A Study on Wheel Sinkage and Rolling Resistance with variations in wheel geometry for Plain and Lugged wheels on TRI -1 Soil Simulant

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Abstract. Wheel-soil Interaction studies are gaining momentum in the field of Terramechanics, but the basis is Terzaghi’s bearing capacity equation. For the current study, on a lunar soil simulant TRI – 1, two plain rigid wheels are considered, i.e., small wheel (dia. of 210 mm and width of 50 mm) and large wheel (dia.160 mm and width 32 mm). Also, different number of lugs (N= 8, 12, 16) with various lug heights (h= 5 mm, 10 mm, 15 mm) are used. In this paper, the variation of wheel sinkages from experiments obtained for various wheel weights are examined and presented. The parameter, Coefficient of rolling resistance (CRR) is determined for various cases. Hence, rolling resistance was determined and examined from the obtained CRR for all cases. Among the cases examined, the large wheel with weight 67.44 N for plain wheels and weight 67.85 N for lugged wheel (no. of lugs = 16, and height of lugs = 5 mm) registered better mobility. Similarly, for small wheel with weight 52.189 N for plain wheel and weight 52.481 N for lugged wheel (no. of lugs = 16, and height of lugs = 5 mm) registered better mobility, a lesser rolling resistance for these cases.

1. Introduction

Wheel – soil interaction studies are increasing in the field of Terramechanics, but the basis is Terzaghi’s bearing capacity equation. A planetary rover explores terrains on different planets like Mars/Moon (Lunar) surface, and also has some issues when it travels on such natural terrains that consist of dust, obstacles, steeper slopes, loose soil, etc. There are numerous different types of wheeled vehicles (two wheeled, four wheeled, six wheeled and eight wheeled) and tracked vehicles [5], available and used on the lunar/Mars surface to explore the terrain on its surface. This can be done when a planetary rover is allowed to traverse on such difficult surfaces. Hence, investigation on the moon/ Mars - planetary surfaces are necessary during its traverse and during interactions of the rover wheel with the soil while driving on it [2]. Experiments were conducted using single wheel test bed for the wire mesh wheel (WMW) with different loads and velocities to investigate the sinkage characteristics of WMW type. The wire mesh wheel has larger sinkage and tractive efficiency but smaller drawbar pull and driving torque [1]. The overall trend of the net drawbar pull versus slip ratio, is agreed qualitatively, and shows steeper trend when slip ratio is less than 25% (i.e., drawbar pull shows steeper trend when slip ratio is less than 25%, and the trend is flat when slip ratio is larger), indicates effectiveness of 3D FE-DEM [5]. Diameters of wheels were in the range of 36 cm to 124 cm and wheel loads were of 0.19 kN to 36.12 kN [3]. On sandy flat terrain and sandy sloping terrain 61% to 94% vehicle slippage occurrences were noticed and 15 % errors [2, 6].
Wheeled rover/tracked rover navigation studies in unstructured environment/terrain, and on loose soil is one of the most challenging tasks in the field of Terramechanics. One of the reasons for this is that, higher sinkage of wheel during its travel can cause rover to get stuck into the soil, indicating less mobility (or) no mobility [2, 4]. To avoid this problem, the rover must have a high degree of mobility. Single wheel – soil /simulant interactions are considered and mobility aspects are investigated. Many researchers have worked on wheel-soil interaction through numerical and experimental works using different combinations of wheel geometry. Still, scope exists in improving traffic ability to get better mobility.

In this paper, the wheel sinkages, obtained for various wheel weights are examined and presented for, TRI-1 Lunar Soil Simulant. The mobility in terms of rolling resistance are also examined and presented in this paper. Wheel sinkage and rolling resistance for various wheel geometry combinations (Refer Table 1) are ascertained and reported for 2 wheels (small and large) for plain and lugged conditions on TRI-1 Lunar soil simulant.

2. Experimental work

Single wheel test bed is used for carrying out experiments with various rigid wheel combinations of different diameter/width, various lug heights with different number of lugs. The test bed is filled with TRI – 1 Lunar Soil Simulant, and tests were conducted to measure the wheel sinkage. For each case sinkage is measured and noted.

Sinkages are measured and are graphically presented in Fig 3 (a) and 3 (b). Rolling resistance is one of the major factors that affect the travelling performance of rover/rover wheel. This can be found by knowing coefficient of rolling resistance. Hence, the experimental results are used as input for finding the rolling resistance for both the wheels. The minimum sinkages, for both small wheel and large wheel are also presented in section 3. The rolling resistance and rolling resistance coefficient is also graphically presented and the minimum resistance arrived wheel combination are also noted.

3. Results and Discussions

Small wheel (160 mm diameter and 32 mm width ) and large wheel (210 mm diameter and 50 mm width) is considered for the present study along with lugged small and large wheels (h = 5,10,15 mm and no. of lugs, N= 8,12,16). TRI-1 Lunar Soil Simulant [7], is used for the wheel-soil interaction studies. Wheel sinkages were measured for all cases (refer Table 1). Variations of wheel sinkage for various wheel weights from experimental results are graphically presented in Fig. 3(a) and Fig.
3(b). Wheel slip is the ratio of wheel width to the wheel radius, found for all cases and shown graphically in Fig. 3 is for large wheel and in Fig. 3 b is for small wheel.

### Table 1 Wheel Geometry for different cases

| Sl. No. | Type of wheel | Case 1 | Case 2 | Case 3 | Case 4 |
|---------|---------------|--------|--------|--------|--------|
| 1.      | Small wheel (SW) | Plain | h= 5 mm N=8,12,16 | h= 10 mm N=8,12,16 | h= 15 mm N=8,12,16 |
|         | (SW)           | (160 mm x 32 mm) |        |        |        |
| 2.      | Large wheel (LW) | Plain | h= 5 mm N=8,12,16 | h= 10 mm N=8,12,16 | h= 15 mm N=8,12,16 |
|         | (LW)           | (210 mm x 50 mm) |        |        |        |

Fig. 2(a) Wheel weight vs. wheel diameter (SW: b=32 mm)

Fig. 2(b) Wheel weight vs. wheel diameter (LW: b=50 mm)

Fig. 2(a) and Fig. 2(b) show the wheel weights for various wheel diameters. As wheel diameter increases, wheel weight increases and reaches maximum of 68.5N for large wheel, whereas, maximum weight of 52.8N for small wheel, when h=15 mm and no. of lugs, N= 16.
Fig. 3(a) Effect of Wheel weight on its Sinkage (LW: b=50 mm)  
Fig. 3(b) Effect of Wheel weight on its Sinkage (SW: b=32 mm)

Fig. 3(a) and Fig. 3(b) show effect of wheel weight on its sinkage caused during its travel. Increase in wheel weight results in increase in sinkage, for all the lugged wheels. The minimum sinkage of 7.33 mm for large lugged wheel (h=5 mm and N=16) and 7.67 mm of sinkage for small lugged wheel, when h=5mm and N=16. Increase in number of lugs from 8 to 16, reduces wheel sinkage. For plain large wheel the sinkage registered is 3 mm and for plain small wheel, the sinkage registered is 2.66 mm.

Fig. 4(a) Influence of Wheel slip on Wheel sinkage (LW)  
Fig. 4(b) Influence of Wheel slip on Wheel sinkage (SW)

Fig. 4(a) and Fig. 4(b) show the influence of wheel slip on wheel sinkage. Increase in wheel slip, results in reduction in wheel sinkage, for both the wheels. Comparing lugged wheels, large wheel at slip of 0.48 (h=5 mm, N=16) gives minimum sinkage of 7.33 mm, whereas, slip of 0.38 (h=5 mm, N=16) gives minimum sinkage of 7.67 mm, for small wheel. For plain wheels, small wheel gives minimum sinkage of 2.66 mm, when wheel slip is 0.40 and large wheel causes 3 mm sinkage when wheel slip is 0.48.

Rolling resistance plays a major role in mobility performance. Rolling resistance is the horizontal force needed to compact the soil [4]. Rolling resistance depends on wheel sinkage, which is a function of wheel load [4] and is related to soil properties. It is defined as, the product of vertical load applied on the wheel and coefficient of rolling resistance [4] and is given as,

\[ R_r = \mu_r W \]  
\[ \mu_r = \sqrt{\frac{z}{d}} \quad \text{(for rigid wheel)} \]

where, ‘\( \mu_r \)’ is the coefficient of rolling resistance, ‘W’ is the wheel weight, ‘d’ is the wheel diameter.
and ‘z’ is the wheel sinkage.

High rolling resistance indicates poor mobility [4]; lower rolling resistance gives better mobility.

![Rolling resistance Vs. Wheel weight](image)

**Fig. 5(a)** Influence of Wheel weight on Rolling Resistance (LW: b=50 mm)

![Rolling resistance Vs. Wheel weight](image)

**Fig. 5(b)** Influence of Wheel weight on Rolling Resistance (SW: b=32 mm)

Fig. 5(a) and Fig. 5(b) show the Influence of wheel weight on its rolling resistance. As wheel weight increases, rolling resistance also increases at constant no. of lugs. Comparing all cases, for N=8, rolling resistance increases with increase in lug height, h = 5, 10, 15 mm and increase in no. of lugs, results reduction in rolling resistance comparing with N=8 and attains minimum $R_r = 12.425$ N for large lugged wheel, $R_r = 11.190$ N for small lugged wheel, when N=16 and h = 5 mm. For plain wheels, $R_r = 7.598$ N (large wheel) and $R_r = 6.785$ N (small wheel). Hence, lower the rolling resistance, better the mobility [4]. Small lugged wheel with lower rolling resistance have better mobility as well as small plain wheel.
Fig. 6 Effect of Wheel Geometry on Coefficient of Rolling Resistance

Fig. 6 shows effect of wheel geometry on wheel rolling resistance. As diameter of wheel increases, there is a gradual increase in coefficient of rolling resistance ($\mu_r$) for both plain and lugged wheels (small and large). On comparing, small wheel with large wheel (plain and lugged), increase in diameter from small wheel to large wheel, results in decrease in coefficient of rolling resistance (CRR) but increase in rolling resistance (refer Fig. 6 and Fig. 7) from small wheel to large wheel (plain and lugged).

Fig. 7 Influence of Coefficient of Rolling Resistance on Wheel Rolling Resistance

Fig. 7 indicates the influence of coefficient of rolling resistance on wheel rolling resistance, as CRR increases, there is a change in rolling resistance on the higher side for both plain and lugged wheels (plain and lugged) individually. On comparing plain wheels (small and large), small wheel dia. having more CRR (0.130) than large wheel (CRR = 0.118), results in less rolling resistance than plain large wheel (refer Fig. 7) indicating good mobility. Similarly, comparing lugged wheels (small and large), small lugged wheels give lower rolling resistance than large lugged wheels, as the contact area is more. Among all the cases, for small wheel with CRR0.130 for plain wheel and CRR0.243 for lugged wheel (no. of lugs = 16, and height of lugs = 5 mm) registered better mobility, a lesser rolling resistance for these cases. For large wheel with CRR of 0.118 for plain wheel results less rolling resistance than lugged small wheels, also indicates good mobility (refer Fig. 7).
4. Conclusions

1. Various wheel sinkages were examined from experiments, for different wheel weights, and it is found that, plain wheels are giving less sinkage than lugged wheels, i.e., small wheel (z = 2.66 mm) and for large wheel (z = 3.00 mm).
2. Also found, comparing all the lugged wheels (large wheel), with different no. of lugs, wheel with h = 5 mm and N = 16, results in less sinkage (z = 7.33 mm).
3. Similarly, comparing lugged wheels for small wheel, with different no. of lugs, wheel with h = 5 mm and N = 16, results less sinkage (z = 7.67 mm).
4. Coefficient of rolling resistance (CRR) for all the cases are determined and examined. It was found that, increase in diameter from small wheel to large wheel (plain and lugged), results in reduction in CRR.
5. Rolling resistance (Rr) for all the cases are determined and examined.
6. Among the cases examined, the large wheel with weight 67.44 N for plain wheels and weight 67.85 N for lugged wheel (no. of lugs = 16, and height of lugs = 5 mm) registered better mobility. Similarly, for small wheel with weight 52.189 N for plain wheel and weight 52.481 N for lugged wheel (no. of lugs = 16, and height of lugs = 5 mm) registered better mobility, and hence a lesser rolling resistance for these cases.
7. For small wheel (Rr = 6.785 N) and large wheel (Rr = 7.958 N) – plain wheels. Similarly, for lugged wheels (h = 5 mm, N = 16), small wheel (Rr = 11.190 N) and large wheel (Rr = 12.425 N). Lower the rolling resistance better the mobility.
8. Therefore, sinkage and rolling resistance are lesser for lugged small wheel comparing both lugged wheels (small and large). Hence, lugged small wheel (h=5 mm, N=16) indicates better mobility among all the cases presented.

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