01	0.99	0.95	0.93	1.0
	Average z_{ex}/z_e for a given time		1.11	1.11	1.06	1.03	0.99	0.97	

sinkage z_{ex} is 9.26 mm, which takes into account the effect of slip or the slip–sinkage. Similarly, on the same soil on the ground, from the third row of Table 2, under wheel load 1 W (with identical wheel mass of 10 kg) at time 5 s, the wheel sinkage z_e is 10.8 mm. From the third row of Table 3 on the same soil on the ground, under wheel load 1 W at time 5 s, the wheel slip i_e is 0.23. Thus, on the lunar soil simulant with relative density of 50%, on the ground under wheel load of 1 W at slip $i_e = 0.23$, the measured sinkage z_e is 10.8 mm, which takes into account the effect of slip or the slip–sinkage.

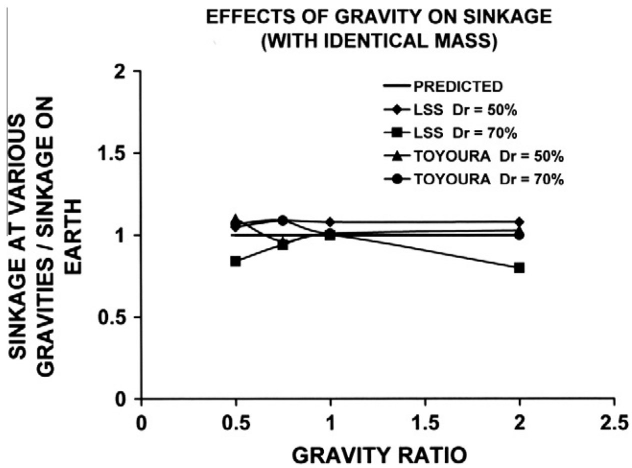

Fig. 6. Comparison of the variations of sinkage ratio z_{ex}/z_e with gravity ratio g_{ex}/g_e of a rigid wheel predicted by the proposed method with those measured on different types of soil.

Figs. 8–11 show the relationships between sinkage z_{ex} and slip i_{ex} measured under various gravities, as well as those between z_e and slip i_e measured on the ground with identical wheel mass, on the lunar soil simulant with relative densities of 50% and 70% and on Toyoura sand with relative densities of 50% and 70%, respectively. A straight line is fitted to the test data shown in each figure using the least squares method. The goodness-of-fit in all cases appears to be excellent, as indicated by the high value of the coefficient of determination R^2. For instance, on Toyoura sand with relative density of 70% shown in Fig. 11, R^2 is 0.988 ($R^2 = 1$ indicating a perfect fit).

It shows that in all cases, the variation with slip of sinkage z_{ex} measured under various gravities and that of sinkage z_e measured on the ground with identical wheel mass exhibit the same trend and that both essentially follow the same fitted line. In other words, at comparable slip, the value of z_{ex} is reasonably close (or equal) to that of z_e. This provides experimental evidence to support the predictions using Eq. (4) that the sinkage of a rigid wheel on the extraterrestrial surface under any gravity should be the same as that measured on the earth surface, even the wheel operating with slip and with notable slip–sinkage, provided that the wheel slip on the extraterrestrial surface and that on the earth surface are comparable.

2.4. Effects of gravity on pressure–sinkage parameters

Eq. (4) in Section 2.1 indicates that with identical mass carried by the wheel on both the extraterrestrial and the earth surfaces, the sinkage of the rigid rover wheel on the extraterrestrial surface with any gravity should be equal to that measured on the earth surface. This is based on the assumption that the soil simulant used in the tests on earth and the regolith on the extraterrestrial surface have the same pressure–sinkage parameters (i.e., $n_e = n_{ex}$ and $K_{\phi e} = K_{\phi ex}$, with negligible K_{ce} and K_{cex}).

This implies that in processing the sinkage data shown in Fig. 2a and b–5a and b, it is assumed that gravity would not affect the pressure–sinkage parameters. In other words, the values of n_{ex} and $K_{\phi ex}$ of the lunar soil simulant and those of Toyoura sand with two relative densities under various gravity conditions produced in the aircraft undergoing parabolic flight manoeuvres are the same as those of n_e and $K_{\phi e}$ of the two types of soil on the ground. This assumption cannot be directly evaluated, as these soil parameters were not measured during tests on the ground and in the aircraft. The reasonably close correlation between the predictions using Eq. (4) and the experimental data presented in Table 2 and Fig. 6, however, does provide support for the notion that gravity has insignificant effect on the values of the pressure–sinkage parameters. In other words, based on the reasonably close correlation between the experimental data presented and the predictions obtained using Eq. (4), it may be inferred that gravity has little effect on the pressure–sinkage parameters of the two types of soil with two different relative densities examined in this study, at least to a first approximation. Further analytical and experimental study will be required, however, before a general conclusion on the effect of gravity on pressure–sinkage parameters of soils can be reached.

It should be pointed out that while the values of the pressure–sinkage parameters of the two types of soil with two relative densities examined (such as n and K_ϕ in Eq. (1)) do not appear to be significantly affected by gravity, the overall pressure–sinkage relationship is still affected by gravity, as Eq. (1) contains the gravity term g.

3. Predicting wheel compaction resistance on extraterrestrial surfaces based on test data obtained on earth, with identical wheel mass on both the extraterrestrial and the earth surfaces

3.1. Analysis

Based on the concept of compaction resistance of a wheel being related to the vertical work done in compressing the soil from the original surface to the rut depth, proposed by Bekker, and making use of Eq. (2) for predicting rigid wheel sinkage (or rut depth), one obtains the following equation for determining the compaction resistance of a rigid wheel R_c [5–7]:

$$\begin{aligned} R_c &= b(K_c + gK_\phi)\left(\frac{z^{n+1}}{n+1}\right) \\ &= \left(\frac{b(K_c + gK_\phi)}{n+1}\right)\left[\frac{3mg}{b(3-n)(K_c + gK_\phi)\sqrt{D}}\right]^{(2n+2)/(2n+1)} \\ &= \left[\frac{1}{(3-n)^{(2n+2)/(2n+1)}(n+1)b^{1/(2n+1)}(K_c + gK_\phi)^{1/(2n+1)}}\right] \\ &\quad \times \left[\frac{3mg}{\sqrt{D}}\right]^{(2n+2)/(2n+1)} \end{aligned} \tag{5}$$

The ratio of the rigid wheel compaction resistance on the extraterrestrial surface R_{cex} to that on the earth surface R_{ce} is given by [1]

Table 3
Summary of wheel slip data on i_{ex}, i_e, and i_{ex}/i_e at different times and under various gravities on the lunar soil simulant (LSS) and Toyoura sand at relative densities of 50% and 70%.

Time (s)			1.5	5	10	15	20	25	30	Average i_{ex}/i_e for a given g
LSS (Dr = 50%)	1/2g	i_{ex}	0.09	0.36	0.54	0.69	0.85			
		i_e	0.1	0.23	0.3	0.38	0.56			
		i_{ex}/i_e	0.9	1.57	1.8	1.82	1.52			1.52
	3/4g	i_{ex}	0.05	0.22	0.37	0.55	0.72	0.79	0.83	
		i_e	0.1	0.23	0.3	0.38	0.56	0.65	0.71	
		i_{ex}/i_e	0.5	0.96	1.23	1.45	1.29	1.22	1.17	1.12
	1g	i_{ex}	0.08	0.33	0.47	0.6	0.67	0.75	0.81	
		i_e	0.1	0.23	0.3	0.38	0.56	0.65	0.71	
		i_{ex}/i_e	0.8	1.43	1.57	1.58	1.20	1.15	1.14	1.17
	2g	i_{ex}	0.04	0.24	0.27	0.35	0.53	0.7	0.83	
		i_e	0.1	0.23	0.3	0.38	0.56	0.65	0.71	
		i_{ex}/i_e	0.4	1.04	0.9	0.92	0.95	1.08	1.17	0.92
LSS (Dr = 70%)	1/2g	i_{ex}	0.09	0.23	0.35	0.42	0.65	0.84	0.9	
		i_e	0.08	0.23	0.34	0.41	0.52	0.76		
		i_{ex}/i_e	1.13	1.0	0.88	1.02	1.25	1.11		1.07
	3/4g	i_{ex}	0.05	0.23	0.38	0.43	0.58	0.71		
		i_e	0.08	0.23	0.34	0.41	0.52	0.76		
		i_{ex}/i_e	0.63	1.0	1.12	1.05	1.12	0.93		0.97
	1g	i_{ex}	0.07	0.26	0.44	0.48	0.63	0.74		
		i_e	0.08	0.23	0.34	0.41	0.52	0.76		
		i_{ex}/i_e	0.88	1.13	1.29	1.17	1.21	0.97		1.11
	2g	i_{ex}	0.05	0.24	0.31	0.35	0.47	0.62		
		i_e	0.08	0.23	0.34	0.41	0.52	0.76		
		i_{ex}/i_e	0.63	1.04	0.91	0.85	0.9	0.82		0.86
Toyoura (Dr = 50%)	1/2g	i_{ex}	0.07	0.45	0.73	0.87	0.93	0.97	0.98	
		i_e	0.1	0.41	0.63	0.79	0.87	0.92	0.93	
		i_{ex}/i_e	0.7	1.10	1.16	1.10	1.07	1.05	1.05	1.03
	3/4g	i_{ex}	0.12	0.47	0.71	0.84	0.9	0.92	0.93	
		i_e	0.1	0.41	0.63	0.79	0.87	0.92	0.93	
		i_{ex}/i_e	1.2	1.15	1.13	1.06	1.03	1.0	1.0	1.08
	1g	i_{ex}	0.11	0.46	0.73	0.85	0.9	0.93	0.94	
		i_e	0.1	0.41	0.63	0.79	0.87	0.92	0.93	
		i_{ex}/i_e	1.1	1.12	1.16	1.08	1.03	1.01	1.01	1.07
	2g	i_{ex}	0.13	0.45	0.63	0.77	0.87			
		i_e	0.1	0.41	0.63	0.79	0.87			
		i_{ex}/i_e	1.3	1.1	1.0	0.97	1.0			1.07
Toyoura (Dr = 70%)	1/2g	i_{ex}	0.12	0.54	0.78	0.89	0.92	0.95	0.96	
		i_e	0.08	0.36	0.64	0.74	0.85	0.9	0.91	
		i_{ex}/i_e	1.5	1.5	1.22	1.20	1.08	1.06	1.05	1.23
	3/4g	i_{ex}	0.08	0.5	0.73	0.86	0.9	0.93	0.93	
		i_e	0.08	0.36	0.64	0.74	0.85	0.9	0.91	
		i_{ex}/i_e	1.0	1.39	1.14	1.16	1.06	1.03	1.02	1.11
	1g	i_{ex}	0.07	0.43	0.71	0.83	0.9	0.92	0.92	
		i_e	0.08	0.36	0.64	0.74	0.85	0.9	0.91	
		i_{ex}/i_e	0.88	1.19	1.11	1.12	1.06	1.02	1.01	1.06
	2g	i_{ex}	0.09	0.41	0.67	0.77	0.86	0.93	0.93	
		i_e	0.08	0.36	0.64	0.74	0.85	0.9	0.91	
		i_{ex}/i_e	1.13	1.14	1.05	1.04	1.01	1.03	1.02	1.06

$$\frac{R_{cex}}{R_{ce}} = \frac{\left[\dfrac{1}{(3-n_{ex})^{(2n_{ex}+2)/(2n_{ex}+1)}(n_{ex}+1)b^{1/(2n_{ex}+1)}(K_{cex}+g_{ex}K_{\phi ex})^{1/(2n_{ex}+1)}}\right] \times \left[\dfrac{3mg_{ex}}{\sqrt{D}}\right]^{(2n_{ex}+2)/(2n_{ex}+1)}}{\left[\dfrac{1}{(3-n_{e})^{(2n_{e}+2)/(2n_{e}+1)}(n_{e}+1)b^{1/(2n_{e}+1)}(K_{ce}+g_{e}K_{\phi e})^{1/(2n_{e}+1)}}\right] \times \left[\dfrac{3mg_{e}}{\sqrt{D}}\right]^{(2n_{e}+2)/(2n_{e}+1)}} \tag{6}$$

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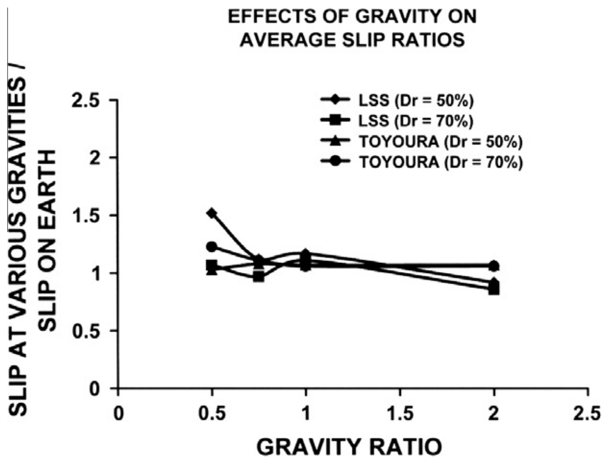

Fig. 7. Variations with gravity of the ratio of wheel slip i_{ex} at which sinkage z_{ex} was measured in an aircraft to the wheel slip i_e at which the corresponding sinkage z_e was measured on the ground on different types of soil.

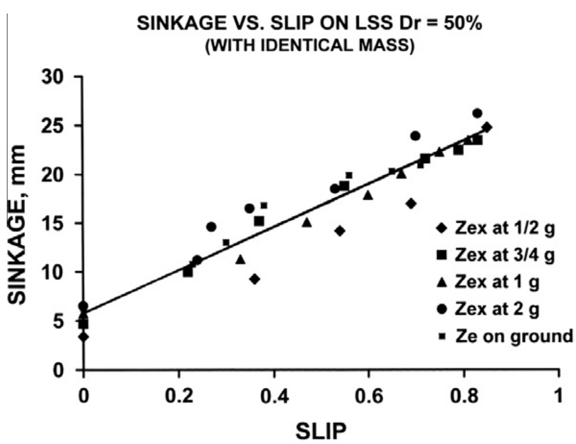

Fig. 8. Relationship between sinkage and slip under various gravities and on the ground on the lunar soil simulant with relative density of 50% (the least squares fit with coefficient of determination $R^2 = 0.9193$).

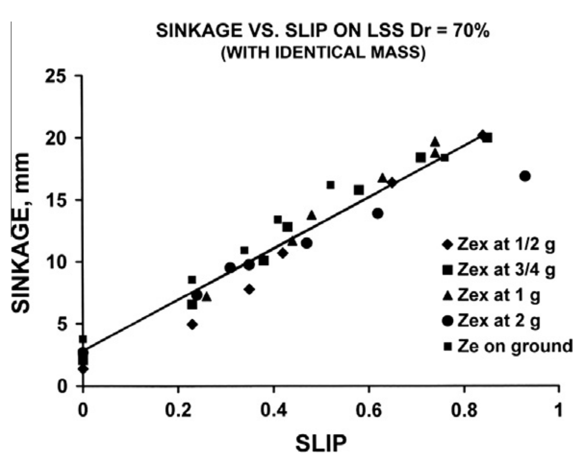

Fig. 9. Relationship between sinkage and slip under various gravities and on the ground on the lunar soil simulant with relative density of 70% (the least squares fit with coefficient of determination $R^2 = 0.9326$).

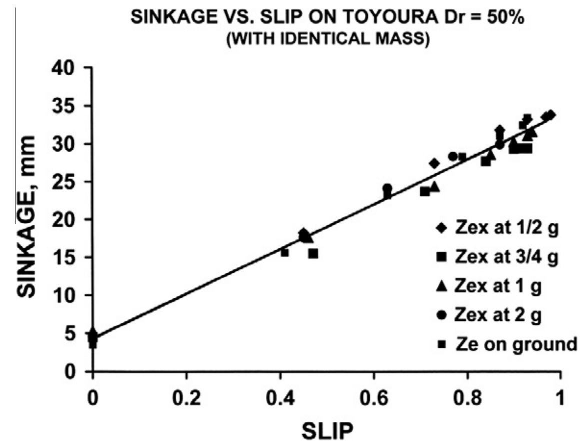

Fig. 10. Relationship between sinkage and slip under various gravities and on the ground on Toyoura sand with relative density of 50% (the least squares fit with coefficient of determination $R^2 = 0.9847$).

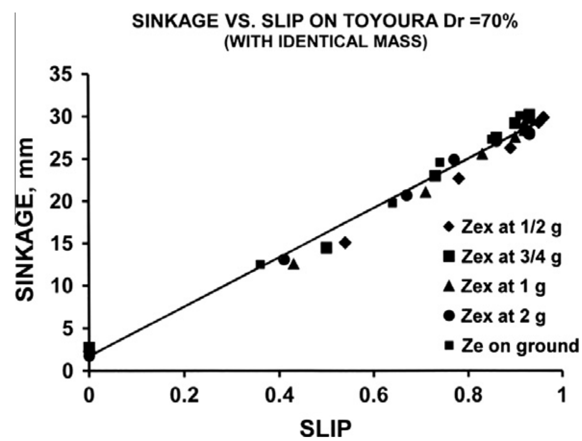

Fig. 11. Relationship between sinkage and slip under various gravities and on the ground on Toyoura sand with relative density of 70% (the least squares fit with coefficient of determination $R^2 = 0.988$).

If the soil simulant used in the tests on earth and the regolith on the extraterrestrial surface are dry with low cohesion (i.e., the values of K_{ce} and K_{cex} being insignificant), and $n_e = n_{ex}$ and $K_{\phi e} = K_{\phi ex}$, then Eq. (6) may be simplified to [1]

$$\frac{R_{cex}}{R_{ce}} = \frac{g_{ex}}{g_e} \tag{7}$$

Eq. (7) indicates that with identical mass carried by the wheel on both the extraterrestrial and the earth surfaces, the compaction resistance ratio R_{cex}/R_{ce} is simply equal to the ratio of the gravity g_{ex} on the extraterrestrial surface to the gravity g_e on the earth surface. This finding is significant, as it simplifies the procedure for predicting the rigid rover wheel compaction resistance R_{cex} on the extraterrestrial surface based on the compaction resistance R_{ce} measured on the ground.

It should be pointed out that while Eq. (7) is based on certain simplifying assumptions, experimental evidence presented later substantiates its effectiveness in estimating the compaction resistance of rigid rover wheels under various gravity conditions based on test data obtained on earth.

3.2. Comparison of predictions with test data

The predictions obtained using Eq. (7), with identical wheel mass on both the extraterrestrial and the earth surfaces, are evaluated with test data obtained under various gravity conditions [8].

Two sets of experiments were performed. One was carried out in the soil bin installed in an aircraft undergoing various parabolic flight manoeuvres to produce different gravity conditions. The measured driving torques applied to the wheel under gravities of $1/6g$, $1/2g$, $3/4g$, $1g$, and $2g$ ($g = 9.81$ m/s^2) at various times on the lunar soil simulant with relative densities of 50% and 70% and on Toyoura sand with relative densities of 50% and 70% are shown in Figs. 12–15, respectively. The measured driving torques obtained under wheel load of 1 W (10 kg × 9.81 m/s^2) on the ground on the two types of soil with two different relative densities are also shown in the respective figures. It should be noted that since the wheel was under self-propelled conditions during the tests, the torque applied to the wheel is proportional to its motion resistance.

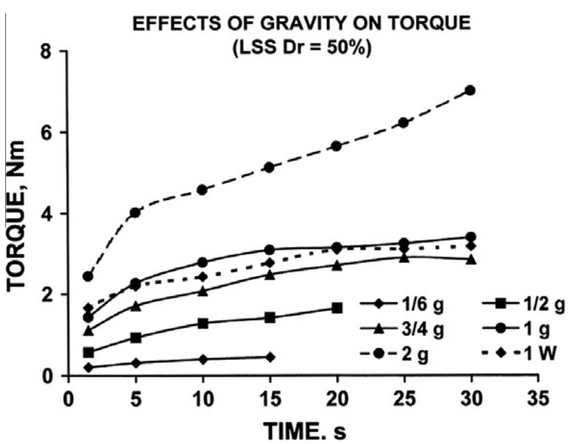

Fig. 12. Wheel torques measured under various gravities in an aircraft and those measured under load of 1 W on the ground at various times on the lunar soil simulant with relative density of 50%.

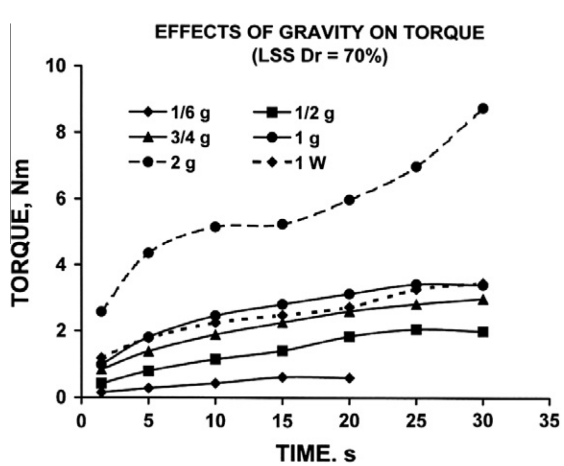

Fig. 13. Wheel torques measured under various gravities in an aircraft and those measured under load of 1 W on the ground at various times on the lunar soil simulant with relative density of 70%.

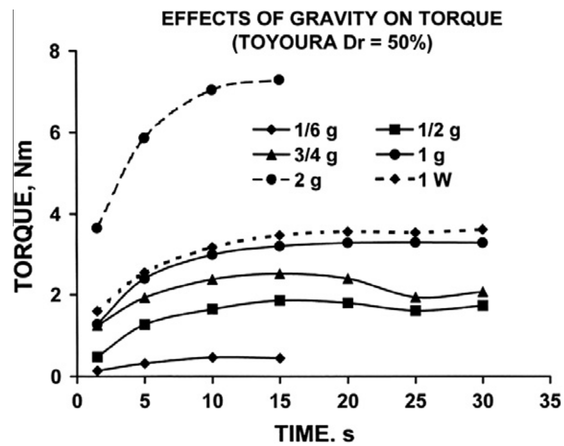

Fig. 14. Wheel torques measured under various gravities in an aircraft and those measured under load of 1 W on the ground at various times on Toyoura sand with relative density of 50%.

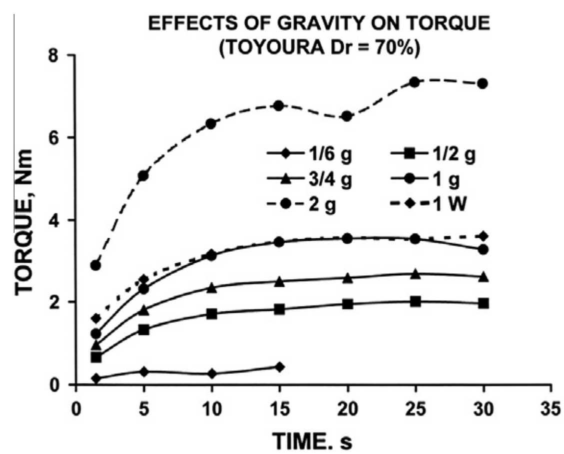

Fig. 15. Wheel torques measured under various gravities in an aircraft and those measured under load of 1 W on the ground at various times on Toyoura sand with relative density of 70%.

As noted previously, one of the objectives of this study is to further verify experimentally the proposed method for estimating the compaction resistance of rigid rover wheels on extraterrestrial surfaces based on test data obtained on earth. Consequently, the focus is on analyzing the test data for determining the ratio of compaction resistance R_{cex} measured at various gravities to that measured on the ground R_{ce} at earth gravity under similar operating conditions (such as at the corresponding time instants from the beginning of the test shown in the figures). Therefore, whether the test run reaches a steady-state or not is of little concern in determining the compaction resistance ratio R_{cex}/R_{ce}. Furthermore, as noted previously, during the tests on the ground and in the aircraft, the wheel was driven by a motor that can maintain a constant rotating speed of 0.314 rad/s (3 rpm). The torque-time characteristics

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Table 4
Summary of measured data on T_{ex}, T_e, and R_{cex}/R_{ce} at different times under various gravities on the lunar soil simulant (LSS) and Toyoura sand at relative densities of 50% and 70%.

Time (s)			1.5	5	10	15	20	25	30	Average R_{cex}/R_{ce} for a given g
LSS (Dr = 50%)	1/6g	T_{ex}, Nm	0.2	0.31	0.4	0.45				
		T_e, Nm	1.66	2.2	2.43	2.77				
		R_{cex}/R_{ce}	0.12	0.14	0.16	0.16				0.15
	1/2g	T_{ex}, Nm	0.57	0.93	1.28	1.42	1.65			
		T_e, Nm	1.66	2.2	2.43	2.77	3.1			
		R_{cex}/R_{ce}	0.34	0.42	0.53	0.51	0.53			0.47
	3/4g	T_{ex}, Nm	1.11	1.71	2.08	2.48	2.71	2.9	2.85	
		T_e, Nm	1.66	2.2	2.43	2.77	3.1	3.11	3.18	
		R_{cex}/R_{ce}	0.67	0.78	0.86	0.90	0.87	0.93	0.90	0.84
	1g	T_{ex}, Nm	1.43	2.27	2.78	3.09	3.15	3.25	3.4	
		T_e, Nm	1.66	2.2	2.43	2.77	3.1	3.11	3.18	
		R_{cex}/R_{ce}	0.86	1.03	1.14	1.12	1.02	1.05	1.07	1.04
	2g	T_{ex}, Nm	2.44	4.02	4.58	5.13	5.65	6.22	7.01	
		T_e, Nm	1.66	2.2	2.43	2.77	3.1	3.11	3.18	
		R_{cex}/R_{ce}	1.47	1.83	1.88	1.85	1.82	2.0	2.20	1.86
LSS (Dr = 70%)	1/6g	T_{ex}, Nm	0.15	0.28	0.43	0.62	0.6			
		T_e, Nm	1.19	1.78	2.25	2.48	2.73			
		R_{cex}/R_{ce}	0.13	0.16	0.19	0.25	0.22			0.19
	1/2g	T_{ex}, Nm	0.42	0.8	1.15	1.41	1.84	2.06	2.0	
		T_e, Nm	1.19	1.78	2.25	2.48	2.73	3.27	3.46	
		R_{cex}/R_{ce}	0.35	0.45	0.51	0.57	0.67	0.63	0.58	0.54
	3/4g	T_{ex}, Nm	0.84	1.39	1.89	2.26	2.6	2.82	2.98	
		T_e, Nm	1.19	1.78	2.25	2.48	2.73	3.27	3.46	
		R_{cex}/R_{ce}	0.71	0.78	0.84	0.91	0.95	0.86	0.86	0.84
	1g	T_{ex}, Nm	0.99	1.81	2.46	2.81	3.13	3.42	3.4	
		T_e, Nm	1.19	1.78	2.25	2.48	2.73	3.27	3.46	
		R_{cex}/R_{ce}	0.83	1.02	1.09	1.13	1.15	1.05	0.98	1.04
	2g	T_{ex}, Nm	2.58	4.36	5.15	5.24	5.98	6.98	8.74	
		T_e, Nm	1.19	1.78	2.25	2.48	2.73	3.27	3.46	
		R_{cex}/R_{ce}	2.18	2.45	2.29	2.11	2.19	2.13	2.53	2.27
Toyoura (Dr = 50%)	1/6g	T_{ex}, Nm	0.14	0.32	0.47	0.45				
		T_e, Nm	1.6	2.55	3.17	3.47				
		R_{cex}/R_{ce}	0.09	0.13	0.15	0.13				0.13
	1/2g	T_{ex}, Nm	0.48	1.27	1.65	1.86	1.8	1.61	1.73	
		T_e, Nm	1.6	2.55	3.17	3.47	3.56	3.54	3.61	
		R_{cex}/R_{ce}	0.3	0.50	0.52	0.54	0.51	0.45	0.48	0.47
	3/4g	T_{ex}, Nm	1.25	1.93	2.38	2.52	2.4	1.94	2.07	
		T_e, Nm	1.6	2.55	3.17	3.47	3.56	3.54	3.61	
		R_{cex}/R_{ce}	0.78	0.76	0.75	0.73	0.67	0.55	0.57	0.69
	1g	T_{ex}, Nm	1.28	2.4	2.99	3.2	3.28	3.29	3.28	
		T_e, Nm	1.6	2.55	3.17	3.47	3.56	3.54	3.61	
		R_{cex}/R_{ce}	0.8	0.94	0.94	0.92	0.92	0.93	0.91	0.91
	2g	T_{ex}, Nm	3.65	5.86	7.04	7.29				
		T_e, Nm	1.6	2.55	3.17	3.47				
		R_{cex}/R_{ce}	2.28	2.30	2.22	2.10				2.22
Toyoura (Dr = 70%)	1/6g	T_{ex}, Nm	0.15	0.31	0.27	0.43				
		T_e, Nm	1.24	2.16	2.92	3.23				
		R_{cex}/R_{ce}	0.12	0.14	0.09	0.13				0.12
	1/2g	T_{ex}, Nm	0.66	1.33	1.71	1.82	1.95	2.01	1.97	
		T_e, Nm	1.24	2.16	2.92	3.23	3.37	3.46	3.53	
		R_{cex}/R_{ce}	0.53	0.62	0.59	0.56	0.58	0.58	0.56	0.57
	3/4g	T_{ex}, Nm	0.96	1.81	2.35	2.5	2.59	2.69	2.62	
		T_e, Nm	1.24	2.16	2.92	3.23	3.37	3.46	3.53	
		R_{cex}/R_{ce}	0.77	0.84	0.80	0.77	0.77	0.78	0.74	0.78
	1g	T_{ex}, Nm	1.23	2.32	3.13	3.34	3.46	3.55	3.54	
		T_e, Nm	1.24	2.16	2.92	3.23	3.37	3.46	3.53	
		R_{cex}/R_{ce}	0.99	1.07	1.07	1.03	1.03	1.03	1.0	1.03
	2g	T_{ex}, Nm	2.89	5.08	6.34	6.77	6.52	7.34	7.31	
		T_e, Nm	1.24	2.16	2.92	3.23	3.37	3.46	3.53	
		R_{cex}/R_{ce}	2.33	2.35	2.17	2.1	1.93	2.12	2.07	2.15

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shown in the figures indicate that the inertia (dynamic) effect on test results is insignificant and negligible. The time-varying characteristics of the wheel torque shown in the figures are likely due to the slip–sinkage effect, similar to that for wheel sinkage described in Section 2.2. The procedure for determining the compaction resistance ratio R_{cex}/R_{ce} from test data is described below.

To compare the measured wheel torque T_{ex}, when both the wheel and the soil are subject to gravity g_{ex} in the aircraft, with the measured wheel torque T_e with identical wheel mass on the ground subject to earth gravity g_e, a specific procedure is followed to process the test data shown in the figures. The data shown in Fig. 12 for the lunar soil simulant with relative density of 50% are used as an example to illustrate the procedure involved. For instance, the compaction resistance ratio R_{cex}/R_{ce} (equivalent to the torque ratio T_{ex}/T_e) under gravity $g_{ex} = 1/6g$ and at time 1.5 s is calculated by the ratio of the torque T_{ex} at $1/6g$ and at time 1.5 s shown in Fig. 12 (or Table 4) to the torque T_e at wheel load of 1 W at time 1.5 s measured on the ground shown in the figure (or Table 4). It should be noted that the mass carried by the wheel (10 kg) while under various gravities in the aircraft is identical to that on the ground with wheel load of 1 W (10 kg × 9.81 m/s^2).

From the data shown in Fig. 12 or Table 4, on the lunar soil simulant with relative density 50%, at $1/6g$ the torque T_{ex} at time 1.5 s is 0.2 Nm, whereas at wheel load of 1 W on the ground, the torque T_e at time 1.5 s is 1.66 Nm. Therefore, with identical wheel mass of 10 kg, under gravity $g_{ex} = 1/6g$ and at time 1.5 s, the compaction resistance ratio $R_{cex}/R_{ce} = 0.2/1.66 = 0.12$, as shown in the fourth row under the column of time 1.5 s in Table 4. In the table, the first row lists the times at which measurements of wheel torque were taken. In the second row, the wheel torque T_{ex} under gravity $g_{ex} = 1/6g$ at various times are given, whereas in the third row, the wheel torque T_e under wheel load of 1 W measured on the ground under earth gravity g_e at various times are shown. In the fourth row, the values of compaction resistance ratio R_{cex}/R_{ce} (or T_{ex}/T_e) at various times are given. Following the same procedure, the measured values of the compaction resistance ratio R_{cex}/R_{ce} under various gravities g_{ex} and at different times on the lunar soil simulant and on Toyoura sand with relative densities of 50% and 70% are presented in Table 4.

It can be seen from the table that the values of the measured compaction resistance ratio R_{cex}/R_{ce} under different gravities and in the range of time shown are close to those predicted using Eq. (7). For instance, on the lunar soil simulant with relative density of 50%, at gravity $1/6g$ (or gravity ratio $g_{ex}/g_e = 1/6$), the average measured value of the compaction resistance ratio $R_{cex}/R_{ce} = 0.15$, as shown in the fourth row of the last column on the right of Table 4. It is quite close to 1/6 (or 0.167) predicted using Eq. (7). Thus the predictions using Eq. (7) are quite well borne out by test data, at least to a first approximation.

In the last column on the right of Table 4, the average values of the compaction resistance ratio R_{cex}/R_{ce} under various gravity conditions over the specific range of time, on the lunar soil simulant and Toyoura sand with two relative densities, are given. It can be seen the average measured values of the compaction resistance ratio R_{cex}/R_{ce} are reasonably close to those predicted using Eq. (7). These values are plotted against the gravity ratio g_{ex}/g_e in Fig. 16. It should be noted that the variation of the compaction resistance ratio R_{cex}/R_{ce} with gravity ratio g_{ex}/g_e predicted by Eq. (7) is represented by an inclined line with slope of g_{ex}/g_e in Fig. 16.

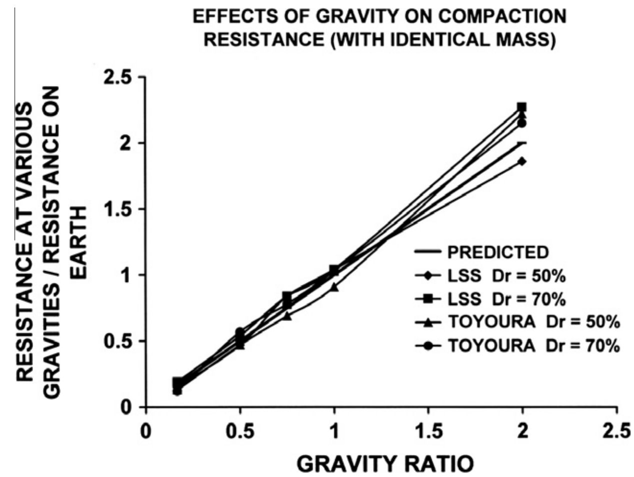

Fig. 16. Comparison of the variations of compaction resistance ratio R_{cex}/R_{ce} with gravity ratio g_{ex}/g_e of a rigid wheel predicted by the proposed method with those measured on different types of soil.

In summary, despite the probable errors in measurements of wheel torque, and the neglect of the effect of slip and soil cohesion in the analysis, all experimental evidence presented above appears to substantiate the predictions using Eq. (7), at least to a first approximation. Eq. (7) indicates that for a rigid wheel with identical mass on the extraterrestrial and the earth surfaces, the compaction resistance R_{cex} on the extraterrestrial surface under gravity g_{ex} should be equal to the compaction resistance R_{ce} measured on the ground under earth gravity g_e, multiplied by the gravity ratio g_{ex}/g_e, provided that the regolith on the extraterrestrial surface and the soil simulant used in the tests conducted on earth have negligible cohesion and the same pressure–sinkage parameters (i.e., $n_{ex} = n_e$ and $K_{\phi ex} = K_{\phi e}$).

4. Closing remarks

(A) In comparison with the current practice of conducting tests on earth with the normal load (force) applied by the rover/rover wheel to the soil simulant identical to that expected on the extraterrestrial surface, the proposed method with the rover/rover wheel carrying the identical mass to that on the extraterrestrial surface has the following merits:

(a) It does not require additional equipment to reduce (or control) the load of the rover/rover wheel applied to the soil simulant in conducting tests on earth.

(b) The procedures for predicting the sinkage and compaction resistance of rigid rover wheels on extraterrestrial surfaces based on test results obtained on earth are greatly simplified.

(B) With identical wheel mass on both the extraterrestrial and the earth surfaces, the predictions of sinkage and compaction resistance under various gravities by the proposed methods correlate reasonably well with available test data, obtained in an aircraft undergoing parabolic flight manoeuvres to produce different gravity conditions.

(C) With identical wheel mass on both the extraterrestrial and the earth surfaces, experimental evidence indicates that Eq. (4) may be used to predict the sinkage of a rigid wheel on the extraterrestrial surface with any gravity based on that measured on the earth surface, even the wheel operating with slip and with notable slip–sinkage, provided that the wheel slip on the extraterrestrial surface and that on the earth surface are comparable.

(D) Based on the tests data obtained on the lunar soil simulant and on Toyoura sand with two relative densities, it appears that gravity has insignificant effects on the values of their pressure–sinkage parameters, at least to a first approximation. Further analytical and experimental study will be required, however, before a general conclusion on the effect of gravity on the pressure–sinkage parameters can be reached.

(E) It is recognized that the analysis presented in this study is based on certain simplifying assumptions. Experimental evidence, however, does indicate that the proposed method of approach may be adopted in practice for guiding the testing of the performance of rovers/rover wheels conducted on earth, as well as for predicting the sinkage and compaction resistance of rigid rover wheels on extraterrestrial surfaces based on test data obtained on earth.

(F) It is hoped that this study would serve as a catalyst to stimulate further research on the method of approach to testing the performance of extraterrestrial rovers/rover wheels on earth, which is of importance to the development of extraterrestrial rovers/rover wheels.

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