J. Agric. Sci. Mansoura Univ., 32 (6): 6329 - 6346, 2007

EVALUATION OF DIFFERENT METHODS FOR ESTIMATING THE ROLLING RESISTANCE OF AGRICULTURAL TRACTORS BASED ON BEKKER'S SOIL PARAMETERS.

Mohamed, A.A.I
Agricultural Engineering Research Institute, Agric. Res. Center.

ABSTRACT

The general objective of this study was to develop a device to obtain Bekker's soil parameters (k_c, k_Φ and n) in-situ. These parameters could be used to estimate the rolling resistance of agricultural tractors. The specific objective comprises a comparison among four methods for estimating rolling resistance of an agricultural tractor. In order to compare the different methods and find out the most appropriate conditions for using them, a field experiment in which all relevant variables were controlled for further simulation was conducted by using a 2WD tractor. Using the soil parameters obtained in field, a comparison was carried out with the results from the different methods. Bekker's soil parameters are obtained in this study using an ellipse shaped sinkage plate. The field measurements of Bekker's soil parameters and rolling resistance were achieved in sandy, sandy loam and silty clay soil under the same conditions. Cohesion and soil internal frication angle were obtained in laboratory using direct shear test. Three models were developed by multiple linear regressions to get Bekker's soil parameters as a function of soil cohesion, soil internal frication angle, cone index and soil texture index. Using the field measurements and predicted Bekker's soil parameters, tractor rolling resistance was obtained by the help of four methods and then compared to the measured for Nasr tractor. The rolling resistances calculated from Bekker's method (Method 3 and Method 4) were the closest to the measured. Lower absolute relative errors of 5.9, 6.0 and 8.5% for method 3 were found when the tractor was run on sandy, sandy loam and silty clay soils, respectively. Also, there is a clear effect of soil texture index on tractor rolling resistance with linear relationship with coefficients of determination (R^2) ranged from 0.766 to 0.998 based on the method of obtaining rolling resistance.

INTRODUCTION

Management decisions related to farm tractors can affect farm profit in many ways. Fuel, interest and labor costs are three obvious reasons why high productivity and efficiency are needed. To improve productivity and efficiency in farm operations, through research, it is necessary to have detailed information about the forces between tractors and implements (Garner et al., 1988). These forces have many shapes. They are related to tractor as pull force, trust force and rolling resistance. All of these shapes of forces depend on many parameters. On the other hand, simulation in farm machinery machines behavior by mathematical modeling is nowadays an important tool for reducing production costs and making new projects feasible. For agricultural tractors, the measurement of soil properties is one of the fundamental tasks for the prediction and evaluation of tractive performance. There are four soils chosen to represent the mechanical properties of a range of soils: sand for frictional soils, silt for cohesive soils and silty sand and a sandy loam for cohesive frictional soils predominant in the agricultural soils (Benoit and Gotteland, 2005). Meanwhile, the soil physical and mechanical properties and soil dynamics properties have significant influences on the amount of energy required for tillage operation (Zadeh, 2006). The soil mechanical properties can be categorized as soil physical properties and soil strength parameters (Yu, 2005). The techniques currently in use for measuring and characterizing in-situ soil strength properties include the cone penetrometer (ASAE, 2006) and bevameter (Bekker, 1969). The soil parameters for tractor performance are usually measured by laboratory experiments. This probably is the reason why the purely theoretical methods have not been used extensively in-situ measurement in the field (Yu, 2005). The cone penetrometer and bevameter techniques are still the two methods frequently used for soil characterization for traction and mobility modeling (Yu, 2005). So, there is a need to develop a simple portable device that can measure soil characteristics. Such device (Mohamed, 2007) was developed in this study to be used to get soil parameters that could be used to predict rolling resistance of agricultural tractors.

There are three factors affect the tractive efficiency of agricultural tractors, namely net traction ratio, rolling resistance ratio and travel reduction. The net traction ratio and the rolling resistance ratio are influenced by soil strength, tire size and inflation pressure, dynamic wheel load and travel reduction (Wang and Zoerb, 1990). Usually the drawbar pull and travel reduction can be measured easily, thus, the only unknown is the rolling resistance. There are different ways to get tractor rolling resistance. These ways depend on soil, tire tractor specifications and wheel load. However, the theoretical prediction of tractive performance has involved the separation of the problem into two parts, via, the prediction of tractive force and rolling resistance (Macmillan, 2002).The rolling resistance of a wheel is, in general term, the force opposing the motion of the wheel as it rolls on a surface. This force arises from the energy losses that occur due to (1) the elastic but non-ideal deformation of the wheel (2) the inelastic and non-recoverable deformation of the plastic surface and (3) friction in the wheel bearings (usually assumed to be negligible). From this it will be clear that the rolling resistance of a wheel will be a function of the strength – deformation properties of the surface and the size and deformation characteristics of the wheel. For tires, the secondary factors include the air pressure; the structure of the tire carcass (radial or bias ply) and the tread pattern (Macmillan, 2002).To study the interaction between the tire and the soil, the behavior of the soil and the pertinent design parameters of the tire are the basic inputs and must, therefore, be quantitatively defined (Pandey and Tiwari, 2006). The Bekker's soil parameters k_c (soil cohesive modulus), k_Φ (soil friction modulus) and n could be used to obtain the rolling resistance of a wheel. These soil parameters could be obtained by forcing rigid steel plates of different diameters or widths for rectangular plates into the soil surface for the specific test site, a typical family of pressure-sinkage curves can be generated as shown in Fig. (1).

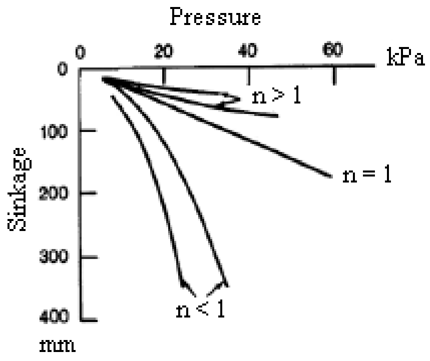

Fig. (1): Typical pressure-sinkage curves (Bekker, 1969).

The soil surface sinkage due to an applied load depends on soil properties such as soil moisture content, soil bulk density, cone index, soil type, depth of hard pan, as well as the load properties such as magnitude, direction, speed, and acceleration, and the shape and area of the contact surface. Considerable progress has been made in predicting the sinkage of soil surface from an applied load such as from vehicle traffic. Plate-sinkage or plate-pressure method is the earliest attempt to model the vertical stress strain relationship in soil, and is often used to predict sinkage due to vehicle traffic (Abou-Zeid et al., 2003). However, Rubinstein and Upadhyaya (2001) used two circular sinkage plates to get values of k and n to estimate five engineering properties of soil. Okello et al. (1998) conducted plate-sinkage tests involved the use of four different plate sizes, viz., 50, 70, 85 and 100 mm diameter to simulate normal loads under the track. The tests were performed by pushing the plate-sinkage into the soil at slow speed. The properties obtained from these tests were used in developing model to study the traction performance of a rubber track unit on soft agricultural soils and also to predict the ground pressure distribution beneath the track.

The plate sinkage test consists of a plate in contact with soil on which a known force is applied, and a mechanism for monitoring the resulting sinkage. Although plate sinkage tests have been used for a long time, plate dimensions have not been standardized and researchers have used many different shapes and sizes. Also, research workers have carried out plate sinkage tests at various penetration velocities and have found the variability of the results for different velocities not to be significant below 80 cm/s (Alexandrou and Earl, 1998). Bahnasy (2004) showed that when determining rolling resistance of 2WD tractor, the Bekker's model based on using rectangular plate to determine soil parameters k_c, k_Φ and n was the closest one to the field experiment for the different soil types. Gomaa (2003) derived equations based on geometrical parameters for driving wheels and techniques of Wismer and Luth (1974) to predict motion resistance of tractor tire. Hayes and Ligon (1981) developed an equation of cone index at zero and 15.2 cm soil depths using basic soil properties in the laboratory, then using the developed equation to modify the tractive performance model developed by Wismer and Luth (1974). Sitkei (1986) cited from (ElAshry and Mark,1993) developed an empirical equation for predicting the coefficient of rolling resistance of tractor tires and this coefficient was dependant on soil type and tire diameter. Kormanek and Walczykova (2006) showed that properties of the terrain had a crucial importance for traction possibilities of agricultural tractors, such as developed driving forces, slips, and rolling resistance.

Correa et al. (1999) indicated that the rolling resistance of agricultural tires is an important parameter to take in to account during agricultural tractor performance evaluation. Botero et al. (2005) used k_c (soil cohesive modulus), k_Φ (soil friction modulus) and n of Bekker's equation to get the friction coefficient between the terrain and the tire. Upadhyaya et al. (1997) reported better success in predicting tractive ability of radial tires using soil sinkage and shear parameters compared to soil cone index values. Mosaddeghi et al. (2004) showed that plate sinkage test was used as an in situ measurement of soil compressibility. A plate sinkage test consists of a plate in contact with soil on which a known load is applied, and a mechanism for monitoring the applied stress and the resulting sinkage.

The general objective of this study was to develop a device to obtain Bekker's soil parameters in-situ. The specific objectives were (1) to conduct tests in the field using the developed device using sinkage plate (ellipse shape to get Bekker's soil parameters k_c (soil cohesive modulus), k_Φ (soil friction modulus) and n in three soil types and to use these parameters to get rolling resistance of an agricultural tractor. The selecting sinkage plate of ellipse shape was selected because Liljedal et al. (1979) showed that for a rubber tire, the "footprint" is approximately in the shape of an ellipse and (2) to compare the rolling resistance obtained by different methods based on Bekker's soil parameters to those obtained from actual measurements.

MATERIALS AND METHODS

Sinkage plate:

The ellipse shape sinkage plate was used to determine Bekker's soil parameters in this study. It had three different dimensions of (10 × 8 cm), (12 × 10 cm) and (12 × 14 cm). The developed device for this case is shown in Fig. (2). It was used to push the ellipse shape sinkage plate in the soil with constant rate. The construction of the developed device was achieved at the Testing and Research Station for Tractors and Farm Machinery, Alexandria Governorate and the details are seen in previous work (Mohamed, 2007). Generally, the developed device consisted of hydraulic cylinder, open center hydraulic system, electrical control panel, hydraulic hoses, frame with three-point hitch and measuring staffs. At the end of hydraulic cylinder, different parts could be attached for collecting soil properties data and one of them is the sinkage plate.

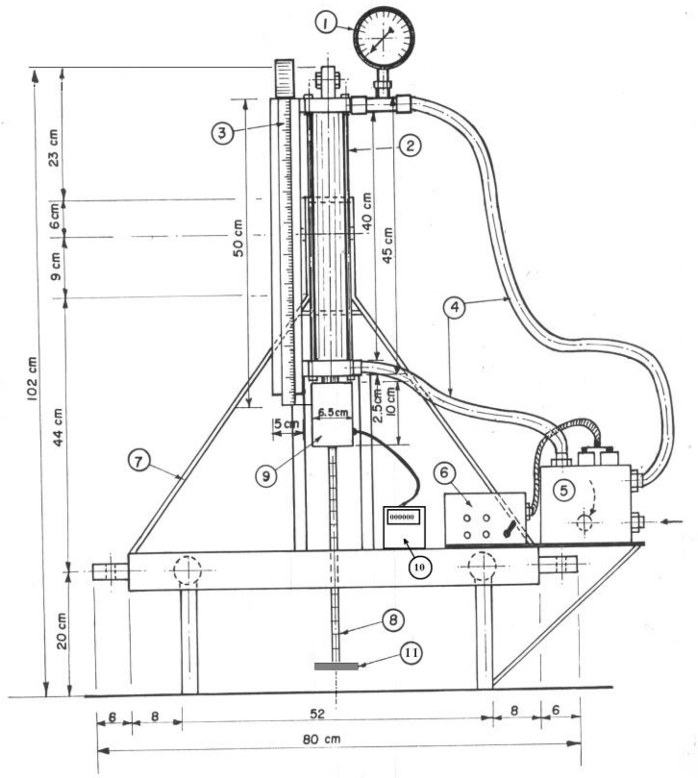

Fig. (2): Schematic diagram of the developed device showing arrangement to how the device used to push plate into the soil (Mohamed, 2007).

(1) Hydraulic gage	(3) Scale	(6) Electrical control panel
(2) Hydraulic cylinder	(4) Hydraulic hoes	(7) Three point hitch
(5) Hydraulic control valve		(9) Load cell
(8) Steel shaft with	(10) Strain meter	(11) Sinkage plate

Three replicates for the sinkage plate size were conducted at corresponding acting force. Experimental tests were conducted in three different field conditions. Table (1) shows average soil characteristics in the experimental sites. However, obtaining the soil fractions, soil moisture contents and bulk densities were as shown in the standard approaches. Also, no crop residues were seen on soil surface in all filed conditions. The tests were performed by pushing the plate-sinkage by the developed device into the soil at slow speed, simulating the rate of wheel sinkage during a normal field operation, down to a given depth and then reducing the load slowly to zero. The calibration data and applied normal loads and corresponding vertical displacements were manually recorded during the repeated loading process as described by Mohamed (2007).

Table (1): Average soil characteristics in the experimental sites.

Soil type	Soil depth	Soil fractions			Cone index	Soil bulk density	Soil moisture content
		Sand	Silt	Clay			
	(cm)	(%)	(%)	(%)	(kPa)	(g/cm^3)	(%,db)
Sandy	0-20	53.0	26.7	20.3	390	1.58	7.5
Sandy loam	0-20	43.3	34.5	22.2	820.3	1.24	13.68
Silty clay	0-20	22.3	34.3	43.4	1714.4	1.13	18.14

Calculating Bekker's soil parameters (k_c, k_Φ and n):

Soil bearing capacity can be assessed and measured using different approaches. The sinkage of the footing, the wheel or the track is used as an output variable and different sinkage models are developed using different soil parameters as input variables. Bekker's method (Bekker, 1956) uses the concept of flotation as a description of soil bearing capacity. Bekker's method is based on elasticity theory, in which the load-sinkage relation is measured using round plates with different diameters. The soil constants are determined from the load/sinkage curve. The simple model for flotation is based on measuring of the soil deformation modulus and soil deformation exponent. Bekker proposed the following pressure sinkage relationships for soils:

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

$$k = \left(\frac{k_c}{b} + k_\phi \right) \qquad \text{.....(2)}$$

Where:

p : Pressure sinkage (kN/m^2).

k_c : Soil cohesive modulus (kN/m^{n+1}).

k_ϕ : Soil friction modulus (kN/m^{n+2})

b : The smaller dimension of the loading area (m).

n : Exponent of deformation.

The parameters "*k*" and "*n*" are the measures of the dynamic property, bearing strength. The value of "*n*" expresses soil characteristics, whereas "*k*" expresses loading area as well as soil characteristics. In any given soil condition, *n* is considered to remain the same for all loading areas. Because of the effect of the shape of the loading area, "*k*" was further divided to provide a cohesive component "k_c "a frictional component, which was independent of the loading area. So, apparatus for assessing bearing strength, as represented by plate of known dimensions, simultaneously measures the load and sinkage as the plate is forced into the ground. Various means for obtaining the measurements have been proposed. Generally, at least three sizes of plate are used for a given soil condition. By taking logarithmic for Eq. (3), linear equation is obtained Eq. (4).

The best fit equation between *log (p)* is plotted against *log (z)*. The series of straight lines equations are obtained as for sand, sandy loam and silty clay soils respectively.

$$p = k \times z^n \qquad \text{..............(3)}$$

$$\log(p) = \log(k) + n \times \log(z) \qquad \text{..............(4)}$$

Measuring rolling resistance in the field:

The tractor used at experimental field was Nasr tractor having 48.75 kW rated power, front wheel weight 8.29 kN and rear wheel weight 13.83 kN. The front wheel size was 6.5-20 radial and the rear wheel size was 14-30 radial. The inflation pressure in the rear tire was 90 kPa. Rolling resistance was measured by using a hydraulic dynamometer (5000 kg) and two tractors. One of the two tractors was towed by the other. The rear (towed) tractor, which it's rolling resistance was being measured (Nasr tractor). Whereas the front tractor was Fiat 90 and thus, was used as a prime mover. A horizontal chain with the hydraulic dynamometer linked the two tractors. When the rear tractor was in neutral condition. The pull (rolling resistance) was recorded in the measure distance of 40 m as well as the time taken to traverse it. The rolling resistance for the tractor was measured for each soil type. This process was achieved on three different soils and repeated three times. The towed force was total rolling resistance of Nasr tractor. The measurements were conducted at 4.5 km/h forward speed and repeated three times. Average soil cone indices for the three soil types were 1715, 820 and 390 kPa for silty clay, sandy loam and sand soils, respectively which were measured using the device and procedures seen in Mohamed (2007).

Models to get (k_c ,k_Φ and n) as a function of some soil properties:

To simplify the method of yielding soil parameters of k_c , k_ϕ and *n*, simple models were developed using multiple regression analysis between these parameters and soil cohesion, internal friction angle, cone index and soil texture index. However, soil cohesion and internal friction angle could be easily measured using direct shear test. This test is an inexpensive, fast, and simple way to determine shear strength characteristics (Holtz and Kovacs 1981). This test is conducted by placing a soil sample into a shear box that is split with the bottom half fixed and the top half free to float. A loading block with a porous stone to allow drainage of water is placed on the sample, a normal load is applied and the loading block and top half of the box are clamped together allowing the two halves to separate slightly. Shear box test is used to determine the angle of internal friction of a soil. As the horizontal displacement increases shear force along the predetermined slip-plane also increases due to one half of the soil being restrained. Eventually, the soil reaches a maximum or peak shear stress and after the peak, the shear resistance decreases and failure occurs. Multiple tests are needed to determine the angle of internal friction. Tests are conducted with varying values of normal stress to determine the stress-displacement curves. From each curve, the maximum shear stress is plotted against the corresponding normal stress to determine the maximum shear stress vs. normal stress plot. This graph is generally linear and the inclination with the horizontal axis is equal to the angle of internal friction of the soil, Fig. (3). Direct shear test was employed to measure these values of soil shear strength under same moisture and density conditions as applied in the field. In this study, these tests were conducted at the Soil Mechanic and Sand Foundations Laboratory of Faculty of Engineering, Alexandria University. However, the developed models were as follows:

$$k_c, k_\phi, n = \alpha_o + \alpha_1 \times STI + \alpha_2 \times CI + \alpha_3 \times C + \alpha_4 \times \phi \quad \text{.......................(5)}$$

$$STI = \frac{\log\,(S_i^{Ca} + S_a)}{100} \qquad \text{(Zein Eldin,1995)} \qquad \text{.....................(6)}$$

Where:

CI	:	Soil penetration resistance (kPa).
ϕ	:	Soil internal friction angle (degree).
C	:	Soil cohesion (kg/cm²).
STI	:	Soil texture Index (dimensionless).
S_i, C_a and S_a	:	Silt, clay and sand contents in the soil, respectively (%).
$\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4$	:	Regression coefficients.

Summary output for regression analysis of Eq. (5) is shown in Table (2). Meanwhile, regression coefficients of Eq. (5) are shown in Table (3).

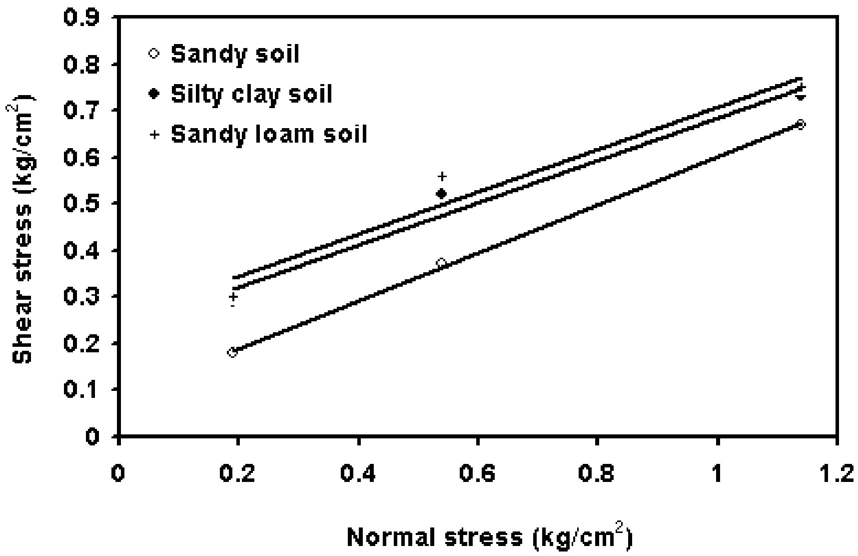

Fig. (3).Method of obtaining cohesion and the angle of internal friction of the soil form direct shear test.

Table (2): Summary output for regression analysis of Eq. (5).

Regression Statistics	k_c (kN/m^{n+1})	k_ϕ (kN/m^{n+2})	n (----)
Multiple R	0.991	0.994	0.991
R^2	0.983	0.989	0.983
Adjusted R^2	0.965	0.978	0.966
Standard Error	0.118	3.932	0.032
Observations	9	9	9

Table (3): Regression coefficients of Eq. (5).

Parameters	Regression coefficients	k_c (kN/m^{n+1})	k_ϕ (kN/m^{n+2})	n (----)
Intercept	α_o	26.769	303.807	1.487
STI	α_1	-3.897	498.319	-0.578
CI	α_2	0.0004	-0.230	0.0001
C	α_3	-18.589	-453.792	-1.834
ϕ	α_4	-0.765	6.250	-0.002

Methods of estimating rolling resistance of a tractor based on soil parameters (k_c ,k_Φ and n):

Method 1:

McKyes (1978) cited from (McKyes, 1985) presented formula to be useful in getting the rolling resistance of agricultural tractors tires as follows:

$$MR = \left[\frac{z+\delta}{d}\right] \times W \qquad \text{.............................(7)}$$

The value of (z) could be calculated as follows:

$$z = \left(\frac{p}{k}\right)^{1/n} \qquad \text{...............................(8)}$$

$$p = \frac{W}{A} \quad , \quad A = b \times \frac{d}{2} \qquad \text{(McKyes, 1985)} \qquad \text{...............................(9)}$$

The values of "*d*" and "δ" could be calculated from the tire size specifications by using the following equation (Srivastava et al., 2006):

$$d = \frac{2.54 \times (d_{nr} + 2 \times r_A \times b_{nr})}{100} \qquad \text{..........................(10)}$$

$$r_L = \frac{2.54 \times \left[\frac{d_{nr}}{2} + 0.81 \times r_A \times b_{nr}\right]}{100} \qquad \text{..........................(11)}$$

$$\delta = \frac{d}{2} - r_L \qquad \text{.........................(12)}$$

Where:

p	:	Vertical average contact pressure (kPa).
A	:	Contact area of the wheel (m^2).
W	:	Load on a single wheel (kN).
d_{nr}	:	Nominal rim diameter for the wheel (inches).
b_{nr}	:	Nominal section width for the wheel (inches).
r_A	:	Aspect ratio = section height over section width and equals to 0.95 for front wheel and 0.85 for rear wheel according to Srivastava et al. (2006).
z	:	Tire sinkage (m).
d	:	Outside tire diameter (m).
b	:	Tire section width and equals to nominal section width for the wheel (m).
MR	:	Rolling resistance (kN).
δ	:	Tire deflection (m).

Method 2:

In this method, Eq (7) will be used to get the rolling resistance, but the tire sinkage (z) will be calculated in this study according to Maclaurin (1990). However, Maclaurin (1990) developed the following wheel sinkage model:

$$z = d \times \left[\frac{0.224}{M^{1.25}}\right] \quad \text{.............................(13)}$$

$$M = \left[\frac{CI \times b \times d}{W}\right] \times \sqrt{\frac{\delta}{h}} \times \left[\frac{d}{d + 0.5 \times b}\right] \quad \text{.....................(14)}$$

The value of *"h"* could be calculated from the tire size specifications by using the following equations (Srivastava et al., 2006):

$$h = \frac{d - \frac{2.54 \times d_{nr}}{100}}{2} \quad \text{.........................(15)}$$

Where:

h	:	Tire section height (m).
M	:	Mobility number according to Dwyer et al. (1976) cited from Macmillan (2002) (dimensionless).

Method 3:

When a wheel rolls over a soft surface it makes a rut or compacted track. The simplest basis for the prediction of its rolling resistance is to therefore assume that the work done against the rolling resistance is the work done in compacting soil. Bekker (1956) assumed that the wheel was equivalent to a plate continuously being pressed into the soil to a depth equal to the depth of the rut produced by the wheel. For soft wheel on soft surface, the rolling resistance could be obtained as follows:

$$MR = \frac{b}{(n+1)\left[\frac{k_c}{b} + k_\phi\right]^{1/n}} \times [p]^{\frac{n+1}{n}} \quad \text{...(16)}$$

Method 4:

In this method, the rolling resistance could be obtained as mentioned in Eq. (16) but changing parameters k_c , k_ϕ and *n* with the obtained by regression analysis on field data as shown in Table (3).

RESULTS AND DISCUSSION

Table (4) shows values of soil internal friction angle, soil cohesion, soil texture index, soil cohesive modulus, soil friction modulus and exponent of deformation during field experiments and laboratory measurements for three replicates. These values were used to get the regression coefficients of Eq. (5). Meanwhile, regression analysis was done to get relationships between soil texture index as calculated by Eq. (6) and both soil cohesion and soil internal friction angle measured by direct shear box method as follows:

$$C\,(kg/cm^2) = 1.59 - 4.86 \times STI \qquad R^2 = 0.997 \qquad \text{.................................(17)}$$

$$\phi\,(\text{degree}) = 0.74 + 84.85 \times STI \qquad R^2 = 0.941 \qquad \text{.................................(18)}$$

It is clear that increasing soil texture index results increasing in soil internal friction angle and the trend is seen inversely for increasing soil texture index, the soil cohesion decreased. Statistical analysis based on the data shown in Table (4) shows there is a significant effect of soil type on soil internal friction angle, soil cohesion, soil texture index, soil cohesive modulus, soil friction modulus and exponent of deformation as shown in Table (5). Generally, the sand soil gave lower cone index, lower soil cohesion; higher soil internal frication angle, higher soil cohesive modulus, higher soil friction modulus and exponent of deformation compared to the other soils. From Table (5) there is no significant effect between sandy loam and silty clay soils in term of soil internal friction angle.

Table (4): Soil internal friction angle, soil cohesion, soil texture index, soil cohesive and soil friction modulus and exponent of deformation during field experiments and laboratory measurements.

Soil type	Soil texture Index	Cone index	Soil cohesion	Soil internal friction angle	Soil cohesive modulus	Soil friction modulus	Exponent of deformation (n)
	(---)	(kPa)	(kg/cm^2)	(degree)	(kN/m^{n+1})	(kN/m^{n+2})	(---)
Sandy	0.311	390	0.086	27.203	3.22	500.21	1.112
Sandy	0.276	382	0.081	27.429	3.41	489.24	1.174
Sandy	0.282	398	0.091	26.976	3.54	478.74	1.132
Sandy loam	0.350	820	0.252	24.513	2.47	324.14	0.871
Sandy loam	0.348	834	0.257	24.323	2.34	324.57	0.811
Sandy loam	0.324	807	0.248	24.702	2.21	320.47	0.844
Silty clay	0.670	1715	0.232	24.132	2.07	284.21	0.741
Silty clay	0.670	1724	0.237	24.132	2.01	287.47	0.784
Silty clay	0.661	1705	0.228	24.513	1.95	289.24	0.748

Using the methods 1, 2, 3 and 4 to get front and rear wheels Nasr tractor rolling resistances need to calculate the values shown in Table (6). For calculating rolling resistance in this study, cone index of front wheel was assumed equal to cone index of rear wheel and the weight on each wheel was static weight, however, the calculation of performance of wheels on agricultural soil based on static weights on the wheel gave no significant difference in the results when it was obtained based on the dynamic weight (Macmillan, 2002). The total rolling resistance of the tractor is the summation of rolling resistance on two front wheel and two rear wheels.

Table (5): Mean* soil internal friction angle, soil cohesion, soil texture index, soil cohesive modulus, soil friction modulus and exponent of deformation as influenced by soil type.

Treatments	Cone index	Soil cohesion	Soil internal friction angle	Soil cohesive modulus	Soil friction modulus	Exponent of deformation (n)
	(kPa)	(kg/cm^2)	(degree)	(kN/m^{n+1})	(kN/m^{n+2})	(---)
Sandy	390c	0.086c	27.20a	3.39a	489.39a	1.139a
Sandy loam	820.3b	0.252a	24.51b	2.34b	323.06b	0.842b
Silty clay	1714.4a	0.232b	24.26b	2.01c	286.97c	0.758c
LSD	21.17	0.009	0.42	0.25	12.99	0.06

***Means followed by different letters in each column are significantly different at P = .05.**
LSD: Least significance difference.

Figure (4) shows average rolling resistance of Nasr tractor obtained from different methods and for different soil types compared to measured values. It is obvious that the nearest values of total rolling resistant to measured values of Nasr tractor was obtained by method 3 and method 4. Statistical analysis based on the rolling resistance data obtained from different methods and for different soil types shows significant effect of soil type and method on soil rolling resistance of Nasr tractor (data not included). However, no significant effect between rolling resistances obtained by method 3 and method 4 and measured. The rolling resistance was high when the tractor run on sandy soil compared to other soils and this is may be due to the tractor tires had higher sinkage values on this soil compared to other soils, Table (6).

To compare the estimating rolling resistance methods with measured values, the absolute relative error percentage (REP) could be calculated as follows:

$$REP = \left[\frac{|MR_a - MR_m|}{MR_a} \right] \times 100 \qquad \text{.....(19)}$$

Where:

REP : Absolute relative error percentage (%).
MR_a : Measured total rolling resistance of Nasr tractor (kN).
MR_m : Total rolling resistance obtained by different methods (kN).

Table (6): The values* needed in methods 1, 2, 3 and 4 to get wheels tractor rolling resistances as three replicates.

Soil type	W	b	d	δ	h	A	M	p	z (Eq.8)	z (Eq.14)
	(kN)	(m)	(m)	(m)	(m)	(m^2)	(--)	(kPa)	(m)	(m)
	Front wheel									
Sandy	4.145	0.165	0.822	0.029	0.157	0.068	5.056	61.11	0.146	0.024
	4.145	0.165	0.822	0.029	0.157	0.068	4.952	61.11	0.164	0.025
	4.145	0.165	0.822	0.029	0.157	0.068	5.16	61.11	0.156	0.024
Sandy loam	4.145	0.165	0.822	0.029	0.157	0.068	10.63	61.11	0.14	0.01
	4.145	0.165	0.822	0.029	0.157	0.068	10.812	61.11	0.121	0.009
	4.145	0.165	0.822	0.029	0.157	0.068	10.462	61.11	0.134	0.01
Silty clay	4.145	0.165	0.822	0.029	0.157	0.068	22.233	61.11	0.119	0.004
	4.145	0.165	0.822	0.029	0.157	0.068	22.35	61.11	0.132	0.004
	4.145	0.165	0.822	0.029	0.157	0.068	22.103	61.11	0.119	0.004
	Rear wheel									
Sandy	6.915	0.356	1.367	0.057	0.302	0.243	10.571	28.46	0.075	0.016
	6.915	0.356	1.367	0.057	0.302	0.243	10.354	28.46	0.087	0.016
	6.915	0.356	1.367	0.057	0.302	0.243	10.788	28.46	0.081	0.016
Sandy loam	6.915	0.356	1.367	0.057	0.302	0.243	22.226	28.46	0.06	0.006
	6.915	0.356	1.367	0.057	0.302	0.243	22.605	28.46	0.049	0.006
	6.915	0.356	1.367	0.057	0.302	0.243	21.873	28.46	0.055	0.006
Silty clay	6.915	0.356	1.367	0.057	0.302	0.243	46.484	28.46	0.044	0.003
	6.915	0.356	1.367	0.057	0.302	0.243	46.728	28.46	0.051	0.003
	6.915	0.356	1.367	0.057	0.302	0.243	23.107	28.46	0.044	0.003

*** All values for single wheel.**

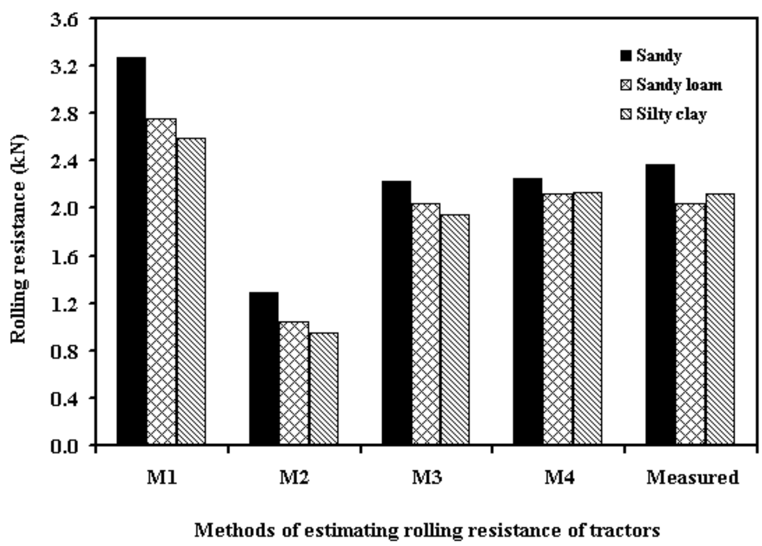

Fig. (4): Average rolling resistance of Nasr tractor obtained from different methods and for different soil types compared to measured values.

Figure (5) shows absolute relative error percentage for different methods for rolling resistance of Nasr tractor run on different soil types. It is seen that, lower absolute relative errors of 5.9, 6.0 and 8.5% for method 3 when the tractor run on sandy, sandy loam and silty clay soils, respectively. Also, the higher absolute relative error due to method 2 that the tire sinkage was obtained by trial formulation and this is may be not suitable for the soil and tires characteristics under test. Whereas, method 1 which took tire sinkage related to the soil and tires characteristics under test, the absolute relative error was about 17.8% when the Nasr tractor run on silty clay soil. The relationship between soil texture index and total rolling resistance is shown in Fig. (6). It is obvious that increasing soil texture index increased rolling resistance obtained by any methods and also measured values. This is may be at lower soil texture index, the tractor wheel had higher sinkage compared to higher soil texture index. Simple regression analysis was done on the curves represented in Fig. (6). Regression coefficients (β_0, β_1) and coefficients of determination (R^2) of different rolling resistance methods are shown in Table (7). It is obvious that high (R^2) means the rolling resistance could be predicted from the soil texture index.

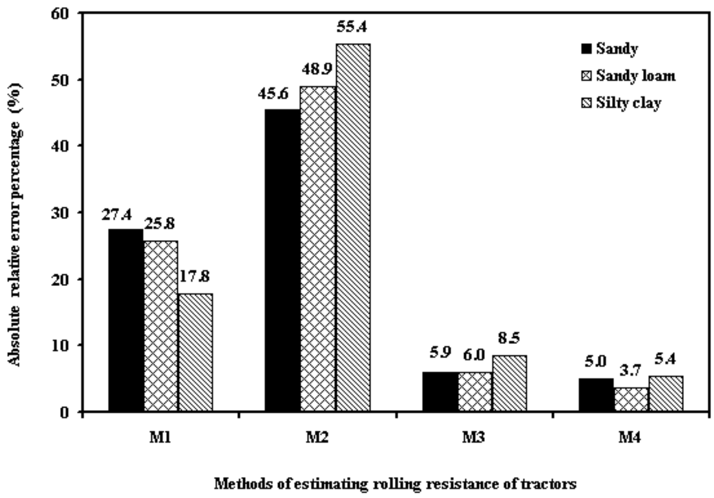

Fig. (5): Absolute relative error percentage for different method for rolling resistance of Nasr tractor run on different soil types.

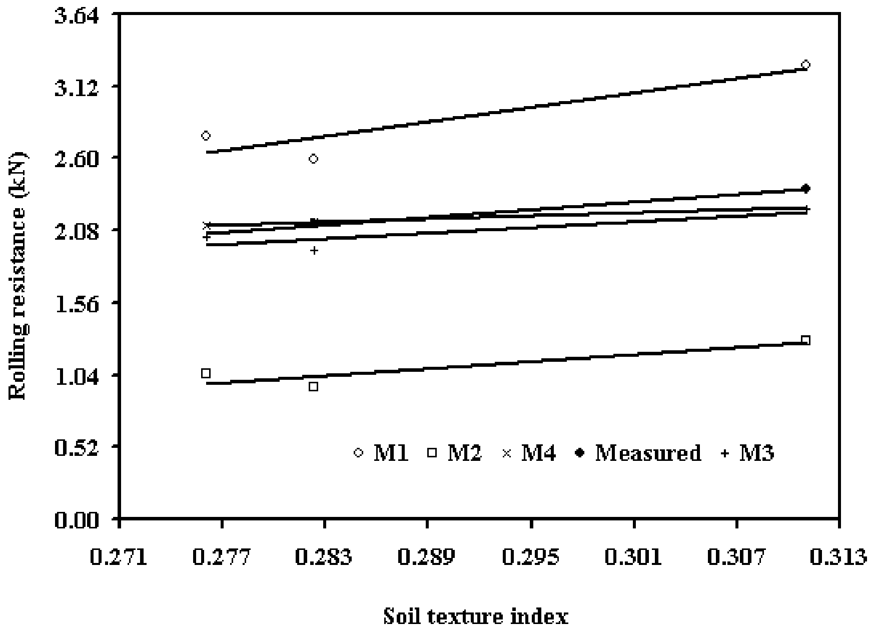

Fig. (6): Relationship between soil texture index and total rolling resistances obtained from different methods and measured values.

Table (7): Regression coefficients (β_0, β_1) and coefficients of determination (R^2) of different methods for curves represented in Fig. (6).

Method of estimating tractor rolling resistance	β_0	β_1	R^2
Method 1	-2.16	17.36	0.838
Method 2	-1.38	8.58	0.814
Method 3	0.07	6.91	0.766
Method 4	1.04	3.89	0.998
Measured	-0.48	9.18	0.994

CONCLUSION

The following conclusions could be obtained:

1. The Bekker's soil parameters (k_c , k_ϕ and *n*), in-situ could be obtained by the developed device in sandy, sandy loam and silty clay soils.
2. The developed statistical models to predict Bekker's soil parameters (k_c , k_ϕ and *n*), using multiple regression analysis as a function of soil cohesion, internal friction angle, cone index and soil texture index could

predict 2 WD tractor rolling resistance with low absolute relative error compared to measured values.

3. The rolling resistance was high when the tractor run on sandy soil compared to other soils due to the tires of the tested tractor had higher sinkage values on this soil compared to other soils.
4. The tire sinkage is related to soil and tire characteristics of the tractor under test.

REFERENCES

Abou-Zeid, A.; R. L. Kushwaha and D. S. D. Stilling (2003). Distributed soil displacement associated with surface loading. ASAE Paper No. 03-1024. St. Joseph, Mich: ASAE. ASAE, St. Joseph, MI. 49805.

Alexandrou, A. and R. Earl (1998). The relationship among the pre-compaction stress, volumetric water content and initial dry bulk density of soil. J. agric. Engng Res.71: 75–80.

ASAE (2006). ASAE Standards S313.3 FEB04: Soil cone penetrometer. St. Joseph, Mich: ASAE. ASAE, St. Joseph, MI. 49805:903-904.

Bahnasy, A.M.F. (2004) Predicting rolling resistance for tractors using soil property. Modern Technology in Agric. Eng. Research and Application, the 12th Annual Conference of Misr Society of Agri. Eng., 4-5 October 2004.

Bekker, M. G. (1969). Introduction to terrain-vehicle systems. University of Michigan Press, Ann Arbor. 846 p.

Bekker, M.G. (1956). Theory of land locomotion-the mechanics of vehicle mobility. University of Michigan Press. Ann Arbor, MI: 522

Benoit, O. and P.H. Gotteland (2005). Modeling of sinkage tests in tilled soils for mobility study. Soil and Tillage Research, 80 (1-2):215-231.

Botero, J.C.; M. Gobbi and G. Mastinu (2005). A new mathematical model of the traction force in pneumatic tire – snow chain systems. Associazione Italiana Per L'analisi Delle Sollecitazioni XXXIV Convegno Nazionale: 14–17 Settembre 2005, Politecnico Di Milano.

Correa, I.M.; K. Yanai; J. V. G. Maziero and K. P. Lancas (1999). Determination of agricultural tire rolling circumference using manual and electronic methods. Bragantia, Campinas, 58 (1):179-184.

Dwyer, M.J.; D.W. Evernden and M. McAllister (1976). Handbook of agricultural tire performance. Report No. 18, National Institute of Agricultural Engineering, Silsoe, UK.

ElAshry, E.R. and S. Mark (1993). Evaluation of some models for predicting the tractor performance of tractor tires. Alex. Sci. Exch, 14 (4):593-605.

Garner, T.H.; R.B. Dodd; D. Wolf and U.M. Peiper (1988). Force analysis and application of a three-point hitch dynamometer. Trans ASAE, 31(4):1047-1053.

Gee-Clough, D. (1978). A comparison of the mobility number and Bekker approaches to traction mechanics and recent advances in both methods. Journal of Terramechanics, 15(2):81-94.

Gomaa, E. A.(2003). Motion resistance and soil-tire geometrical parameters for driving wheels. Misr J. Ag. Eng., 20(2):339-362.

Hayes, J. C. and J. T. Ligon (1981). Traction prediction using soil physical properties. Trans ASAE, 24(6):1420-1425.

Kormanek, M. and M. Walczykova (2006). Characteristic of vertical deformation of some forest soils. Electronic Journal of Polish Agricultural Universities, Forestry, 9(4):10 p.

Liljedahl, J.B.; W.M. Carleton; P.K. Turnquist and O.W. Smith (1979). Tractor and their power units. Third Edition; John Wiley & Sons Ins New York: p221.

Maclaurin, E. B. (1990). The use of mobility numbers to describe the in-field tractive performance of pneumatic tires. Proceedings of the 10th International ISTVS Conference, Kobe, Japan, August 20-24: 177-186.

Macmillan, R. H. (2002). The mechanics of tractor - implement performance. A textbook for students and engineers .http://www.eprints.unimelb.edu.au.

MeKyes, E. (1978). The role of tire size in "economobility". Symposium on Econo-Mobility, Cdn. Soc. for Ter. Veh. Syst., Toronto:32-41.

MeKyes, E. (1985). Soil cutting and tillage. Development in Agricultural Engineering 7, Elsevier Science Publishers.

Mohamed, A.A.I (2007). Development of a field device to collect some soil properties data I. soil penetration resistance. J. Agric. Mansoura Univ., 32 (2): 1079 - 1094

Mosaddeghi,M. R.; M. A. Hajabbasi; A. Hemmat; M. Vafaeian and A. Alexandrou (2004). Factors affecting stress-sinkage curve and precompaction stress determined by in situ plate sinkage test. ASAE Paper No. 04-1017. St. Joseph, Mich: ASAE. ASAE, St. Joseph, MI. 49805.

Okello, J. A. ; M. Watany and D. A. Crolla (1998). A theoretical and experimental investigation of rubber track performance models J. agric. Engng Res. 69:15–24.

Pandey, K. P. and G. Tiwari (2006). Rolling resistance of automobile discarded tires for use in camel carts in sand. ASAE Paper No. 06-1097. St. Joseph, Mich: ASAE. ASAE, St. Joseph, MI. 49805.

Rubinstein, D. and S. K. Upadhyaya (2001). In situ determination of engineering properties of soil. J. agric. Engng Res. 78 (2):199-207.

Sitkei, G. Y. (1986). Modeling of off-road vehicles for agricultural and forestry. Academy Press, Budapest, Hungary.

Srivastava, A. K.; C. E. Goering; R. P. Rohrbach and D. R. Buckmaster (2006). Engineering principles of agricultural machines. 2nd Edition, American Society of Agricultural and Biological Engineers, Chapter 7:139-168.

Upadhyaya, S. K.; M. Sime.; N. Raghuwanshi; and B. Adler (1997). Semi-empirical traction prediction equations based on relevant soil parameters. J. Terramechanics, 34(3):141-154.

Wang, G. and G.C. Zoerb (1990). Indirect determination of tractive efficiency. Can. Agric. Eng.32:243-248.

Wismer, R.D. and H. J. Luth (1974). Off-road traction prediction for wheeled vehicles. Trans ASAE, 17(1):8-10,14.

Yu, T. (2005). The tractive performance of a friction-based prototype track. Ph.D Thesis, Civil and Biosystems Eng. Dept., University of Pretoria, South Africa.

Zadeh, S. R. A. (2006). Modeling of energy requirements by a narrow tillage tool. PhD Thesis, Dept. of Agric. and Bioresource Eng., Univ. of Saskatchewan, Saskatoon, Canada: 190p.

Zein Eldin, A.M. (1995). Predicting soil bulk density from cone index data. Misr J. Ag. Eng., 12 (1): 179-194.

تقييم طرق مختلفة لتقدير مقاومة الدوران للجرارات الزراعية على أساس معاملات التربة الخاصة ببيكر

أحمد على إبراهيم

معهد بحوث الهندسة الزراعية، مركز البحوث الزراعية.

الهدف العام لهذا البحث هو تطوير جهاز حقلي لتجميع بعض بيانات خصائص التربة وبالأخص معاملات التربة الخاصة بمعادلة بيكر. هذه المعاملات تفيد في تقدير مقاومة الدوران للجرارات الزراعية والتي من خلال معرفة قيمتها يمكن محاكاة أداء الجرار الزراعي أثناء العمل الحقلي. تم استخدام لوح الغرز البيضاوي داخل التربة للحصول على معاملات التربة وذلك في ثلاثة أنواع من الأراضي تفاوتت فيها نسب الرطوبة ونسب الرمل والسلت والطين. تمت مقارنة مقاومة الدوران المقاسة فعليًا لجرار نصر ثنائي الدفع (65 حصان) بطرق مختلفة تحسب مقاومة الدوران للجرارات الزراعية رياضيًا وهذا هو الهدف الثانوي للبحث. أوضحت النتائج أنه يوجد تأثير معنوي لنوع التربة على معاملات التربة الخاصة بمعادلة بيكر وكذلك قيم تماسك التربة وزاوية الاحتكاك الداخلي بين حبيبات التربة. تم تطوير نماذج رياضية باستخدام الانحدار الخطي المتعدد للتنبؤ بمعاملات التربة الخاصة بمعادلة بيكر كدالة في تماسك التربة، وزاوية الاحتكاك الداخلي بين حبيبات التربة، ودليل قوام التربة، ومقاومة اختراق التربة، حيث هذه المتغيرات يمكن قياسها بسهولة. تم استخدم النماذج المطورة لمعاملات التربة الخاصة بمعادلة بيكر داخل نموذج بيكر لتقدير مقاومة الدوران وأوضحت النتائج أنه لا يوجد فروقات معنوية بين مقاومة الدوران المقدرة عند الاعتماد على هذه النماذج والمقدرة مباشرة من القياسات الحقلية لثوابت معادلة بيكر. وأوضحت النتائج أن مقاومة الدوران المحسوبة للجرار نصر من طريقة بيكر مستخدما سواء معاملات التربة الخاصة بمعادلة بيكر الناجمة من لوح الغرز البيضاوي المقاسة أو المتنبأ بها هي الأقرب لمقاومة الدوران المقاسة في الحقل عند العمل في الثلاث أنواع من الأراضي ، حيث تراوحت قيم الخطأ النسبي حوالي 5.9، 6.0، 8.5 % لنوع التربة الرملية، الرملية اللومية والسلتية الطينية على الترتيب. وهذا البحث يفيد في الحصول على معاملات التربة الخاصة بمعادلة بيكر ومن ثم حساب مقاومة الدوران وإيجاد معايير الأداء للجرارات الزراعية والتي من خلالها يمكن معظمة الإنتاجية وتوفير استهلاك الوقود بطريقة سهلة وبجهاز محلي الصنع لا يتكلف كثيرا عند تصنيعه بخامات محلية.