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Predicting the performances of rigid rover wheels on extraterrestrial surfaces based on test results obtained on earth

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Abstract

With a growing number of nations interested in planetary exploration, research and development of extraterrestrial rovers have been intensified. The usual practice is to test the performances of rovers on soil simulants on earth, prior to their deployment to extraterrestrial bodies. It is noted that in the tests the soil simulant is subject to the earth gravity, while the terrain on the extraterrestrial surface is subject to a different gravity. Therefore, it is uncertain whether the rover/rover wheel would exhibit the same performance on the extraterrestrial surface as that obtained from tests conducted on earth. This paper describes a practical methodology that can be employed to predict the performances of rover wheels on extraterrestrial surfaces, based on test results obtained on earth. As rigid wheels are used in many extraterrestrial rovers, this study focuses on examining the effects of gravity on the sinkage and compaction resistance of rigid rover wheels. Predictions obtained using the methodology are shown to correlate reasonably well with test data.

Keywords: Compaction resistance; Extraterrestrial rovers; Gravity effects; Parabolic flights; Performance; Rover wheels; Sinkage; Soil simulants

1. Introduction

In the development of extraterrestrial rovers, it is desirable to test their performances under the same gravity as that on the extraterrestrial surface, prior to their deployment to the extraterrestrial body. This can be achieved, for instance, by conducting tests of rovers/rover wheels in a soil bin installed in an aircraft, while it performs appropriate parabolic flight manoeuvres to produce the desired gravity conditions, as shown in Fig. 1 [1]. However, this is costly and the duration available for conducting tests under a specific gravity is relatively short during a given flight manoeuvre. Consequently, this type of test has been limited to certain kinds of simple experiments [1,2].

The usual practice for experimentally evaluating the performances of rovers/rover wheels is to conduct tests on earth using a soil simulant, appropriate to the extraterrestrial body of interest. In these tests, the load applied by the rover/rover wheel to the soil simulant usually corresponds to that expected on the extraterrestrial surface, taking into account its acceleration due to gravity. For instance, various wheel candidates for the lunar roving vehicle for the Apollo missions of the US National Aeronautics and Space Administration (NASA) were tested with normal loads on the wheels corresponding to those expected on the lunar surface with gravity equal to 1/6 of that on the earth surface, while the soil simulant used in the tests was subject to the earth gravity [3]. This raises the question as to whether the performances of the rovers/rover wheels obtained from this type of test on earth represent those on the lunar surface, because the soil on the lunar surface is subject to the lunar gravity, while the soil simulant used in the tests is subject to the earth gravity [4].

If a methodology can be developed that will predict the performances of rovers/rover wheels on extraterrestrial surfaces based on test results obtained under the earth gravity, it would make a significant contribution to the

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Nomenclature

b	smaller dimension of the contact patch
c	cohesion of the soil
D	diameter of a wheel
g	acceleration due to earth gravity (9.81 m/s^2)
g_e	acceleration due to gravity on the earth surface
g_{ex}	acceleration due to gravity on the surface of an extraterrestrial body
K_c, K_ϕ	pressure-sinkage parameters for the modified Reece equation
k_c, k_ϕ	pressure-sinkage parameters for the Bekker equation
k'_c, k'_ϕ	pressure-sinkage parameters for the original Reece equation
m	mass carried by a wheel
n	exponent of the Bekker or the Reece pressure-sinkage equation
p	pressure
R_c	compaction resistance of a wheel
R_{ce}	compaction resistance of a rigid wheel on the earth surface
R_{cex}	compaction resistance of a rigid wheel on an extraterrestrial surface
W	normal load (force) on a wheel
z	sinkage
z_e	sinkage of a rigid wheel on the earth surface
z_{ex}	sinkage of a rigid wheel on an extraterrestrial surface
γ	weight density of soil
γ_m	mass density of soil
ϕ	angle of internal shearing resistance of soil

development of extraterrestrial rovers by alleviating the need for testing rovers or their running gear under the gravity of the extraterrestrial body. This paper describes an attempt to develop such a methodology. As rigid wheels are used in many extraterrestrial rovers, this study focuses on examining the effects of gravity on the sinkage and compaction resistance of rigid rover wheels. Predictions obtained using the proposed methodology are compared with experimental data [1]. It is shown that the effects of gravity on sinkage and compaction resistance of rigid rover wheels predicted using the methodology exhibit similar trends to those demonstrated by test data, obtained under various gravity conditions produced in an aircraft undergoing parabolic flight manoeuvres.

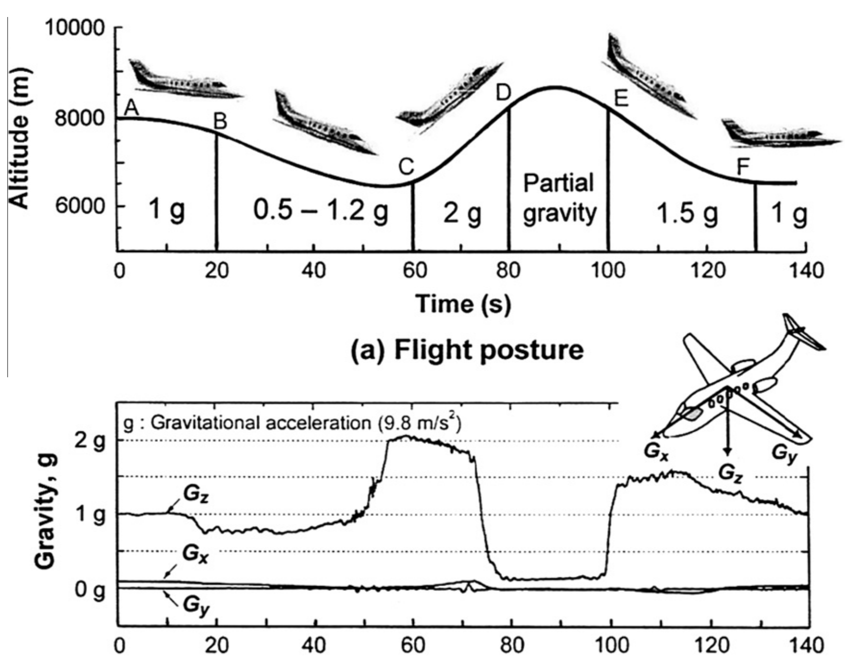

Fig. 1. Parabolic flight manoeuvres to create various gravity conditions. (From T. Kobayashi et al. [1].)

2. Characterization of mechanical properties of soil in rover mobility study

In the study of extraterrestrial rover mobility, the Bekker pressure-sinkage equation for predicting wheel sinkage and associated resistance due to soil compaction is widely used [5–8].

$$p = \left(\frac{k_c}{b} + k_\phi\right) z^n \tag{1}$$

where b is the smaller dimension of the contact patch (m); p is pressure (kPa); z is sinakage (m); n is a non-dimensional exponent; and k_c and k_ϕ are pressure-sinkage parameters with dimensions of kN/m^{n+1} and kN/m^{n+2}, respectively.

The Bekker pressure-sinkage equation was evolved from the pressure-settlement equation for foundations used in civil engineering soil mechanics [9].

Inspired by the Terzaghi bearing capacity theory in soil mechanics, Reece proposed another pressure-sinkage equation [10]:

$$p = (ck'_c + \gamma b k'_\phi)\left(\frac{z}{b}\right)^n \tag{2}$$

where b, p and z are defined in the same way as those in Eq. (1); n, k'_c and k'_ϕ are non-dimensional pressure-sinkage parameters; and γ is the weight density of the soil, kN/m^3. If the weight density of the soil γ is expressed as the product of the soil mass density γ_m and the acceleration due to gravity g, then Eq. (2) may be re-written as

$$p = (ck'_c + \gamma_m g b k'_\phi)\left(\frac{z}{b}\right)^n = \left(\frac{ck'_c}{b^n} + \frac{\gamma_m g k'_\phi}{b^{n-1}}\right) z^n = (K_c + K_\phi g) z^n \tag{3}$$

where $K_c = \frac{ck'_c}{b^n}$ and $K_\phi = \frac{\gamma_m k'_\phi}{b^{n-1}}$.

The basic features of the Reece pressure-sinkage equation have been verified by experimental data obtained with homogeneous soils [10,11]. Eq. (3) shows that the acceleration due to gravity affects the pressure-sinkage relationship.

Comparing the Bekker equation, Eq. (1), with the Reece equation, Eq. (3), one finds that for a given soil and for the same smaller dimension of the contact patch b, the pressure-sinkage parameters K_c and K_ϕ in the Reece equation may be derived from the pressure-sinkage parameters k_c and k_ϕ in the Bekker equation, and

$$K_c = \frac{ck'_c}{b^n} = \frac{k_c}{b} \tag{4}$$

$$K_\phi = \frac{\gamma_m k'_\phi}{b^{n-1}} = \frac{k_\phi}{g} \tag{5}$$

When pressure-sinkage tests are conducted on the earth surface, g in the above equation is the acceleration due to gravity on the earth surface, g_e.

It is noted that on the surfaces of the Moon, Mars and other extraterrestrial bodies, the soil is usually dry and its cohesion is low. The values of k_c and K_c in comparison with those of k_ϕ and K_ϕ in Eqs. (1) and (3), respectively, are usually insignificant and may be neglected in many cases.

The Reece pressure-sinkage equation, Eq. (3), which contains the term of acceleration due to gravity, provides a basis for evaluating the effects of gravity on wheel sinkage and motion resistance due to soil compaction.

3. Evaluation of the effects of gravity on rigid rover wheel sinkage

3.1. With identical wheel load on both the extraterrestrial and the earth surfaces

3.1.1. Analysis

Using the model for rigid wheel-soil interaction proposed by Bekker [9] and incorporating the Reece pressure-sinkage equation, Eq. (3), the sinkage z for a rigid wheel may be expressed by [9,11,12]

$$z = \left[\frac{3W}{b(3-n)(K_c + K_\phi g)\sqrt{D}}\right]^{2/(2n+1)} \tag{6}$$

where W is the normal load (normal force) that the wheel applies to the soil; D is the diameter of the wheel; and all other parameters have been defined earlier.

When a rigid wheel operates on the earth surface with acceleration due to gravity g_e, the sinkage z_e of the wheel is expressed by

$$z_e = \left[\frac{3W}{b(3-n)(K_c + K_\phi g_e)\sqrt{D}}\right]^{2/(2n+1)} \tag{7}$$

On the extraterrestrial surface with acceleration due to gravity g_{ex}, the sinkage of the wheel z_{ex} is expressed by

$$z_{ex} = \left[\frac{3W}{b(3-n)(K_c + K_\phi g_{ex})\sqrt{D}}\right]^{2/(2n+1)} \tag{8}$$

The ratio of the rigid wheel sinkage on the extraterrestrial surface z_{ex} to that on the earth surface z_e is given by

$$\frac{z_{ex}}{z_e} = \frac{\left[\frac{3W}{b(3-n)(K_c + K_\phi g_{ex})\sqrt{D}}\right]^{2/(2n+1)}}{\left[\frac{3W}{b(3-n)(K_c + K_\phi g_e)\sqrt{D}}\right]^{2/(2n+1)}} \tag{9}$$

As noted earlier, in this case the wheel and its load exerted on the extraterrestrial surface are the same as those used in the tests on the earth surface. If the soil simulant used in the tests on earth and the soil on the extraterrestrial surface are dry with low cohesion (i.e., the values of c and K_c being insignificant) and have the same values of the pressure-sinkage parameters n and K_ϕ, Eq. (9) may be simplified as

$$\frac{z_{ex}}{z_e} = \left[\frac{g_e}{g_{ex}}\right]^{2/(2n+1)} \tag{10}$$

Eq. (10) indicates that with identical wheel load exerted on both the extraterrestrial and the earth surfaces, the ratio of the rigid wheel sinkage on the extraterrestrial surface to that on the earth surface, z_{ex}/z_e, is a function of the ratio of the acceleration due to gravity on the earth surface to that on the extraterrestrial surface, g_e/g_{ex}, and the exponent n of the pressure-sinkage equation.

For instance, if the soil on the lunar surface has the same properties as those of the soil simulant DLR-A with $n = 0.63$ [13], than the ratio of the sinkage of a rigid wheel on the lunar surface to that on the earth surface, z_{ex}/z_e, can be predicted using Eq. (10), taking into account that the acceleration due to gravity on the earth surface is 6 times that on the lunar surface. That is,

$$z_{ex}/z_e = (g_e/g_{ex})^{2/(2n+1)} = (6)^{2/(1.26+1)} = 4.88$$

Similarly, if the soil on the Martian surface has the same properties as those of the soil simulant DLR-A with $n = 0.63$, then the ratio of the sinkage of a rigid wheel on the Martian surface to that on the earth surface, z_{ex}/z_e, can be predicted using Eq. (10), taking into account that the acceleration due to gravity on the earth surface is 2.63 times that on the Martian surface. That is,

$$z_{ex}/z_e = (g_e/g_{ex})^{2/(2n+1)} = (2.63)^{2/(1.26+1)} = 2.35$$

Fig. 2 shows the variations of the ratio of rigid wheel sinkage on the extraterrestrial surface to that on the earth surface, z_{ex}/z_e, with the gravity on the extraterrestrial surface in g units ($g = 9.81$ m/s^2), predicted using Eq. (10) for three types of soils with different values of n. Of the three curves marked as "Predicted" in the figure, one is for a soil similar to the soil simulant DLR-A with $n = 0.63$ [13]; one is for a soil similar to the soil simulant with $n = 0.91$ used in testing wheel candidates for the lunar roving vehicle for NASA's Apollo missions [3]; and the other is for a soil with $n = 0.40$. As can be seen in the figure, if the gravity is equal to 1 g (equivalent to that on the earth surface and read from the horizontal axis of Fig. 2), then from the curves shown in the figure $z_{ex}/z_e = 1$ (read from the vertical axis of Fig. 2). If the gravity is equal to 1/6 g (equivalent to that on the lunar surface), then from the curves shown in the figure, $z_{ex}/z_e = 7.32$, 4.88 and 3.56 for $n = 0.40$, $n = 0.63$ and $n = 0.91$, respectively. If the gravity is equal to 0.38 g (equivalent to that on the Martian surface), then from the curves shown in Fig. 2, $z_{ex}/z_e = 2.93$, 2.35 and 1.99 for $n = 0.40$, $n = 0.63$ and $n = 0.91$, respectively. The trends of the curves show that with identical wheel load exerted on both the extraterrestrial and the earth surfaces, if the gravity decreases, the sinkage ratio z_{ex}/z_e for a rigid rover wheel will increase exponentially with an exponent of $(2/(2n + 1))$.

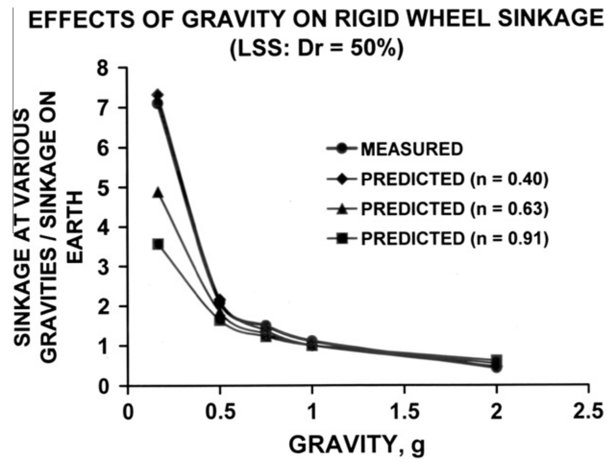

Fig. 2. Comparison of the effect of gravity on the sinkage ratio z_{ex}/z_e of a rigid wheel (with identical load on both the extraterrestrial and earth surfaces) on the lunar soil simulant with relative density of 50% predicted by the proposed method with that measured in an aircraft undergoing parabolic flight manoeuvres.

3.1.2. Comparison of predictions with test data

The effects of gravity on the sinkage ratio z_{ex}/z_e for a rigid wheel predicted using Eq. (10) are evaluated with test data obtained under various gravity conditions and reported in [1]. 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. 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 [1]. 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 soils (such as n, k_c and k_ϕ in the Bekker equation or n, K_c and K_ϕ in the Reece equation) used in the tests are, however, not given [1].

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/

Table 1
Bulk densities, void ratio and shear strength parameters of the two types of soils used in the tests [1].

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.

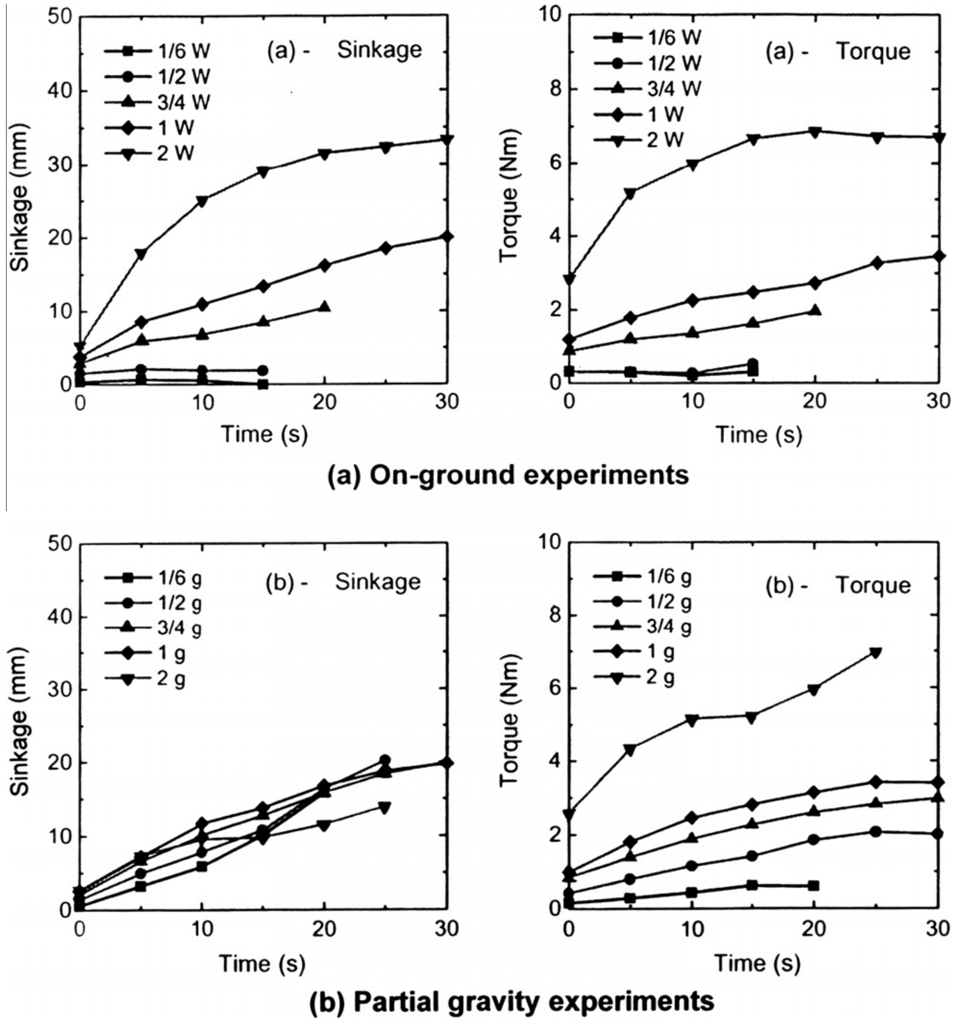

Fig. 3. Comparison of test results on the lunar soil simulant with relative density of 70% obtained on earth with those obtained under various gravity conditions produced by an aircraft undergoing parabolic flight manoeuvres. (From T. Kobayashi et al. [1].)

s^2). The sinkages of the wheel with loads of $1/6W$, $1/2W$, $3/4W$, $1W$, and $2W$, while moving under self-propelled conditions (without drawbar load), on the two types of soils with two different relative densities on the ground at different times were measured. As an example, the results of the tests on the lunar soil simulant with relative density of 70% are shown in the left diagram of Fig. 3(a). 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 sinkages of the rigid wheel under gravities of $1/6g$, $1/2g$, $3/4g$, $1g$, and $2g$ ($g = 9.81\ \mathrm{m/s^2}$) at various times are shown in the left diagram of Fig. 3(b).

It should be noted, for instance, that a load of 1/6 W applied by the wheel to the soil on the ground ($1/6 \times 10\ \mathrm{kg} \times 9.81\ \mathrm{m/s^2}$) is identical to the load applied to the soil when the wheel is subject to gravity of $1/6g$ ($1/6 \times\ 9.81\ \mathrm{m/s^2} \times 10\ \mathrm{kg}$). This means that the loads applied by the wheel to the soil on the ground are identical to those in the aircraft at the corresponding gravities.

As shown in Fig. 3, the sinkage and torque of the wheel vary with time. For sinkages and torques measured on the ground, there are 4 data points at times of 0, 5, 10, and 15 s for loads of $1/6W$ and $1/2W$, and 5 data points for the load of $3/4W$. To provide a common basis for evaluation, sinkages at times 5 and 10 s shown in the left diagrams of Fig. 3(a) and (b) were averaged and the average values are taken as the representative sinkages for different levels of loads and gravities, respectively. The ratio z_{ex}/z_e of the average value of the sinkage obtained under a given level of gravity, from the left diagram of Fig. 3(b), to that obtained under the same level of load on the ground, from the left diagram of Fig. 3(a), is plotted against gravity and marked as "Measured" in Fig. 4, for tests performed on the lunar soil simulant (identified by LSS in the figure) with relative density of 70%. Similar measured curves obtained from tests conducted on the lunar soil simulant with relative density of 50% and on the Toyoura sand (identified by Toyoura in the figure) with relative densities of 50 and 70% are shown in Figs. 2, 5 and 6, respectively.

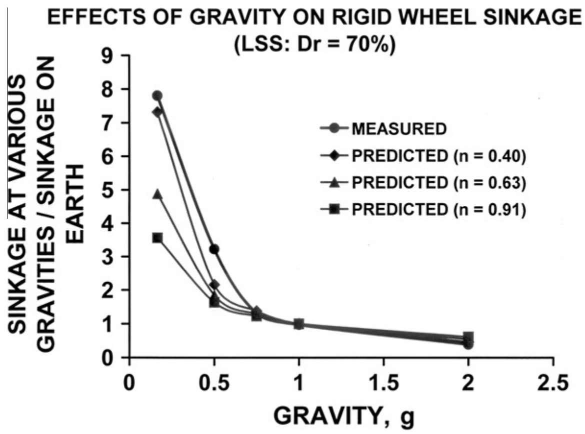

Fig. 4. Comparison of the effect of gravity on the sinkage ratio z_{ex}/z_e of a rigid wheel (with identical load on both the extraterrestrial and earth surfaces) on the lunar soil simulant with relative density of 70% predicted by the proposed method with that measured in an aircraft undergoing parabolic flight manoeuvres.

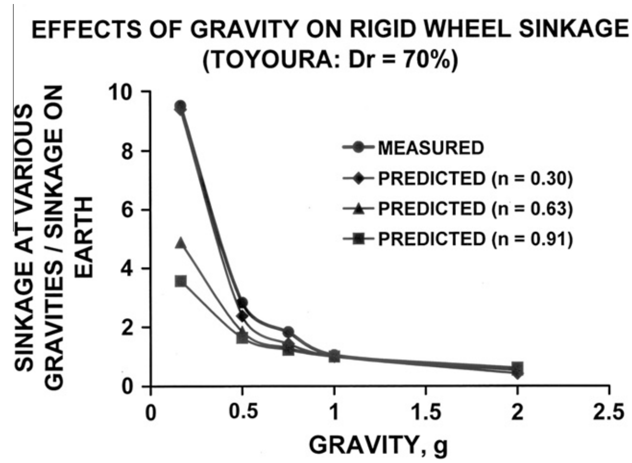

Fig. 6. Comparison of the effect of gravity on the sinkage ratio z_{ex}/z_e of a rigid wheel (with identical load on both the extraterrestrial and earth surfaces) on the Toyoura sand with relative density of 70% predicted by the proposed method with that measured in an aircraft undergoing parabolic flight manoeuvres.

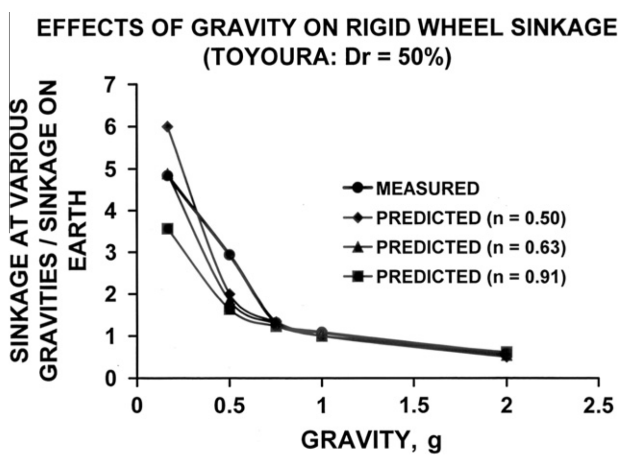

Fig. 5. Comparison of the effect of gravity on the sinkage ratio z_{ex}/z_e of a rigid wheel (with identical load on both the extraterrestrial and earth surfaces) on the Toyoura sand with relative density of 50% predicted by the proposed method with that measured in an aircraft undergoing parabolic flight manoeuvres.

It can be seen from Fig. 2 that the "Predicted" curve for $n = 0.40$ obtained using Eq. (10) fits remarkably well to the "Measured" curve. This suggests that the lunar soil simulant with relative density of 50% might have a value of $n = 0.40$. As noted previously, the values of the exponent n for the pressure-sinkage equation for the lunar soil simulant and the Toyoura sand with different relative densities used in the tests are not given in Reference [1] and are therefore unknown. The "Predicted" curve for $n = 0.40$ in Fig. 4 also shows a strong resemblance to the "Measured" curve obtained from the test data shown in Fig. 3 for the lunar soil simulant with relative density of 70%. In Fig. 5, the "Predicted" curve with $n = 0.63$ appears in general to have a reasonable correlation with the "Measured" curve for the Toyoura sand with relative density of 50%. The "Predicted" curve for $n = 0.30$ obtained using Eq. (10) fits very well to the "Measured" curve for the Toyoura sand with relative density of 70%.

It should be mentioned that the predicted curves shown in the figures are only a function of the exponent n of the pressure-sinkage equation for the soils. Consequently, the predicted curves in Figs. 2 and 4–6 with the same value of n are identical. While the "Predicted" curves are not directly related to the type or conditions of the soil, these factors would have an influence on the value of n.

While the "Predicted" curve with a particular value of n shows a strong resemblance to the corresponding "Measured" curve obtained from tests on the lunar soil simulant and the Toyoura sand with different relative densities, as shown in Figs. 2 and 4–6, one should view this in perspective and take into consideration the following factors:

(a) As mentioned previously, the values of the exponent n in the Bekker or the Reece pressure-sinkage equation, Eqs. (1) and (3), for the lunar soil simulant and the Toyoura sand are not reported in [1]. Therefore, it cannot be ascertained that for instance, $n = 0.4$ is indeed the exponent of the pressure-sinkage equation for the lunar soil simulant with relative density of 50%.
(b) In spite of a reasonably close correlation, in general, between the "Predicted" curve with a particular value of n and the corresponding "Measured" curve, there are differences between predicted and measured values. These differences, however, may not necessarily be due to inaccuracies in predictions. For instance, it can be seen from the left diagram of Fig. 3(a) that at low levels of loads, such as $1/6W$, the wheel sinkage is very small. At these levels, a small error in

the measurement of sinkage would result in a significant discrepancy in the ratio z_{ex}/z_e. For example, if the overall error of the system in measuring sinkage (including the instrument for sinkage measurement) is 0.1 mm (corresponding to 0.2% at the full scale of the sinkage measuring instrument of 50 mm), then from the left diagram of Fig. 3(a), at a load of $1/6W$ on the ground, the probable sinkage will be in the range of 0.6 ± 0.1 mm (i.e., 0.5–0.7 mm). The value of 0.6 mm is the average value of sinkages measured at times of 5 and 10 s. From the left diagram of Fig. 3(b), at the gravity of $1/6g$, the probable sinkage will be in the range of 4.5 ± 0.1 mm (i.e., 4.4–4.6 mm). The value of 4.5 mm is the average value of sinkages measured at times of 5 and 10 s. The probable wheel sinkage ratio z_{ex}/z_e (i.e., the probable value of the ratio of the wheel sinkage measured under $1/6g$ in the aircraft to that under $1/6W$ on the ground) would be in the range of 6.29 (4.4/0.7) to 9.20 (4.6/0.5). This indicates that the predicted value of z_{ex}/z_e of 7.32 for $n = 0.4$ shown in Fig. 4 is well within the lower and upper bounds, 6.29 and 9.20, of the probable value of the wheel sinkage ratio z_{ex}/z_e.

(c) It is noted from Reference [1] that for instance, on the lunar soil simulant with relative density of 70%, the wheel slip at low levels of gravities, such as $1/6g$, measured in the aircraft is higher than that at low levels of loads, such as $1/6W$, measured on the ground. This effect has not been taken into account in calculating the wheel sinkage ratio z_{ex}/z_e shown in Figs. 2 and 4–6. It should also be pointed out that Eq. (6) for predicting the rigid wheel sinkage does not take into consideration the effect of wheel slip (commonly referred to as the slip-sinkage).

(d) In deriving Eq. (10), soil cohesion is neglected, whereas the soils used in the tests have some cohesion, as noted in Table 1.

(e) As mentioned previously, the soil depth in the bin was 100 mm. However, the wheel sinkage at 2 W shown in the left diagram of Fig. 3(a) was as high as 34 mm. Consequently, the soil depth used in the tests may be too shallow. The constraint imposed on the flow or deformation of the soil by the floor of the bin (commonly referred to as the "wall effect") may have a significant impact on the accuracy of measurements, as pointed out by Bekker [14]. Similar comment may be made on the soil bin width in relation to the wheel width.

In summary, despite the values of the exponent n for the soils used in the tests being unknown, the probable errors in the measurements of wheel sinkage, and the effects of slip-sinkage and soil cohesion being neglected in predictions, the trends for the effects of gravity on the sinkage ratio z_{ex}/z_e for a rigid wheel predicted using Eq. (10) show a strong resemblance to those exhibited by the measured data. This indicates that the experimental data do lend support, in general, to the proposed method for predicting the probable sinkage of a rigid rover wheel on the surface of an extraterrestrial body, based on test data obtained on the earth surface.

3.2. With identical wheel mass on both the extraterrestrial and the earth surfaces

3.2.1. Analysis

With identical mass carried by the wheel on both the extraterrestrial and the earth surfaces, Eq. (9) may be rewritten as follows:

$$\frac{z_{ex}}{z_e} = \frac{\left[\dfrac{3mg_{ex}}{b(3-n)(K_c + K_\phi g_{ex})\sqrt{D}}\right]^{2/(2n+1)}}{\left[\dfrac{3mg_e}{b(3-n)(K_c + K_\phi g_e)\sqrt{D}}\right]^{2/(2n+1)}} \tag{11}$$

where m is the mass carried by the wheel, and all other parameters are defined in the same way as those in Eq. (9).

If the soil simulant used in the tests on earth and the soil on the extraterrestrial surface are dry with low cohesion (i.e., the values of c and K_c being insignificant) and have the same values of the pressure-sinkage parameters n and K_ϕ, Eq. (11) may be simplified as

$$\frac{z_{ex}}{z_e} = 1 \tag{12}$$

Eq. (12) 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 is simply equal to that on the earth surface. This will greatly simplify the procedure for predicting the rigid rover wheel sinkage on the extraterrestrial surface based on that measured on earth, in comparison with that with identical load carried by the wheel on both the extraterrestrial and the earth surfaces.

3.2.2. Comparison of predictions with test data

The variations of the sinkage ratio z_{ex}/z_e with the gravity ratio g_{ex}/g_e of a rigid wheel with identical mass on both the extraterrestrial and the earth surfaces predicted using Eq. (12) are evaluated with test data obtained under various gravity conditions presented in Reference [1]. The test data shown in the left diagrams of Fig. 3(a) and (b) for the lunar soil simulant with relative density of 70% are used as an example to illustrate the procedure involved. For instance, the sinkage ratio z_{ex}/z_e at the gravity ratio $g_{ex}/g_e = 3/4$ is calculated by the ratio of the average sinkage at times 5 and 10 s at $3/4g$ shown in the left diagram of Fig. 3(b) to that at $1W$ shown in left diagram of Fig. 3(a). It should be noted that the mass carried by the wheel (10 kg) while in the aircraft under gravity of 3/4 g is identical to that on the ground with load $1W$ (10 kg $\times$ 9.81 m/s^2). From the data shown in the left diagram of Fig. 3(b), at $3/4g$ the average sinkage at times 5 and 10 s is 8.3 mm. From

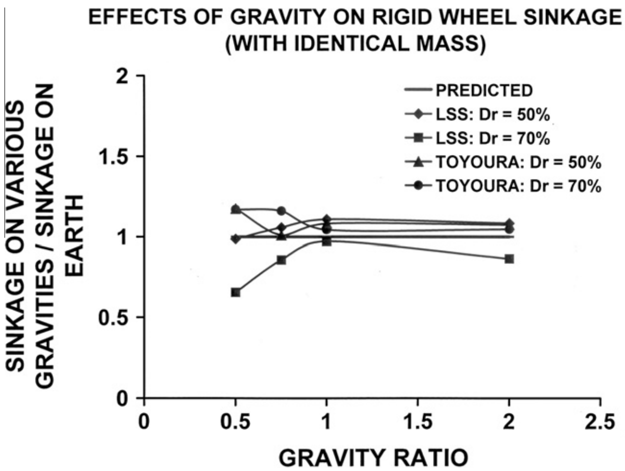

Fig. 7. Comparison of the variation of the sinkage ratio z_{ex}/z_e with the gravity ratio g_{ex}/g_e of a rigid wheel (with identical mass on both the extraterrestrial and earth surfaces) predicted by the proposed method with those measured on different soils in an aircraft undergoing parabolic flight manoeuvres.

the left diagram of Fig. 3(a) at $1W$, the average sinkage at times 5 and 10 s is 9.7 mm. Therefore, at the gravity ratio $g_{ex}/g_e = 3/4$, the sinkage ratio $z_{ex}/z_e = 8.3/9.7 = 0.86$, as indicated on the curve for LSS: $D_r = 70\%$ in Fig. 7. Following the same procedure, the variations of the measured values of the sinkage ratio z_{ex}/z_e with the gravity ratio g_{ex}/g_e for the lunar soil simulant with relative density of 50% and for the Toyoura sand with relative densities of 50% and 70% are plotted in Fig. 7. The variation of the sinkage ratio z_{ex}/z_e with the gravity ratio g_{ex}/g_e predicted by Eq. (12) is represented by a horizontal line with $z_{ex}/z_e = 1$ in Fig. 7. It should be mentioned that at gravity of $1/6g$, the sinkage is small and is susceptible to errors in measurements. This causes irregularities in the wheel sinkage ratio z_{ex}/z_e at the gravity ratio $g_{ex}/g_e = 1/6$ in some cases. For this reason, the values of the wheel sinkage ratio z_{ex}/z_e at the gravity ratio $g_{ex}/g_e = 1/6$ for the lunar soil simulant and the Toyoura sand with different relative densities are not shown in Fig. 7.

As can be seen in Fig. 7, the measured curves show a reasonable correlation with the predicted one in the range of gravity ratio g_{ex}/g_e higher than 0.5, with the exception for the lunar soil simulant with relative density of 70% at $g_{ex}/g_e = 0.5$. The differences between the predicted and measured curves may be attributed to factors (b) to (e) identified in Section 3.1.2.

In summary, despite the probable errors in the measurements of wheel sinkage, as well as the effects of slip-sinkage and soil cohesion being neglected in predictions, for a rigid wheel with identical mass on the extraterrestrial and the earth surfaces, the prediction that the sinkage z_{ex} on the extraterrestrial surface is the same as that on the earth surface z_e is, in many cases, borne out by test data. Thus, it would seem preferable that in conducting performance testing of rigid rover wheels on soil simulants on the earth surface, the wheel carries the same mass as that for operations on the extraterrestrial surface, instead of carrying the same normal load, as employed in the usual practice. With the wheel carrying identical mass on both the extraterrestrial and the earth surfaces, the wheel sinkage on the extraterrestrial surface is simply equal to that on the earth surface, according to Eq. (12).

4. Evaluation of the effects of gravity on rigid rover wheel compaction resistance

4.1. With identical wheel load on both the extraterrestrial and the earth surfaces

4.1.1. 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, and making use of Eq. (6) for predicting rigid wheel sinkage (or rut depth), one obtains the following equation for determining the compaction resistance of a rigid wheel R_c [9,11,12]:

$$\begin{aligned} R_c &= b(K_c + K_\phi g)\left(\frac{z^{n+1}}{n+1}\right) \\ &= \left(\frac{b(K_c + K_\phi g)}{n+1}\right)\left[\frac{3W}{b(3-n)(K_c + K_\phi g)\sqrt{D}}\right]^{(2n+2)/(2n+1)} \\ &= \left[\frac{1}{(3-n)^{(2n+2)/(2n+1)}(n+1)b^{1/(2n+1)}(K_c + K_\phi g)^{1/(2n+1)}}\right] \\ &\quad \times \left[\frac{3W}{\sqrt{D}}\right]^{(2n+2)/(2n+1)} \end{aligned} \tag{13}$$

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

$$\frac{R_{cex}}{R_{ce}} = \frac{\left[\frac{1}{(3-n)^{(2n+2)/(2n+1)}(n+1)b^{1/(2n+1)}(K_c + K_\phi g_{ex})^{1/(2n+1)}}\right] \times \left[\frac{3W}{\sqrt{D}}\right]^{(2n+2)/(2n+1)}}{\left[\frac{1}{(3-n)^{(2n+2)/(2n+1)}(n+1)b^{1/(2n+1)}(K_c + K_\phi g_e)^{1/(2n+1)}}\right] \times \left[\frac{3W}{\sqrt{D}}\right]^{(2n+2)/(2n+1)}} \tag{14}$$

As noted earlier, in this case the wheel and its load exerted on the extraterrestrial surface are the same as those used in the tests on the earth surface. If the soil simulant used in the tests on earth and the soil on the extraterrestrial surface are dry with low cohesion (i.e., the values of c and

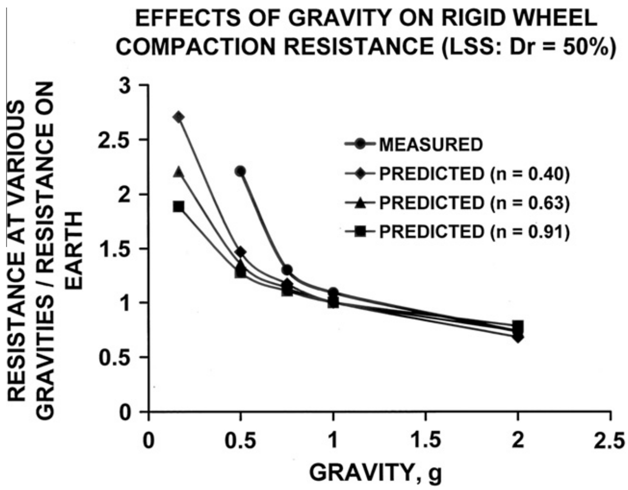

Fig. 8. Comparison of the effect of gravity on the compaction resistance ratio R_{cex}/R_{ce} of a rigid wheel (with identical load on both the extraterrestrial and earth surfaces) on the lunar soil simulant with relative density of 50% predicted by the proposed method with that measured in an aircraft undergoing parabolic flight manoeuvres.

K_c being insignificant) and have the same values of the pressure-sinkage parameters n and K_ϕ, Eq. (14) may be simplified as

$$\frac{R_{cex}}{R_{ce}} = \left(\frac{g_e}{g_{ex}}\right)^{1/(2n+1)} \tag{15}$$

For instance, if the soil on the lunar surface has the same properties as those of the soil simulant DLR-A with $n = 0.63$, then the ratio of the compaction resistance of a rigid wheel on the lunar surface to that on the earth surface can be predicted using Eq. (15), taking into account that the acceleration due to gravity on the earth surface is 6 times that on the lunar surface. That is,

$$R_{cex}/R_{ce} = (g_e/g_{ex})^{1/(2n+1)} = (6)^{1/(1.26+1)} = 2.21$$

Similarly, if the soil on the Martian surface has the same properties as those of the soil simulant DLR-A with $n = 0.63$, than the ratio of the compaction resistance of a rigid wheel on the Martian surface to that on the earth surface can be predicted using Eq. (15), taking into account that the acceleration due to gravity on the earth surface is 2.63 times that on the Martian surface. That is,

$$R_{cex}/R_{ce} = (g_e/g_{ex})^{1/(2n+1)} = (2.63)^{1/(1.26+1)} = 1.53$$

Fig. 8 shows the variations of the ratio of rigid wheel compaction resistance on the extraterrestrial surface to that on the earth surface, R_{cex}/R_{ce}, with the gravity on the extraterrestrial surface in g units ($g = 9.81$ m/s^2), predicted using Eq. (15) with $n = 0.40$, $n = 0.63$ and $n = 0.91$ (shown by the curves marked as "Predicted"). As can be seen in the figure, if the gravity is equal to 1 g (equivalent to that on the earth surface and read from the horizontal axis of Fig. 8), then from the curves shown in the figure $R_{cex}/R_{ce} = 1$ (read from the vertical axis of Fig. 8). If the gravity is equal to $1/6g$ (equivalent to that on the lunar surface), then from the curves shown in the figure $R_{cex}/R_{ce} = 2.71$, 2.21 and 1.89 for $n = 0.40$, $n = 0.63$ and $n = 0.91$, respectively, If the gravity is equal to $0.38g$ (equivalent to that on the Martian surface), then from the curves shown in Fig. 8, $R_{cex}/R_{ce} = 1.71$, 1.53 and 1.41 for $n = 0.40$, $n = 0.63$ and $n = 0.91$, respectively. The trends of the curves show that with identical wheel load exerted on both the extraterrestrial and the earth surfaces, if the gravity decreases, the compaction resistance ratio R_{cex}/R_{ce} for a rigid rover wheel will increase exponentially with an exponent of $(1/(2n + 1))$.

4.1.2. Comparison of predictions with test data

As an example, the experimental data obtained on the lunar soil simulant with relative density of 70% reported in [1] and shown in the right diagrams of Fig. 3(a) and (b) are analyzed to evaluate the effects of gravity on the compaction resistance ratio R_{cex}/R_{ce} for the rigid wheel used in the tests described in Section 3.1.2.

The measured driving torques applied to the wheel with loads of $1/6W$, $1/2W$, $3/4W$, $1W$, and $2W$ while operating under self-propelled conditions (without drawbar load) on the ground at various times are shown in the right diagram of Fig. 3(a). It should be noted that since the wheel was under self-propelled conditions, the torque applied to the wheel is proportional to the motion resistance of the wheel. Another set of experiment was performed under various gravity conditions produced in the aircraft undergoing parabolic flight manoeuvres. The driving torques of the rigid wheel in self-propelled conditions under gravities of $1/6g$, $1/2g$, $3/4g$, $1g$, and $2g$ at various times are shown in the right diagram of Fig. 3(b). As explained earlier, for instance, the load of $1/6W$ applied by the wheel to the soil on the ground is equivalent to that applied by the wheel at gravity of $1/6g$.

As shown in the right diagrams of Fig. 3(a) and (b), the driving torque of the wheel varies with time. Similar to the

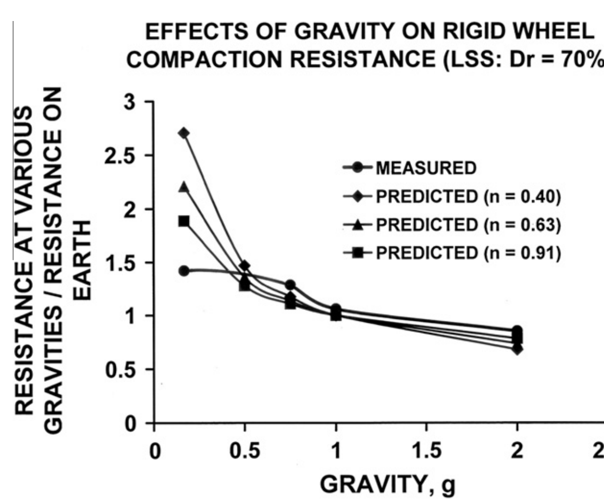

Fig. 9. Comparison of the effect of gravity on the compaction resistance ratio R_{cex}/R_{ce} of a rigid wheel (with identical load on both the extraterrestrial and earth surfaces) on the lunar soil simulant with relative density of 70% predicted by the proposed method with that measured in an aircraft undergoing parabolic flight manoeuvres.

procedure for processing the wheel sinkage data described in Section 3.1.2, the driving torques at times of 5 and 10 s shown in the right diagrams of Fig. 3(a) and (b) were averaged for different levels of loads and gravities. The ratio of the average value of the driving torque obtained under a given level of gravity, from the right diagram of Fig. 3(b), to that obtained under a given level of load on the ground, from the right diagram of Fig. 3(a), is taken as the corresponding compaction resistance ratio R_{cex}/R_{ce} and is plotted against gravity and marked as "Measured" in Fig. 9, for tests performed on the lunar soil simulant with relative density of 70%. Similar measured curves for tests conducted on the lunar soil simulant with relative density of 50% and on the Toyoura sand with relative densities of 50% and 70% are shown in Figs. 8, 10 and 11, respectively.

It should be noted that in the right diagram of Fig. 3(a), at low levels of loads, such as $1/6W$ and $1/2W$, the driving torque is very small. In this range, torque measurements are susceptible to errors. This would lead to irregularities in the test data. As shown in the right diagram of Fig. 3(a), the measured driving torques for loads of $1/6W$ and $1/2W$ between 0 and 10 s are essential the same. This leads to an anomaly in the ratio of the driving torque (or compaction resistance) at gravity of $1/2g$ to that at load of $1/2W$ on the ground. For this reason, the value of the compaction resistance ratio R_{cex}/R_{ce} at gravity of $1/2g$ on the lunar soil simulant with relative density of 70% is not shown in Fig. 9. Similar irregularities are found in the test data at low gravity of $1/6g$ obtained on the lunar soil simulant with relative density of 50% and on the Toyoura sand with relative densities of 50% and 70%. Accordingly, the values of R_{cex}/R_{ce} at $1/6g$ are not shown in Figs. 8, 10 and 11.

As shown in Figs. 8 and 9 for the lunar soil simulant with relative densities of 50% and 70%, respectively, the "Predicted" curve for $n = 0.4$ obtained using Eq. (15) shows a reasonable resemblance to the "Measured" curve in the range of gravity above $0.5g$. In Fig. 10 for the Toyoura sand with relative density of 50%, the "Predicted" curve for $n = 0.63$ shows a close resemblance to the "Measured" curve in the range of gravity higher than 0.5 g. In Fig. 11 for the Toyoura sand with relative density of 70%, the "Predicted" curve for $n = 0.3$ shows a reasonable resemblance to the "Measured" curve in the range of gravity higher than 0.5 g. These are similar to the correlations between the "Predicted" curves with corresponding values of n and "Measured" curves for the wheel sinkage ratio on the lunar soil simulant and the Toyoura sand with different relative densities shown in Figs. 2 and 4–6.

It should be mentioned that the predicted curves shown in the figures are only a function of the exponent n of the pressure-sinkage equation for the soil. Consequently, the predicted curves in Figs. 8–11 with the same value of n are identical. While the "Predicted" curves are not directly related to the type or conditions of the soil, these factors would have an influence on the value of n.

While the "Predicted" curve with a particular value of n shows a reasonable resemblance to the corresponding "Measured" curve obtained from tests on the lunar soil simulant and the Toyoura sand with different relative densities, there are differences between them. These differences may be attributed to factors similar to some of those identified in Section 3.1.2.

In summary, despite the values of the exponent n for the soils used in the tests being unknown, the probable errors in the measurements of the wheel torque, and the effects of slip-sinkage and soil cohesion being neglected in predictions, the trends for the effects of gravity on the compaction resistance ratio R_{cex}/R_{ce} for a rigid wheel predicted using Eq. (15) show a reasonable resemblance to those exhibited by the measured data. This indicates that the

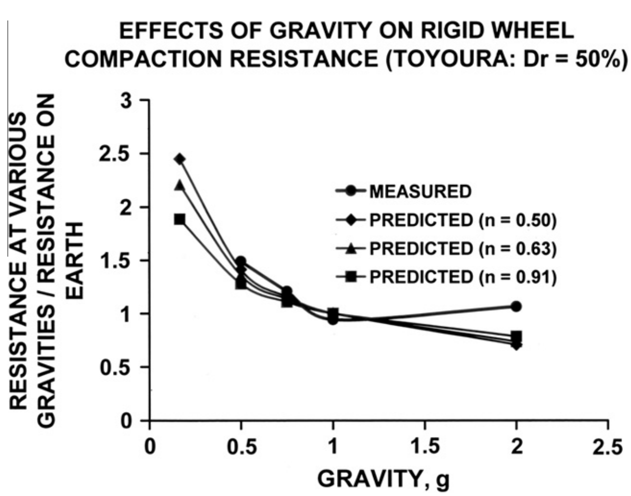

Fig. 10. Comparison of the effect of gravity on the compaction resistance ratio R_{cex}/R_{ce} of a rigid wheel (with identical load on both the extraterrestrial and earth surfaces) on the Toyoura sand with relative density of 50% predicted by the proposed method with that measured in an aircraft undergoing parabolic flight manoeuvres.

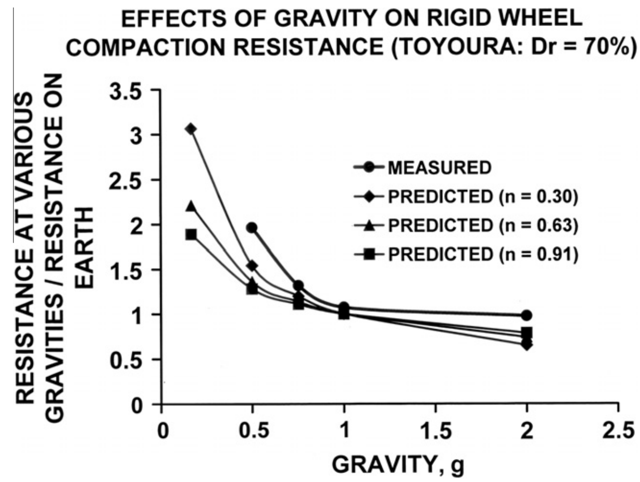

Fig. 11. Comparison of the effect of gravity on the compaction resistance ratio R_{cex}/R_{ce} of a rigid wheel (with identical load on both the extraterrestrial and earth surfaces) on the Toyoura sand with relative density of 70% predicted by the proposed method with that measured in an aircraft undergoing parabolic flight manoeuvres.

experimental data do lend support, in general, to the proposed method for predicting the probable compaction resistance of a rigid rover wheel on the surface of an extraterrestrial body, based on test data obtained on the earth surface.

4.2. With identical wheel mass on both the extraterrestrial and the earth surfaces

4.2.1. Analysis

With identical mass carried by the wheel on both the extraterrestrial and the earth surfaces, Eq. (14) may be rewritten as follows:

$$\frac{R_{cex}}{R_{ce}} = \frac{\left[\dfrac{1}{(3-n)^{(2n+2)/(2n+1)}(n+1)b^{1/(2n+1)}(K_c+K_\phi g_{ex})^{1/(2n+1)}}\right] \times \left[\dfrac{3mg_{ex}}{\sqrt{D}}\right]^{(2n+2)/(2n+1)}}{\left[\dfrac{1}{(3-n)^{(2n+2)/(2n+1)}(n+1)b^{1/(2n+1)}(K_c+K_\phi g_{e})^{1/(2n+1)}}\right] \times \left[\dfrac{3mg_{e}}{\sqrt{D}}\right]^{(2n+2)/(2n+1)}} \tag{16}$$

where m is the mass carried by the wheel, and all other parameters are defined in the same way as those in Eq. (14).

If the soil simulant used in the tests on earth and the soil on the extraterrestrial surface are dry with low cohesion (i.e., the values of c and K_c being insignificant) and have the same values of the pressure-sinkage parameters n and K_ϕ, Eq. (16) may be simplified as

$$\frac{R_{cex}}{R_{ce}} = \frac{g_{ex}}{g_e} \tag{17}$$

Eq. (17) 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 gravity ratio g_{ex}/g_e. This will greatly simplify the procedure for predicting the rigid rover wheel compaction resistance on the extraterrestrial surface based on that measured on earth, as the exponent n of the pressure-sinkage equation is not required in the prediction.

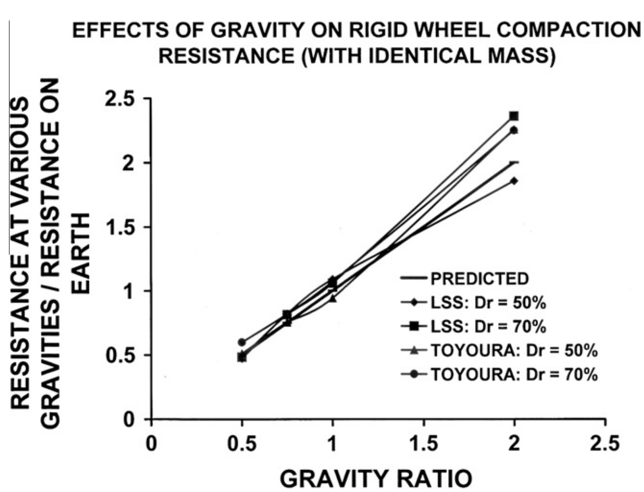

Fig. 12. Comparison of the variation of the compaction resistance ratio R_{cex}/R_{ce} with the gravity ratio g_{ex}/g_e of a rigid wheel (with identical mass on both the extraterrestrial and earth surfaces) predicted by the proposed method with those measured on different soils in an aircraft undergoing parabolic flight manoeuvres.

4.2.2. Comparison of predictions with test data

The variations of the compaction resistance ratio R_{cex}/R_{ce} with the gravity ratio g_{ex}/g_e of a rigid wheel with identical mass on both the extraterrestrial and the earth surfaces predicted using Eq. (17) are evaluated with test data obtained under various gravity conditions presented in Reference [1]. The test data shown in the right diagrams of Fig. 3(a) and (b) for the lunar soil simulant with relative density of 70% are used as an example to illustrate the procedure involved. For instance, the compaction resistance ratio R_{cex}/R_{ce} at the gravity ratio $g_{ex}/g_e = 3/4$ is calculated by the ratio of average torque at times 5 and 10 s at $3/4g$ shown in the right diagram of Fig. 3(b) to that at $1W$ shown in right diagram of Fig. 3(a). It should be noted that the mass carried by the wheel (10 kg) while in the aircraft under gravity of $3/4g$ is identical to that on the ground with load $1W$ (10 kg $\times$ 9.81 m/s^2). From the data shown in the right diagram of Fig. 3(b), at $3/4g$ the average torque at times 5 and 10 s is 1.64 Nm. From the right diagram of Fig. 3(a) at $1W$, the average torque at times 5 and 10 s is 2.02 Nm. Therefore, at the gravity ratio $g_{ex}/g_e = 3/4$, the torque ratio or the compaction resistance ratio $R_{cex}/R_{ce} = 1.64/2.02 = 0.81$, as indicated on the curve for LSS: $D_r = 70\%$ in Fig. 12. Following the same procedure, the variations of the measured values of the compaction resistance ratio R_{cex}/R_{ce} with the gravity ratio g_{ex}/g_e for the lunar soil simulant with relative density of 50% and for the Toyoura sand with relative densities of 50% and 70% are plotted in Fig. 12. The variation of the compaction resistance ratio R_{cex}/R_{ce} with the gravity ratio g_{ex}/g_e predicted by Eq. (17) is represented by an inclined straight line in Fig. 12. It should be mentioned that at gravity of $1/6g$, the wheel torque is small and is susceptible to errors in measurements. This causes irregularities in the compaction resistance ratio R_{cex}/R_{ce} at the gravity ratio $g_{ex}/g_e = 1/6$ in some cases. For this reason, the values of the compaction resistance ratio R_{cex}/R_{ce} at the gravity ratio $g_{ex}/g_e = 1/6$ on the lunar soil simulant and the Toyoura sand with different relative densities are not shown in Fig. 12.

As can be seen in Fig. 12, the measured curves show a reasonable correlation with the predicted one in the range of gravity ratio g_{ex}/g_e higher than 0.5. The differences between the predicted and measured curves may be attributed to factors (b) to (e) identified in Section 3.1.2.

In summary, despite the probable errors in the measurements of wheel torque, as well as the effects of slip-sinkage and soil cohesion being neglected in predictions, for a rigid wheel with identical mass on the extraterrestrial and the earth surfaces, the measured curves for the compaction resistance ratio R_{cex}/R_{ce} vs. the gravity ratio g_{ex}/g_e have a reasonably close correlation with the predicted one obtained using Eq. (17). Thus, it would appear preferable that in conducting performance testing of rigid rover wheels on soil simulants on the earth surface, the wheel carries the same mass as that for operations on the extraterrestrial surface, instead of carrying the same normal load, as employed in the usual practice. This would allow the use of a simpler procedure, without requiring the exponent n of the pressure-sinkage equation for the soil as an input, to predict the compaction resistance of the rigid rover wheel on the extraterrestrial surface based on that measured on the earth surface.

5. Concluding remarks

A. To experimentally evaluate the performances of rover wheels, the usual practice is to test them on soil simulants on earth and to set the normal loads exerted by the wheels on the soil simulants in accordance with those expected on extraterrestrial surfaces. As the soil simulant used in the test is subject to the earth gravity and the soil on the extraterrestrial surface is subject to a different gravity, a question is raised as to whether the performances of rover wheels measured on the soil simulant under the earth gravity represent those on the extraterrestrial surface. This paper attempts to address this critical issue in the development and testing of extraterrestrial rovers/rover wheels.

B. Methods have been developed for predicting the sinkage and compaction resistance of the rigid rover wheel on an extraterrestrial surface based on those measured on the earth surface with identical normal load on the wheel. It is shown that the predicted rigid rover wheel sinkage and compaction resistance on the extraterrestrial surface are functions of gravity, as well as the exponent of the pressure-sinkage equation for the soil. The basic features of the methods have been evaluated with experimental data. It is shown that the effects of gravity on the rigid rover wheel sinkage and compaction resistance predicted using the methods have reasonable correlations with results of tests conducted under various gravity conditions produced in an aircraft undergoing parabolic flight manoeuvres.

C. Methods have also been developed for predicting the sinkage and compaction resistance of the rigid rover wheel on an extraterrestrial surface based on those measured on the earth surface with identical mass carried by the wheel. It is shown that the predicted rigid rover wheel sinkage on the extraterrestrial surface is equal to that on the earth surface and that the predicted rigid rover wheel compaction resistance on the extraterrestrial surface is only a function of the ratio of the gravity on the extraterrestrial surface to that on the earth surface. The exponent of the pressure-sinkage equation for the soil is not required in predictions. The basic features of the methods have been evaluated with experimental data. It is shown that the effects of gravity on the rigid rover wheel sinkage and compaction resistance predicted using the methods have reasonable correlations with results of tests conducted under various gravity conditions produced in an aircraft undergoing parabolic flight manoeuvres.

D. In view of the above, it is suggested that in conducting performance testing of rigid rover wheels on soil simulants on the earth surface, the wheel carries the same mass as that for operations on the extraterrestrial surface, instead of carrying the same normal load, as employed in the current practice. This would allow the use of a simpler procedure, without requiring the exponent of the pressure-sinkage equation for the soil as an input, to predict the sinkage and compaction resistance of the rigid rover wheel on the extraterrestrial surface based on those measured on the earth surface.

E. While it is desirable to further evaluate the proposed methods with reliable test data over a wider range of soil conditions, particularly under low gravities, the methods proposed in this paper may, in the meantime, be used as practical engineering tools for estimating the sinkage and compaction resistance of rigid rover wheels on the surfaces of extraterrestrial bodies based on test data obtained on earth.

F. Developments are needed of methods for predicting the sinkage and compaction resistance of flexible rover wheels, and for predicting the overall tractive performance of both rigid and flexible rover wheels, as well as the mobility of rovers on extraterrestrial surfaces, based on test data obtained on earth.

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References

[1] Kobayashi T, Fujiwara Y, Yamakawa J, Yasufuku N, Omine K. Mobility performance of a rigid wheel in low gravity environments. J Terramechanics 2010;47(4):261–74.

[2] Nakashima H, Shioji Y, Kobayashi T, Aoki S, Shimizu H, Miyasaka J, Ohdoi K. Determining the angle of repose of sand under low-gravity conditions using discrete element method. J Terramechanics 2011;48(1):17–26.

[3] Freitag DR, Green AJ, Melzer KJ. Performance evaluation of wheels for lunar vehicles. Technical Report M-70-2, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, USA; March 1970.

[4] Wong JY, Asnani VM. Study of the correlation between the performances of lunar vehicle wheels predicted by the Nepean wheeled vehicle performance model and test data. Proc Inst Mech Eng, D: J Automob Eng 2008;222(D11):1939–54.

[5] Iagnemma K, Kang S, Brooks C, Dubowsky S. Multi-sensor terrain estimation for planetary rovers. In: Proceedings of the 7th international symposium on artificial intelligence, robotics and automation in space: i-SAIRAS 2003, Nara, Japan; May 19–23, 2003.

[6] Shibly H, Iagnemma K, Dubowsky S. An equivalent soil mechanics formulation for rigid wheels in deformable terrain, with application to planetary exploration rovers. J Terramechanics 2005;42(1):1–13.

[7] Ishigami G, Miwa A, Nagatani K, Yoshida K. Terramechanics-based model for steering maneuver of planetary exploration rovers on loose soil. J Field Robotics 2007;24(3):233–50.

[8] Scharringhausen M, Beermann D, Kromer O, Richter L. A wheel-soil interaction model for planetary applications. In: Proceedings of 11th European regional conference of ISTVS, Bremen, Germany; 2009.

[9] Bekker MG. Off-the-road locomotion. Ann Arbor: The University of Michigan Press; 1960.

[10] Reece AR. Principles of soil-vehicle mechanics. Proc Inst Mech Eng 1965–66;180(Part 2A No. 2):45–67.

[11] Wong JY. Theory of ground vehicles. 4th ed. NY: Wiley; 2008.

[12] Wong JY. Terramechanics and off-road vehicle engineering. 2nd ed. Oxford: Elsevier; 2009.

[13] Krenn R, Hirzinger G. Simulation of rover locomotion on sandy terrain – modeling, verification and validation. In: 10th ESA workshop on advanced space technologies for robotics and automation – ASTRA; 2008.

[14] Bekker MG. Introduction to terrain-vehicle systems. Ann Arbor: The University of Michigan Press; 1969.