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Relationship Between Tire Pressure and Tractive Characteristic of Beach Cleaner

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Abstract: This study proposes a mathematical model that uses the traction coefficient as an evaluation index for predicting the traction trafficability of a tire with low inflation pressure while rolling on a sandy beach. Employing sand taken from the sandy beach on the Huli Mountain in Xiamen and a 400/60-15.5R14 tire, we performed a tire sand trough orthogonal experiment using different tire pressures, loads and slip rates. The experimental results were found to be consistent with the predictions of the mathematical model and the optimum tire pressure was determined. The numerical and experimental results provide a reliable basis for designing a beach cleaner.

Key words: Tire pressure, traction coefficient, sand, beach cleaner

INTRODUCTION

A beach cleaner is an important equipment used in the cleaning of coastal beaches and studies on vehicle terramechanics have revealed that large-diameter wheels are advantageous to the movement of the cleaner over soft beach surfaces (Ray, 2009). However, owing to the special structure of a beach cleaner, the need to limit the diameter of the tire requires the use of a broader width and low inflation pressure. Several studies have been conducted to analyze and simulate the traction of the vehicle during operation on desert or a beach, although most of them focused on improving the structure of the tire. Attempts have also been made to reduce sand erosion under the wheel to improve the bearing capacity of the sand (Li *et al*., 2012). In actual use of the vehicle, however, the high cost of the required special structure of the tire has led to the alternative utilization of low-pressure and wide tires. The inflation pressure of the tire affects the traction on sand and the trough capacity of the tire is closely related to the specific ground pressure (Stoilov, 2007). There is a linear positive correlation among the specific ground pressure, tire inflation pressure and load (Wehrspann, 2013). The effect of the tire inflation pressure on the vehicle trough capacity is, thus, worthy of study. In this study, the traction coefficient is proposed as an evaluation index for calculating the compaction resistance using the dynamic subsidence quantity under the conditions of a beach cleaner operating at a low speed on a beach. The proposed method is based on the theory of Bekker and ignores the bulldozing resistance as well as other insignificant factors and is used to investigate the effect of the tire pressure on the vehicle traction (Wehrspann, 2013). Employing sand taken from the beach on the Hu Li Mountain in Xiamen and a 400/60-15.5R14 tire, tire sand trough orthogonal experiments were performed using different tire pressures, loads and slip rates.

TRACTION COEFFICIENT CALCULATION MODEL

The drawbar pull of a spring tire is related to the load applied to it. To eliminate the effect of the load on the hook traction and compare the drawbar pulls for different loads, the traction coefficient CT is generally used in engineering as the main indicator of the vehicle trough. The reserves of the “net thrust” and the traction performance increase with increasing drag coefficient. The relationship is as follows (Sano *et al*., 2013):

$$C_T = DP / W = (T - \sum F_t) / W \tag{1}$$

where, DP is the drawbar pull which is the difference between the driving force and the driving resistance of the tires. The difference is directly determined using the draw hook:

$$DP = T - \sum F_t$$

where, T is the driving force of the tire generated by the shear force of the tire acting on the sand. Dry sand is categorized as “plastic” soil which has zero cohesion.

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Based on the principle of Terramechanics, the driving force can be expressed as (Yamakawa and Watanabe, 2007):

$$T = BLq\tan\varphi + \frac{BLq\,j_0\tan\varphi}{sL}(e^{-sL/j_0}-1) = W\tan\varphi\left[1+\frac{j_0}{sL}(e^{-sL/j_0}-1)\right] \quad (2)$$

where, B is the width of the tire contact (mm), L is the ground contact length of the tire (mm), φ is the angle of the internal friction of the sand (°), s is the tire slip ratio (%), q is the bearing strength of the sand (MPa), $q = p_c+p_1$, where, p_c is the equivalent air pressure acting on the tire sidewall (MPa) and p_1 is the inflation pressure of the tire (MPa) and W = BLq, where, W is the vertical load acting on the tire (N).

Various factors resist the running of a beach cleaner on soft sand at a low speed, they mainly comprise the compaction resistances caused by repetitive deformation of the low-pressure tires and the elastic hysteresis loss due to the vertical compaction deformation of the beach.

$$\Sigma f_t = F_1+F_2 \quad (3)$$

where, Σf_t is the total running resistance of the tire (N), F_1 is the compaction resistance of the tire (N) (Yang *et al*., 2013):

$$F_1 = B\int_0^{Z_d} kz^n dz = Bk\frac{Z_d^{n+1}}{n+1} \quad (4)$$

where, k is the deformation modulus, n is the slip ratio effect coefficient, (mm), Z_d is the dynamic subsidence of the tire: $z_d = A_s+z_0$, A is the slip ratio effect coefficient which is experimentally determined, s is slip rate and Z_0 is the static sinkage (mm): $Z_0 = (q/k)^{1/n}$.

F_2 is the resistance caused by the tire deformation (Whitby, 2010):

$$F_2 = \frac{\alpha_1\alpha_2}{2(p_c+p_1)\alpha^3}W^2 = uW^2(p_c+p_1)-\alpha \quad (5)$$

where u, α_1, α_2, α_3 and α are coefficients related to the structure of the tire.

Substituting Eq. 4 and 5 into Eq. 3 (Bennett, 2011), it gives:

$$\Sigma F_t = F_1+F_2 = Bk\frac{Z_d^{n+1}}{n+1}+uW^2(p_c+p_1) \quad (6)$$

Substituting Eq. 2 and 6 into Eq. 1 gives the formula for calculating the traction coefficient:

$$C_T = \tan\varphi\left[1+\frac{j_0}{sL}(e^{-sL/j_0}-1)\right]-Bk\frac{Z_d^{n+1}}{(n+1)W}-uW(p_c+p_1)-\alpha \quad (7)$$

where, L is the ground contact length:

$$L = \sqrt{D(z_d+z_c)-(z_d+z_c)^2}+\sqrt{D\cdot z_c-z_c^{\,2}}$$

and Z_c is the radial deflection of the tire:

$$Z_c = \frac{7.18(1.5\times10^{-3}B+0.42)W^{0.85}}{B^{0.7}D^{0.43}p_1^{\,0.6}}$$

SAND TROUGH ORTHOGONAL EXPERIMENT

Physical parameters of dry sand: The experiment was performed using sand taken from the beach on the Huli Mountain in Xiamen. Other apparatus included a sand sieve, libra, circular knives and a pycnometer for testing oven-dried sand. The physical performance parameters of the dry sand are given in Table 1.

Analysis of pressure performance: Using test methods for laminated sheets, three different square plates with side lengths 40, 60 and 80 mm, respectively, were tested. The logarithmic function of both sides of each plate were obtained using the verified formula developed by Bekker:

$$\lg P = \lg K+n\lg Z$$

By numerical fitting in logarithmic coordinates, the following were obtained:

$$n = 0.99,\ K = 5523\ \text{KN/mm}^2$$

Shear strength: Strain-controlled direct shear apparatus tests were conducted using vertical pressures of 50, 100, 200, 300 and 400 KPa, respectively. Based on the test results, the following values were obtained:

$$J_0 = 113\ \text{mm},\ \varphi = 33.11°\ \text{and}\ C = 0.$$

Tire performance parameters: A UP2092 tire plunger testing system was used to conduct stiffness and internal resistance tests on a 400/60-15.5R14 tire which is a wide low-pressure tire. The test results were as follows: $u = 3\times10^{-8}$, $\alpha = 3°$.

Table 1: Physical performance parameters of dry sand

Constrained grain size, d_{60}(mm)	Coefficient of nonuniformity, Cu	Coefficient of curvature, C_c	Proportion of particles, Gs	Natural density, ρ_0 (g cm^{-3})	Porosity, e_0	Water content, w_0 (%)
0.36	2.4	1.2	2.653	1.6793	0.629	3.1

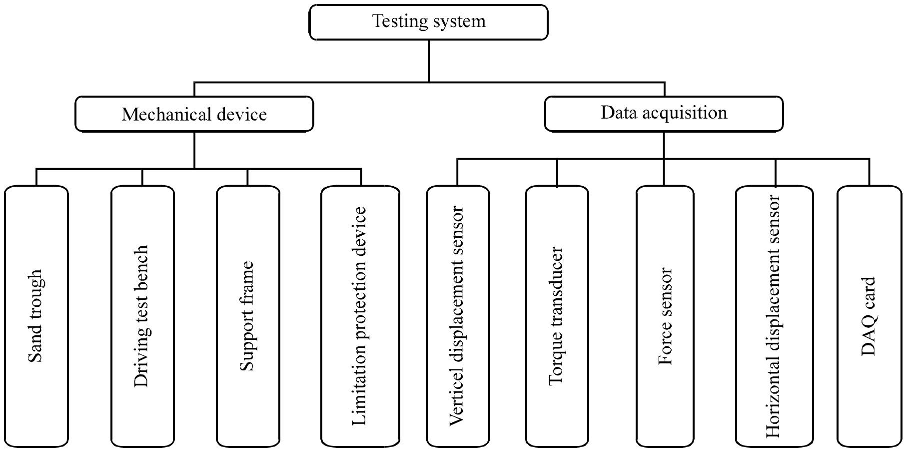

Fig. 1: Functional modules for sand trough experiment

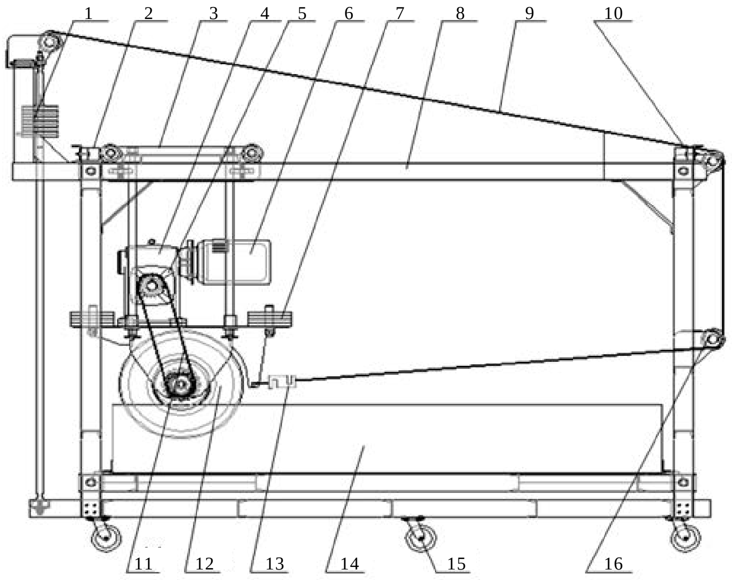

Fig. 2: Structural profile of sand trough experiment. 1: Traction load, 2: Draw-wire displacement sensors, 3: Driving test bench, 4: Retarder, 5: Torque sensor, 6: Variable-frequency adjustable-speed motor, 7: Balance masses of tire load, 8: Running rail, 9: Wire rope, 10: Lead limit switch, 11: Transmission chains, 12: Test tire, 13: Tension sensor, 14: Sand trough, 15: Supporting wheel, 16: Pulley

Based on the results of the sand trough orthogonal experiment, the dynamic subsidence of the 400/60-15R14 tire was obtained as:

$$z_d = 0.39s+z_0$$

Sand trough orthogonal experiment: The Automotive Engineering Research Center of the Xiamen University of Technology developed a driven wheel sand traction performance device for verifying test results. The traction performance system includes two modules, their mechanical devices and a data acquisition device. The analog sensor signals are converted into digital signals for display by the data acquisition device. This is done throughout the test, thereby affording real-time measurement data. The structure of the test equipment module is shown in Fig. 1, 2 and the test site is shown in Fig. 3 and 4.

Employing the 400/60-15.5R14 tire and sand taken from the beach on the Hu Li Mountain in Xiamen, orthogonal experiments were performed using a single driven wheel. Different applied loads were used for the experiments, namely, 6000, 7500 and 9000 N. The different tire pressures used were 0.07, 0.09, 0.11, 0.13, 0.15, 0.17 and 0.19 MPa and the applied slip rates were 15.1, 28.1, 44.9 and 62.3%, respectively.

Fig. 3: Test systems for sand trough experiment

Comparison of simulation and experimental results: The traction coefficient curve can be obtained by varying the tire pressure during the test. The test and simulation results shown in Fig. 5 indicate that for given load and slip rate, there is a maximum coefficient of traction tire pressure. If the tire pressure is too low, the tire

Fig. 4: Slip rate of 15.1% during traction test

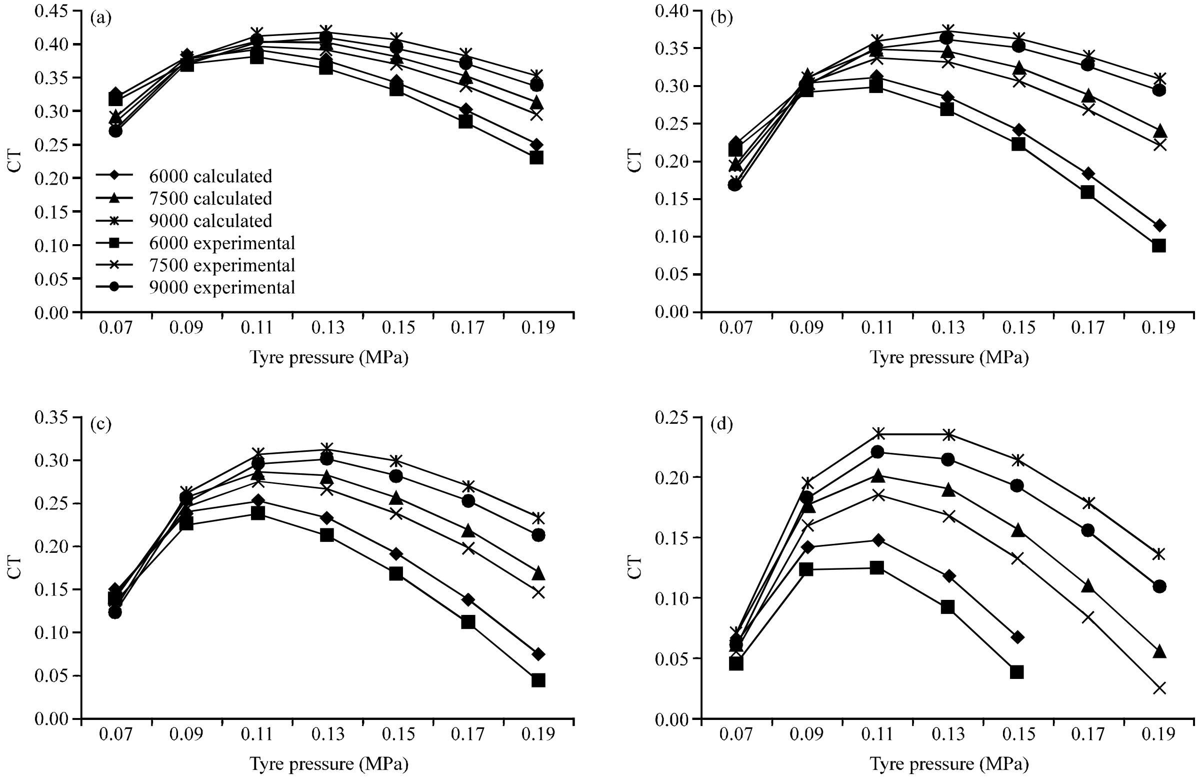

Fig. 5(a-d): Control curve of traction coefficient varies with tire pressure with split rate of, (a) 15.1%, (b) 28.1%, (c) 44.9% and (d) 26.3%

deformation would be excessive, resulting in a sharp increase in the bomb stagnation resistance and a similar decrease in the drawbar pull. However, if the tire pressure is too high, although the loss of the bomb stagnation would be little, the reduction in the tire contact area would increase the subsidence and compaction resistance but decrease the drawbar pull. There is thus an optimal pressure that maximizes the traction coefficient. This optimal pressure satisfies the condition $dC_T/dp_1 = 0$.

The obtained results show that for given load and slippage rate, the pressure would be between 0.11-0.13 MPa at the maximum traction coefficient. The trends of the test and simulation results are similar, although the experimental values are less than the simulations values and the deviation increases with increasing slip rate. This is because the simulation calculation did not take the bulldozing resistance into consideration. At the best tire pressure, the traction coefficient error was 2-3% for a slip rate of 15.1%, whereas, it was 3-5% for a slip rate of 28.1%, 5-7% for a slip rate of 44.9% and 9-11% for a slip rate of 62.3%.

For a given slip rate, the best tire pressure increased with increasing vertical tire load and traction coefficient. However, for a given vertical load, the best tire pressure decreased with increasing vertical tire load and traction coefficient. When the slip rate was more than 62.3%, the traction coefficient reduced sharply. This was because, the cohesion was zero and the subsidence of the tire increased dramatically.

CONCLUSION

This study proposed a mathematical model that uses the traction coefficient as an indicator for predicting the troughs and performance of low-pressure tires. Employing sand taken from the beach on the Huli Mountain in Xiamen and a wide-base low-pressure 400/60-15.5R14 tire, tire-sand trough orthogonal experiments were performed using different tire inflation pressures, tire loads and slip rates. The findings are as follows:

- The indoor sand tank orthogonal test results were consistent with the predictions of the proposed model, thereby confirming the feasibility of the model. The model and test results also confirmed the existence of an optimal tire inflation pressure and the model can thus be reliably used for the design of a wheeled beach cleaner
- When using wide-base low-pressure 400/60-15.5R14 tires for a beach cleaner, operation on both beach surface and hard ground should be taken into consideration. The study results indicated that the inflation pressure should be controlled within the range of 0.13-0.15 MPa; the tire slip rate should be within 15-45% and the tire load should be about 7500 N

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