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Multiplate Penetration Tests to Determine Soil Stiffness Constants in Bekker Model under Field Conditions

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Abstract: Prediction of the soil sinkage under load is very important for determining the performance of off-road vehicles and the level of compaction in the soil. Soil stiffness constants govern the soil sinkage and the pressure-sinkage behaviour of the soil under load. To determine soil stiffness constants in Bekker model 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 different rectangular plates. The determined soil stiffness constants (k_c, k_φ and n) for the experimental site were-20.79 kPa/m^{n-1}, 2010 kPa/m^n and 0.472, respectively. Although for the risk of using the soil stiffness constants determined with tests that use only two plates, five different plates were used in this study for accurately determining soil stiffness constants, evaluation of Bekker model in predicting soil pressure-sinkage behaviour under field conditions is necessary before the model can be recommended for wider use.

Key words: Soil · Pressure-sinkage · Bekker model · Stiffness constants · 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 so on. 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, 6-16]. The overall objective of this study was to determine soil stiffness constants in Bekker model 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, 11-15, 17]:

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

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

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.

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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, 17]:

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

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 out 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, 18]. 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 [15].

Fig. 1: Selected field for conducting multiplate penetration tests

Fig. 2: Tractor mounted pressure-sinkage test apparatus

Experimental Site: For conducting required multiplate penetration tests, a field reflecting general character of an agricultural soil was selected (Fig. 1). 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. 2). The test apparatus had

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 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

Fig. 3: Five rectangular plates used to determine soil stiffness constants in Bekker model

Fig. 4: A digital caliper used to measure soil sinkage

five different rectangular plates (Fig. 3). The dimensions of five 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.

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, 30 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. 4). The soil pressure-sinkage tests were replicated six times for each plate.

RESULTS AND DISCUSSION

The results of the field pressure-sinkage tests were analyzed using the Bernstein model. Table 3 shows the calculated constants k and n for the five 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 3, regression analysis was applied to the soil stiffness constant (k) and the inverse of plate width (1/b). From the linear regression results,

Table 3: 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 4: Soil stiffness constants in Bekker model determined for the experimental site

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

k_c and k_φ 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 4. Although for the risk of using the soil stiffness constants determined with tests that use only two plates, five different plates were used in this study for accurately determining soil stiffness constants, these poor agreements may break the trust of any scientist on the soil stiffness constants in Bekker model under field conditions. These results may not be in line with the results reported by McKyes and Fan [18]. They stated that Bekker model is very useful method for predicting the pressure-sinkage behaviour of soil under tires or tracks of tractors and agricultural machines in the Laboratory conditions without going to the field. Also, these results may not be in agreement with those of Çakir *et al*. [13], Rashidi *et al*. [14] and Rashidi and Seyfi [15] who reported that Bekker model can be used effectively to predict soil pressure-sinkage behaviour of a larger plate under Laboratory conditions.

CONCLUSIONS

Although for the risk of using the soil stiffness constants determined with tests that use only two plates, five different plates were used in this study for accurately determining soil stiffness constants, evaluation of Bekker model in predicting soil pressure-sinkage behaviour under field conditions is necessary before the model can be recommended for wider use.

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