

Multiplate Penetration Tests to Predict Soil Pressure-Sinkage Behaviour

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Abstract: Soil compaction may cause considerable damage to the structure of the tilled soil and the subsoil and consequently to crop production and the environment. The prediction of soil sinkage under wheels and tracks is of great importance for determining the off-road vehicle performance and the level of compaction in the agricultural soils. Soil stiffness constants govern the soil sinkage and the behaviour of soil under load. To determine the stiffness constants of soil in the rectangular region, a sandy-loam soil reflecting general character of an agricultural soil was selected and multiplate penetration tests were conducted. Two low (1350 kg m^{-3}) and high (1650 kg m^{-3}) apparent bulk densities were considered as treatments in the sandy-loam soil. For each treatment, from the pressure versus sinkage relationship of soil under different loads, the average soil stiffness constants k_c , k_ϕ and n were determined from the sets of three sinkage tests using three small rectangular plates that differ in plate width and having aspect ratios close to those of agricultural tires' contact area. Tests were replicated three times for each of the three small rectangular plates. Using the calculated soil stiffness constants for each treatment, the pressure-sinkage behaviour of a large rectangular plate was predicted. For the apparent low bulk density the amounts of RMSE and MRPD were 6 mm and 8%, respectively. For the apparent high bulk density the amounts of RMSE and MRPD were 2 mm and 11.5%, respectively. The results showed that the prediction was better for the lower density soil.

Key words: Soil stiffness · pressure-sinkage · bekker · compaction

INTRODUCTION

Soil compaction is a process through which pore spaces are decreased. It alters the structure of cultivated soil, i.e., the spatial arrangement, size and the shape of clods and aggregates and consequently the pore spaces inside and between these units [1]. Soil compaction can be caused by natural phenomena such as rainfall impact, soaking, internal water tension and the like. Artificial soil compaction occurs under the downward forces of agricultural machines [2]. In this paper we are concerned with compaction by the wheeling of agricultural machines.

Soil compaction under tractors and farm machinery is of special concern because weights of these machines have been increased dramatically in the last decades and these implements create persistent subsoil compaction [3]. Agronomists are concerned about the effects of heavy tractors and agricultural machines on agricultural soils due to the possibility of excessive soil compaction that impedes root growth leading to yield reduction [4].

Hence, the prediction of soil sinkage under loads is an important task to determine the level of compaction in the soil.

For the last five decades, prediction of soil pressure-sinkage behaviour has been of great interest to researchers in both agriculture and cross-country mobility and transport (Bekker [5]; Reece [6]; Hegedus [7]; Kogure [8]; Upadhyaya [9]; Upadhyaya *et al.* [10] Çakir *et al.* [11], Defosse and Richard [1]; Rashidi *et al.* [12-15]; Rashidi and Seyfi [16]). Moreover, the ability to predict soil sinkage can enable agricultural engineers to till or traffic the soil when it is not in a highly compatible state or to estimate the damage being done to the soil structure due to their excessive loading when tillage or traffic is necessary. Models presented in the literature are from a simple exponential function to an elastoplastic complicated one. Usually, in a more complete (and thus, a more complicated) model, many parameters and variety of properties are present and have to be known prior to solving the model.

Therefore, the overall objective of this study was to use a relatively simple model to predict the soil sinkage under a rectangular region using rectangular plates having aspect ratios close to the agricultural tractor tires' contact area. The specific objectives of the study were: a) to determine the soil stiffness constants for sinkage of rectangular region with tests that use three small rectangular plates in low and high apparent bulk densities and b) to predict the soil sinkage under a large rectangular plate using the soil stiffness constants measured with three small rectangular plates in the same soil conditions.

MATERIALS AND METHODS

Pressure-sinkage models: Investigations into the nature of such phenomena and the soil parameters involved have arrived at findings in two different categories: situations in which time is considered as an important factor and those where it is not. For the case where time is not considered to be a factor, one of the earlier models was reported by Bernstein (1913) and Goriatchkin (1937) and the following equation was proposed to describe it [2, 10]:

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

where:

P= Vertical average contact pressure, kPa

k = A soil stiffness constant for sinkage, kPa/mⁿ

z = Depth of sinkage, m

n = A soil constant related to the soil characteristics, non-dimensional

The principal deficiency of Eq. (1) for prediction of soil sinkage was found to be the variability of the soil stiffness k with the size of the object on the soil. In civil engineering technology, it was known that the sinkage of the rectangular plate, at a given average vertical pressure on a particular soil, depends also on the width of the rectangle. Bekker [5] combined the two concepts, namely the exponential pressure-sinkage relationship of Eq. (1) and the plate size dependence of the soil stiffness constant as follow [11, 17]:

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

where:

b = Plate width, m

k_c and k_φ = Soil stiffness constants for sinkage, which are presumed to be independent of plate width, kPa/mⁿ⁻¹ and kPa/mⁿ, respectively.

The two parameters k_c and k_φ separate the sinkage stiffness constant k into two components. Thus, three parameters are required to describe the sinkage phenomenon. These parameters are determined using surface pressure-sinkage tests. In order to evaluate the soil constant in Eq. (2), it is necessary to conduct at least two soil penetration tests using plates of different widths. 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 k_c and k_φ as shown below [17]:

$$k_c = b_1 b_2 (k_1 - k_2) / (b_2 - b_1) \quad (3)$$

$$k_\phi = (k_2 b_2 - k_1 b_1) / (b_2 - b_1) \quad (4)$$

where subscripts 1 and 2 refer to the values measured for Plates 1 and 2.

However, 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 pressure level and thus inconvenient and costly to perform, but smaller rectangular plates in the range of five to ten cm are handy for testing by one person.

It has been shown that the variation in k_c and k_φ can be considerable when only two small plates are used. When several plates are used rather than two and the observations are pooled to find average stiffness constants, then the variation in k_c and k_φ are reduced dramatically. When more than two sinkage plates are tested, a statistical method can be used to calculate the stiffness constants. Constants k and n are found for each plate. Then a graph can be made of k versus 1/b, in order to solve for k_c and k_φ. A best-fit line is found by least square analysis and k_c and k_φ are the slope and intercept of this line [18].

Test unit development: A test unit was developed to determine soil stiffness constants for sinkage. A self-explanatory schematic picture of the test unit is presented in Fig. 1. Three different rectangular plates were used in these tests. The plate dimensions are listed in Table 1. Note that the three plates have the same contact area,

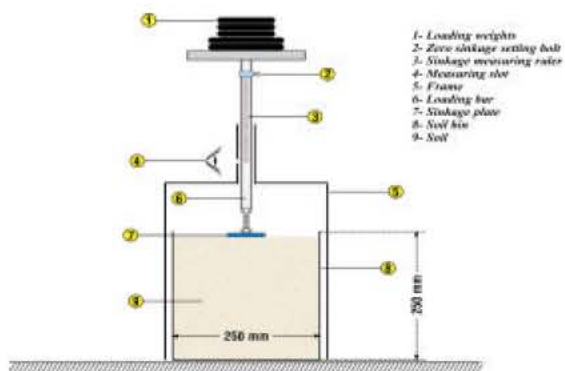


Fig. 1: Test unit

Table 1: Dimensions of the three small rectangular plates

Sinkage plate	Width, mm	Length, mm	Aspect ratio
1	30	83	2.8
2	33	73	2.5
3	41	61	1.5

but differ in width only. The aspect ratio (length/width) of these plates ranged from 1.5 to 2.8, which are similar to the ones expected for contact area of pneumatic tires (for tracks long narrow strips are recommended). The aspect ratio of a tire or track can be defined as the length of the ground contact area divided by the width.

Experimental procedure: A sandy-loam soil was chosen for characterizing the agricultural soil. The sandy-loam soil was consisted of 16% clay, 22% silt and 62% sand. To prepare soil samples, as a first step, soil was sieved using a mesh size of 5 mm. Then, the soil was watered and covered with a sheet of plastic during the night in order to achieve a uniform moisture distribution. The measured soil moisture content was about 20% (d.b.), which made the soil sample to be in an arable condition as in the field. The soil was leveled and then firmed in the cubic soil bin by a wooden packer piston with the aid of a hydraulic press. Two low (1350 kg m^{-3}) and high (1650 kg m^{-3}) apparent bulk densities, representing the field apparent bulk densities, were considered as treatments. For each test run, each of three small rectangular plates was loaded slowly up to about 170 kPa and pushed downwards into the soil and at the same time the downward displacement (sinkage) was measured with the sinkage measuring ruler. Different loads were applied using different loading weights and tests were replicated three times for each of the three small rectangular plates in both apparent bulk densities.

RESULTS AND DISCUSSION

Results of pressure-sinkage tests: The results of the pressure-sinkage tests were analyzed using the Bernstein and Goriatchkin formula. Table 2 shows the calculated constants k and n for each plate and treatment. Very high values of coefficients of determination, R^2 ranging from 0.90 to 0.99 was 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.

As shown in Fig. 2 and 3, to obtain k_c and k_p by using the data from Table 2, regression analysis was applied to the constant k and the inverse of the plate width, $1/b$. From the linear regression results, k_c and k_p are the slope and the intercept of the regression line, respectively. Our attempts to relate k to $1/b$ using Eq. (2) resulted in very good agreements. The calculated constants k_c and k_p for each treatment are given in Table 3.

Sinkage prediction of a large rectangular plate: Since circular footings have already been used to test the validity of the Bekker formula [11, 18], using Eq. (2), the soil stiffness constants measured with three small rectangular plates was used to predict the pressure-sinkage behaviour of a large rectangular plate and about three times the width. Besides, no results have been reported in the literature yet for verification of the model for different bulk densities. Hence, a large rectangular plate with dimensions listed in Table 4 was used to test the model in two apparent bulk densities.

Table 2: Values of constants k and n for each plate and treatment

Sinkage plate	Treatment					
	Low apparent bulk density			High apparent bulk density		
	k (kPa/m ⁿ)	R^2	n	k (kPa/m ⁿ)	R^2	n
1	1080.8	0.95	0.8332	1489.4	0.98	0.6906
2	1029.6	0.90	0.8243	1507.5	0.97	0.6956
3	970.8	0.94	0.7883	1646.0	0.99	0.7384

Table 3: Values of constants k_c , k_p and n for each treatment

Treatment	n	k_c (kPa / m ⁿ⁻¹)	k_p (kPa / m ⁿ)	R^2
Low apparent bulk density	0.8153	11.98	675.5	0.98
High apparent bulk density	0.7082	-16.99	2046.4	0.95

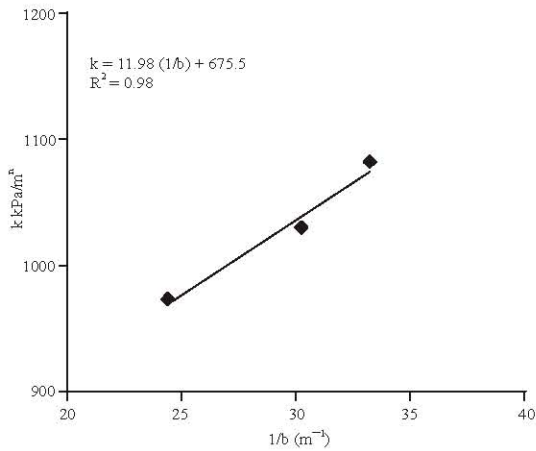


Fig. 2: Determination of k_c and k_ϕ from k values of individual sinkage tests with plates of different sizes in low apparent bulk density soil

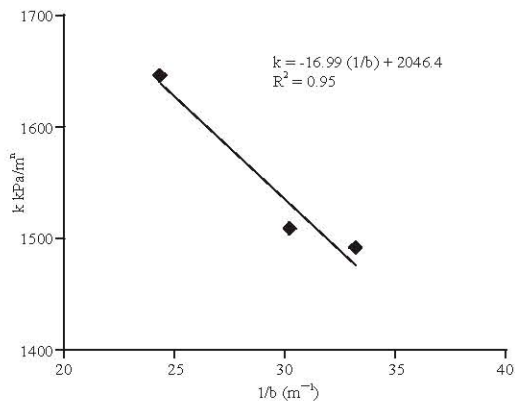


Fig. 3: Determination of k_c and k_ϕ from k values of individual sinkage tests with plates of different sizes in high apparent bulk density soil

Table 4: Dimensions of the large rectangular plate

Sinkage plate	Width, mm	Length, mm	Aspect ratio
Large rectangular	100	150	1.5

Low apparent bulk density soil: Figure 4 shows the predicted pressure-sinkage behaviour of the large rectangular plate, using the soil stiffness constants derived from tests on three small rectangular plates on the soil sample with a low apparent bulk density along with the measured values. For measuring pressure-sinkage behaviour, the large rectangular plate was loaded slowly up to about 125 kPa and at the same time the sinkage depth was measured with the sinkage measuring ruler. From comparison of two curves, it could be concluded that prediction is very reasonable over the measured sinkage range.

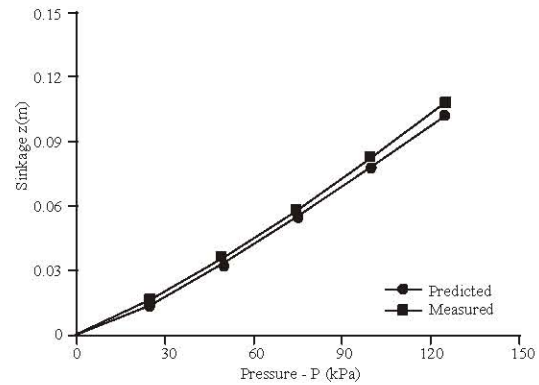


Fig. 4: Predicted pressure-sinkage behaviour of the large rectangular plate compared with that measured experimentally on low apparent bulk density soil

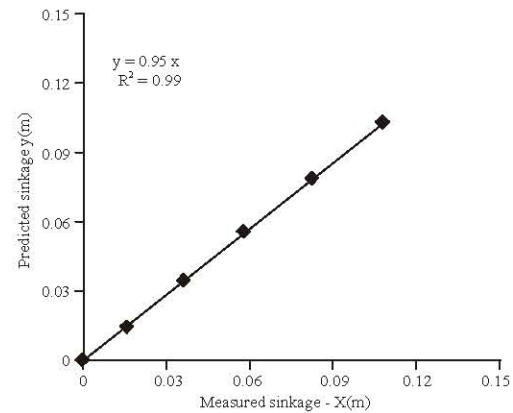


Fig. 5: Predicted and measured sinkage values on low apparent bulk density soil

A linear regression was performed to verify the validity of the prediction. Figure 5 shows that the sinkage values predicted using the soil stiffness constants derived from tests and those measured experimentally were plotted against each other and fitted with a linear equation with zero intercept. The slope of the line of the best fit and its coefficient of determination were 0.95 and 0.99, respectively.

Root of mean square errors (RMSE) and mean relative percentage deviation (MRPD) were used to check the discrepancies between the predicted and measured results. The amounts of RMSE and MRPD were 6 mm and 8%, respectively. Regarding the statistical results, the validity of the prediction was confirmed.

High apparent bulk density soil: Figure 6 shows the predicted pressure-sinkage behaviour of the large rectangular plate, using the soil stiffness constants derived from tests on three small rectangular plates on the

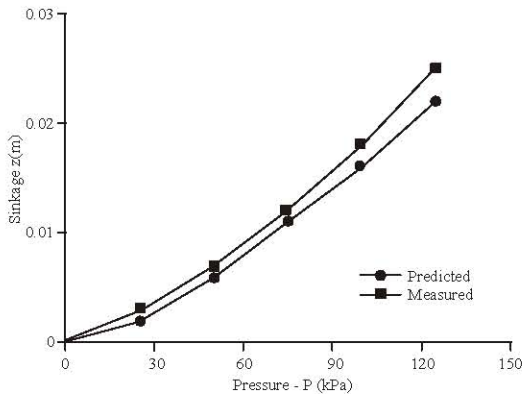


Fig. 6: Predicted pressure-sinkage behaviour of the large rectangular plate compared with that measured experimentally on high apparent bulk density soil

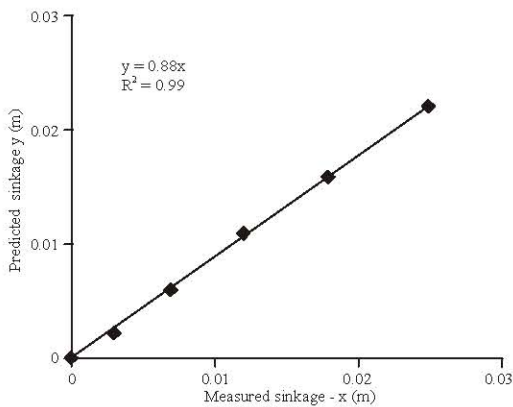


Fig. 7: Predicted and measured sinkage values on high apparent bulk density soil

soil sample with a high apparent bulk density along with the measured values. Again, for measuring pressure-sinkage behaviour, the large rectangular plate was loaded slowly up to about 125 kPa and at the same time the sinkage depth was measured with the sinkage measuring ruler. From comparison of two curves, it could be concluded that prediction is very reasonable over the measured sinkage range.

As before, a linear regression was performed to verify the validity of the prediction. Figure 7 shows that the sinkage values predicted using the soil stiffness constants derived from tests and those measured experimentally were plotted against each other and fitted with a linear equation with zero intercept. The slope of the line of best fit and its coefficient of determination were 0.88 and 0.99, respectively.

Again, Root of Mean Square Errors (RMSE) and Mean Relative Percentage Deviation (MRPD) were used to check the discrepancies between the predicted and

measured results. The amounts of RMSE and MRPD were 2 mm and 11.5%, respectively. Regarding the statistical results, the validity of the prediction was confirmed again.

More likely, reason for such negligible discrepancies between the predicted and measured results using the soil stiffness constants stem out primarily from using three plates to enhance the level of confidence of the calculated soil stiffness constants. Had it been four or even five plates, the results would have been improved further [18].

The model, to some extent, showed better results for the lower bulk density soil. Although the results for the higher bulk density soil are reasonable, it appears that due to a probable unevenness of bulk density, a more packed soil seems to build higher stress concentrations underneath some parts of the plate from the very first moment of the application of the load. Therefore, occurrence of a small variation in the bulk density during the soil sample preparation, could adversely affect the result.

CONCLUSIONS

The k_c and k_p constants were calculated using three different rectangular plates with different aspect ratios similar to those of pneumatic agricultural tires. In this study, the best-fitted regression model was obtained when the data from three rectangular plates were used in two soil conditions of low and high apparent bulk densities. The soil stiffness constants measured with three small rectangular plates were used to predict the pressure-sinkage behaviour of a large rectangular plate. The statistical results confirmed the validity of the prediction, especially in the low bulk density soil and demonstrated that under some conditions, it could be very useful to determine the sinkage behaviour of tires and tracks of tractors and agricultural machines in the laboratory condition without going to the field.

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