Middle-East Journal of Scientific Research 12 (10): 1364-1369, 2012
ISSN 1990-9233

DOI: 10.5829/idosi.mejsr.2012.12.10.1897

Evaluation of Bekker Model in Predicting Soil Pressure-Sinkage Behaviour under Field Conditions

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Abstract: In order to evaluate Bekker model in predicting soil pressure-sinkage behaviour under field conditions, a field reflecting general character of an agricultural soil was selected and multiplate penetration tests were conducted. The soil stiffness constants in Bekker model were determined from five sets of soil pressure-sinkage tests using five small rectangular plates. Bekker model was then used to predict pressure-sinkage behaviour of soil under a large rectangular plate. Soil pressure-sinkage behaviour predicted by Bekker model was finally verified through field tests using the large rectangular plate. The paired samples t-test results indicated that the sinkage values predicted with Bekker model were significantly less than the sinkage values measured by test apparatus. Also, to check the discrepancies between the sinkage values measured by test apparatus with the sinkage values predicted by Bekker model, RMSE and MRPD were calculated. The amounts of RMSE and MRPD pertaining to Bekker model prediction were 0.039 m and 71.9%, respectively. Results of this study indicated that Bekker model may not be suggested as an accurate and suitable model and can not be directly used to predict soil pressure-sinkage behaviour under field conditions. However, to predict soil sinkage values measured by test apparatus (z_M) based on soil sinkage values predicted by Bekker model (z_P) the polynomial regression model $z_M = - 29.68\ z_P^2 + 3.341\ z_P + 0.009$ with $R^2 = 0.986$ can be recommended.

Key words: Soil · Pressure-sinkage · Bekker model · Prediction · Field conditions

INTRODUCTION

There are many concerns regarding the effects of soil compaction that impedes root growth [1]. Soil compaction is a process through which pore spaces are decreased [2]. Soil compaction can be caused by natural phenomena such as rainfall impact, soaking, internal water tension and the like. On the other hand, artificial soil compaction occurs by tractors and agricultural machines [3]. Soil compaction under tractors and agricultural machines is of special concern [4]. The main cause of soil compaction is soil sinkage imposed by wheels or tracks. Therefore, prediction of soil sinkage is extremely important for determining soil compaction level. Furthermore, the ability to predict soil sinkage under field conditions can enable agricultural engineers to till or traffic the soil when it is not in a highly compactable state or to estimate the damage being done to the soil structure due to their excessive loading when tillage or traffic is necessary [5]. For the last five decades, prediction of soil sinkage has been of great interest to researchers in both agriculture and cross-country mobility and transport [2, 6-19]. The overall objective of this study was to evaluate Bekker model in predicting soil pressure-sinkage behaviour under field conditions.

MATERIALS AND METHODS

Pressure-Sinkage Models: One of the earlier models was reported by Bernstein and Goriatchkin and equation 1 was proposed to describe it [3, 6, 11-13, 16, 18, 20]:

$$P = kz^n \quad (1)$$

where:
P = Contact pressure, kPa
k = Soil stiffness constant, kPa/m^n
z = Sinkage, m
n = Soil constant related to the soil characteristics, non-dimensional

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The principal deficiency of equation 1 for prediction of soil sinkage was found to be the variability of the soil stiffness constant k with the size of the object on the soil. In civil engineering technology, it was known that the sinkage of a rectangular plate, at a given contact pressure on a particular soil, depends also on the width of the rectangle [3, 6]. Bekker combined the two concepts, namely the exponential pressure-sinkage relationship of equation 1 and the plate size dependence of the soil stiffness constant as equation 2 [11, 12, 20]:

$$P = (k_c/b+k_\varphi)z^n \quad (2)$$

where:

k_c and k_φ = Soil stiffness constants, which are presumed to be independent of plate width, kPa/m^{n-1} and kPa/m^n, respectively

In order to evaluate the soil stiffness constants in equation 2, it is necessary to conduct at least two soil pressure-sinkage tests using plates of different width. The measured sets of pressure and sinkage values must then be analyzed graphically or analytically to find the best fit. From the best fit exponential curves, constants k and n can be determined for each plate of the tests. The average value of n is used together with the k values from the two plates to obtain the soil stiffness constants. However, it has been shown that the variation in soil stiffness constants can be considerable when only two small plates are used and it may be risky to attempt the measurement of soil stiffness constants with tests that use only two plates, especially if they are small plates. A large variability exists in soils, even in carefully prepared Laboratory samples, let alone at different locations in a field. Large rectangular plates of the order 30 cm or more in width, can reduce the variation in experimental results, but they require large loads to approach practical sinkage levels and thus inconvenient and costly to perform, but smaller rectangular plates are handy for testing by one person [3]. When several plates are used rather than two and the observations are pooled to find average soil stiffness constants, the variation in soil stiffness constants are reduced dramatically [13] and the measured soil stiffness constants can be used successfully to predict the pressure-sinkage behaviour of a large plate about three times the width. When more than two sinkage plates are tested, a statistical method can be used to calculate the soil stiffness constants [3, 21]. Constants k and n are found for each plate. Then a graph can be drawn between k versus b in order to solve for stiffness constants. A best fit line is found by least square analysis and k_c and k_φ are the slope and intercept of this line, respectively [18].

Experimental Site: For conducting required multiplate penetration tests, a field reflecting general character of an agricultural soil was selected. The experimental site was located at the Ahmadabad-e-Mostofi, Tehran Province, Iran. Soil samples from 36 points were collected from 0-30 cm depth and analyzed in the Laboratory for bulk density, moisture content and particle size distribution (sand, silt and clay). Details of soil physical properties of the experimental site are given in Table 1.

Tractor Mounted Pressure-Sinkage Test Apparatus: To study soil pressure-sinkage behaviour and to determine soil stiffness constants under field conditions, a tractor mounted pressure-sinkage test apparatus was designed and constructed (Fig. 1). The test apparatus had five different small rectangular plates and one large rectangular plate, i.e., two times the area of small plates (Fig. 2). The dimensions of five small plats are given in Table 2. These plates have the same contact area and different aspect ratio. The aspect ratio (length/width) of these plates ranged from 1.0 to 9.0, which are similar to the ones expected for tires or tracks contact area. The aspect ratio of a tire or track contact area can be defined as the length of contact area divided by the width of contact area. The dimensions of large plate are given in Table 3.

Soil Pressure-Sinkage Tests Procedure: To reduce soil mechanical resistance and pressure-sinkage tests difficulties, the experimental site was prepared by performing primary and secondary tillage practices using a moldboard plow, an offset disk harrow and a land leveler two weeks before the tests. Within the experimental site, 36 testing points were selected. For each test run, every plate was loaded and pushed downwards into the soil using the hydraulic cylinder of the test apparatus and at the same time the downward displacement (sinkage) was measured with a digital caliper (Fig. 3). The soil pressure-sinkage tests were replicated six times for each plate.

Statistical Analysis: A paired samples t-test was used to compare the sinkage values predicted using Bekker model with the sinkage values measured by test apparatus.

Table 1: Soil physical properties of the experimental site (0-30 cm depth)

Soil texture	Sand (%)	Silt (%)	Clay (%)	Bulk density (gcm^{-3})	Moisture content (%)
Sandy loam	74.0	15.0	11.0	1.46	6.00

Table 2: Dimensions of the five small rectangular plates used to determine soil stiffness constants in Bekker model

Plate number	Length (m)	Width (m)	Area (m^2)	Aspect ratio (Length/Width)
1	0.150	0.150	0.0225	1.00
2	0.225	0.100	0.0225	2.25
3	0.300	0.075	0.0225	4.00
4	0.375	0.060	0.0225	6.25
5	0.450	0.050	0.0225	9.00

Table 3: Dimensions of the large rectangular plate used to evaluate Bekker model

Plate number	Length (m)	Width (m)	Area (m^2)	Aspect ratio (Length/Width)
6	0.300	0.150	0.0450	2.0

Fig. 1: Tractor mounted pressure-sinkage test apparatus

Fig. 2: Five rectangular plates (No. 1-5) used to determine soil stiffness constants in Bekker model and one large rectangular plate (No. 6) used to evaluate Bekker model

Fig. 3: A digital caliper used to measure soil sinkage

Also, to check the discrepancies between the sinkage values measured by test apparatus with the sinkage values predicted by Bekker model, root mean squared error (RMSE) and mean relative percentage deviation (MRPD) were calculated using the equations 3 and 4, respectively [14, 15, 17]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(z_{Mi} - z_{Pi})^2}{n}} \quad (3)$$

where:

$RMSE$ = Root mean squared error, m
z_{Mi} = Soil sinkage measured by test apparatus, m
z_{Pi} = Soil sinkage predicted using Bekker model, m

$$MRPD = \frac{100 \times \sum_{i=1}^{n} \frac{|z_{Mi} - z_{Pi}|}{z_{Mi}}}{n} \quad (4)$$

where:

$MRPD$ = Mean relative percentage deviation, %

RESULTS

The results of the field pressure-sinkage tests were analyzed using the Bernstein model. Table 4 shows the calculated constants k and n for the five small plates. Relatively high values of coefficients of determination (R^2) ranging from 0.775 to 0.879 were obtained for individual sinkage tests. However, the analysis indicated that the values of sinkage parameter k varied considerably between plates. On the other hand, the exponent n was less susceptible to this variation between plates. Also, to obtain k_c and k_φ by using the data from Table 4, regression analysis was applied to the soil stiffness constant (k) and the inverse of plate width (1/b). From the linear regression results, k_c and $k\varphi$ the slope and intercept of the regression line, respectively. Our attempts to relate k to 1/b using equation 2 resulted in very poor agreements ($R^2 = 0.270$). The determined soil stiffness constants (k_c, k_φ and n) for the experimental site are given in Table 5.

DISCUSSION

To evaluate Bekker model under field conditions, the soil stiffness constants (k_c, k_φ and n) determined for the experimental site were used to predict soil pressure-sinkage behaviour of a large rectangular plate, i.e. two times the area of small plates. The sinkage values predicted by Bekker model were compared with the sinkage values measured by test apparatus and are shown in Table 6. The paired samples t-test results indicated that the sinkage values predicted by Bekker model were significantly less than the sinkage values measured by test apparatus (Table 7). The mean sinkage difference between two methods was -0.035 m (95% confidence interval: -0.044 m and -0.027 m; P = 1.000). The standard deviation of sinkage differences was 0.017 m. These results are not in line with the results reported by McKyes and Fan [21] that soil stiffness constants measured with several small plates can be used successfully to describe the sinkage of a larger plate. Also, these results are not in agreement with those of Rashidi and Seyfi [18] who reported that Bekker model in the company of soil stiffness constants measured with three small plates can be used effectively to predict soil pressure-sinkage behavior of a larger plate under Laboratory conditions.

Also, to check the discrepancies between the sinkage values measured by test apparatus with the sinkage values predicted by Bekker model, RMSE and MRPD were calculated. The amounts of RMSE and MRPD were 0.039 m and 71.9%, respectively. Thus, sinkage values predicted by Bekker model may be 0.039 m or 71.9% less than sinkage values measured by test apparatus. Such significant discrepancies between the Bekker model results and results of the field pressure-sinkage test confirm that this model may not be suggested as an accurate and suitable model and can not be directly used to predict soil pressure-sinkage behaviour under field conditions. However, as it is shown

Table 4: Determined soil stiffness constants k and n for each sinkage plates

Plate number	k (kPa/m^n)	n (non-dimensional)	R^2
1	1775	0.448	0.827
2	1878	0.488	0.855
3	1677	0.472	0.879
4	1935	0.543	0.868
5	1400	0.407	0.775

Table 5: Soil stiffness constants in Bekker model determined for the experimental site

k_c (kPa/m^{n-1})	kφ (kPa/m^n)	n (non-dimensional)	R^2
-20.79	2010	0.472	0.270

Table 6: Contact pressure and soil sinkage values used in evaluating Bekker model under field conditions

	Soil sinkage (m)	
Contact pressure (kPa)	Measured by test apparatus	Predicted by Bekker model
65.00	0.0030	0.0008
87.00	0.0100	0.0015
109.0	0.0170	0.0024
131.0	0.0240	0.0035
153.0	0.0290	0.0049
174.0	0.0340	0.0065
196.0	0.0390	0.0083
218.0	0.0440	0.0104
240.0	0.0490	0.0128
262.0	0.0550	0.0154
283.0	0.0600	0.0183
305.0	0.0650	0.0214
327.0	0.0720	0.0248
349.0	0.0780	0.0284
371.0	0.0840	0.0323
393.0	0.0900	0.0364
414.0	0.0960	0.0409
436.0	0.1040	0.0456

Table 7: Paired samples t-test analyses on comparing soil sinkage determination methods

Determination methods	Average difference (m)	Standard deviation of difference (m)	p-value	95% confidence intervals for the difference in means (m)
Test apparatus vs. Bekker model	-0.035	0.017	1.000	-0.044, -0.027

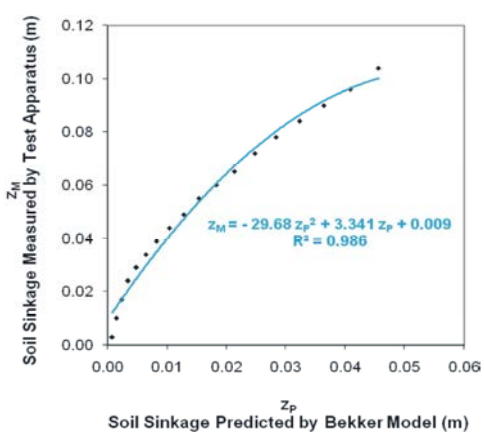

Fig. 4: Curve of soil sinkage measured by test apparatus based on soil sinkage predicted by Bekker model

in Fig. 4, our attempts to relate soil sinkage values measured by test apparatus (z_M) to soil sinkage values predicted by Bekker model (z_P) using polynomial equation resulted in very good agreements ($R^2 = 0.986$) as equation 5.

$$z_M = - 29.68\, z_P^2 + 3.341\, z_P + 0.009 \qquad (5)$$

CONCLUSIONS

It can be concluded that Bekker model may not be suggested as an accurate and suitable model and can not be directly used to predict soil pressure-sinkage behaviour under field conditions. However, to predict soil sinkage values measured by test apparatus (z_M) based on soil sinkage values predicted by Bekker model (z_P) the polynomial regression model $z_M = - 29.68\ z_P^2 + 3.375\ z_P + 0.009$ with $R^2 = 0.986$ can be recommended.

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