Comparison of Bekker and Upadhyaya Models in Predicting Soil Pressure-Sinkage Behaviour under Field Conditions

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Abstract: In order to compare Bekker and Upadhyaya models 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 ($k_1$, $k_2$, and $n$) and Upadhyaya model ($k_1$, $k_2$, and $n$) were determined from five sets of soil pressure-sinkage tests using five small rectangular plates. Both models were then used to predict pressure-sinkage behaviour of soil under a large rectangular plate. Soil pressure-sinkage behaviour predicted by both models was finally verified through field tests using the large rectangular plate. The paired samples t-test results indicated that the sinkage values predicted with both models 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 both models, RMSE and MRPD were calculated. The amounts of RMSE and MRPD pertaining to Bekker model prediction were 0.039 m and 71.9%, respectively. Also, the amounts of RMSE and MRPD pertaining to Upadhyaya model prediction were 0.039 m and 72.1%, respectively. Results of this study indicated that both models may not be suggested as accurate and suitable models 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 ($z_{ap}$) based on soil sinkage values predicted by Bekker model ($z_{be}$) the polynomial regression model $z_{ap} = -29.68z_{be}^2 + 3.341z_{be} + 0.009$ with $R^2 = 0.986$ can be recommended. Moreover, to predict soil sinkage values measured by test apparatus ($z_{up}$) based on soil sinkage values predicted by Upadhyaya model ($z_{up}$) the polynomial regression model $z_{up} = -30.28z_{up}^2 + 3.375z_{up} + 0.009$ with $R^2 = 0.986$ can be proposed.

Key words: Soil · Pressure-sinkage · Bekker model · Upadhyaya model · Prediction · Comparison · 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]. Models presented in the literature are from
simple exponential model to an elastoplastic complicated one. Bekker and Upadhyaya models are two modified form of the exponential model which can be easily studied by researchers and scientists. Therefore, the main objectives of this study were to evaluate and to compare Bekker and Upadhyaya models 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 Goriatckhin and equation 1 was proposed to describe it [3, 6, 11-13, 16, 18, 20]:

\[ P = kz^n \]  

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. 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]:

\[ P = \left(\frac{k}{b+k_0}\right)z^n \]  

where:

- \( k \) and \( k_0 \) = soil stiffness constants, which are presumed to be independent of plate width, kPa/m\(^n\) and kPa/m\(^2\), respectively

Upadhyaya proposed a modified form of the equation 1 in which the depth of sinkage was normalized by the width of the impression surface as equation 3 [11, 12, 20]:

\[ P = (k+b)(z/b)^n \]  

where:

- \( k \) and \( k_0 \) = soil stiffness constants, which are presumed to be independent of plate width, kPa and kPa/m, respectively.

In order to evaluate the soil stiffness constants in equations 2 and 3, 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 made of \( k \) versus \( 1/b \) in order to solve for stiffness constants in Bekker model. A best fit line is found by least square analysis and \( k_0 \) and \( k \) are the slope and intercept of this line, respectively. Also, a graph can be made of \( k \) versus \( b \) in order to solve for stiffness constants in Upadhyaya model. A best fit line is found by least square analysis and \( k_1 \) and \( k_2 \) are the intercept and slope 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. 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 both models with 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 both models, root mean squared error (RMSE) and mean relative percentage deviation (MRPD) were calculated using the equations 4 and 5, respectively [14, 15, 17]:

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (z_{Mi} - z_{Pi})^2}{n}} \tag{4}
\]

where:
- \( RMSE \) = Root mean squared error, m
- \( z_{Mi} \) = Soil sinkage measured by test apparatus, m
- \( z_{Pi} \) = soil sinkage predicted using model (Bekker or Upadhyaya), m

\[
MRPD = \frac{100 \times \sum_{i=1}^{n} \frac{z_{Mi} - z_{Pi}}{z_{Mi}}}{n} \tag{5}
\]

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. To obtain \( k_s \) and \( k_o \) 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, \( k_s \) and \( k_o \) the slope and intercept of the regression line, respectively. Our attempts to relate \( k \) to \( b \) using equation 2 resulted in very poor agreements \((R^2 = 0.270)\). The determined soil stiffness constants \((k_s, k_i, k_j\) and \( n)\) for the experimental site are given in Table 5. Table 6 shows the results of the paired samples t-test.

<table>
<thead>
<tr>
<th>Soil sinkage (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact pressure (kPa)</td>
</tr>
<tr>
<td>65.00</td>
</tr>
<tr>
<td>87.00</td>
</tr>
<tr>
<td>109.0</td>
</tr>
<tr>
<td>131.0</td>
</tr>
<tr>
<td>153.0</td>
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<tr>
<td>174.0</td>
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<td>196.0</td>
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<td>218.0</td>
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<td>240.0</td>
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<tr>
<td>262.0</td>
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<td>283.0</td>
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<td>305.0</td>
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<tr>
<td>327.0</td>
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<td>349.0</td>
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<tr>
<td>371.0</td>
</tr>
<tr>
<td>393.0</td>
</tr>
<tr>
<td>414.0</td>
</tr>
<tr>
<td>436.0</td>
</tr>
</tbody>
</table>

**DISCUSSION**

To compare Bekker and Upadhyaya models under field conditions, the soil stiffness constants in Bekker model \((k_s, k_i, k_j\) and \( n)\) and Upadhyaya model \((k_s, k_i, k_j\) 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 both models were compared with the sinkage values measured by test apparatus and are shown in Table 7. The paired samples t-test results

<table>
<thead>
<tr>
<th>Plate number</th>
<th>k (kPa/m²)</th>
<th>n (non-dimensional)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1775</td>
<td>0.448</td>
<td>0.827</td>
</tr>
<tr>
<td>2</td>
<td>1878</td>
<td>0.488</td>
<td>0.855</td>
</tr>
<tr>
<td>3</td>
<td>1677</td>
<td>0.472</td>
<td>0.879</td>
</tr>
<tr>
<td>4</td>
<td>1935</td>
<td>0.543</td>
<td>0.868</td>
</tr>
<tr>
<td>5</td>
<td>1400</td>
<td>0.407</td>
<td>0.775</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>k (kPa/m²)</th>
<th>k (kPa/m)</th>
<th>n (non-dimensional)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20.79</td>
<td>2010</td>
<td>0.472</td>
<td>0.270</td>
</tr>
</tbody>
</table>

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

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

**Table 6: Soil stiffness constants in Upadhyaya model determined for the experimental site**

**Table 7: Contact pressure and soil sinkage values used in comparing Bekker and Upadhyaya models under field conditions**
indicated that the sinkage values predicted by both models were significantly less than the sinkage values measured by test apparatus (Table 8). The mean sinkage difference between test apparatus and Bekker model 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. Also, the mean sinkage difference between test apparatus and Upadhyaya model was -0.036 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 & 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 & Seyfi [18] who reported that Bekker and Upadhyaya models 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.

To check the discrepancies between the sinkage values measured by test apparatus with the sinkage values predicted by both models, RMSE and MRPD were calculated. The amounts of RMSE and MRPD pertaining to Bekker model prediction were 0.039 m and 71.9%, respectively. Also, the amounts of RMSE and MRPD pertaining to Upadhyaya model prediction were 0.039 m and 72.1%, respectively. Such significant discrepancies between the models’ results and results of the field tests using test apparatus confirm that both models may not be suggested as accurate and suitable models and can not be directly used to predict soil pressure-sinkage behavior under field conditions. However, as it is shown in Fig. 3, our attempts to relate soil sinkage values measured by test apparatus \( z_{MT} \) to soil sinkage values predicted by Bekker model \( z_{PB} \) using a polynomial equation resulted in very good agreements \( (R^2 = 0.986) \) as equation 6.

\[
\text{Equation 6: } z_{MT} = -29.68 z_{PB}^2 + 3.341 z_{PB} + 0.009
\]

Also, as it is shown in Fig. 4, our attempts to relate soil sinkage values measured by test apparatus \( z_{MT} \) to soil sinkage values predicted by Upadhyaya model \( z_{PU} \) using a polynomial equation resulted in very good agreements \( (R^2 = 0.986) \) as equation 7.

\[
\text{Equation 7: } z_{MT} = -30.28 z_{PU}^2 + 3.375 z_{PU} + 0.009
\]

**CONCLUSIONS**

It can be concluded that Bekker and Upadhyaya models may not be suggested as accurate and suitable models 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_{test}) based on soil sinkage values predicted by Bekker model (z_{bekker}) the polynomial regression model $z_{test} = -29.68 z_{bekker}^2 + 3.341 z_{bekker} + 0.009$ with $R^2 = 0.986$ can be recommended. Moreover, to predict soil sinkage values measured by test apparatus (z_{test}) based on soil sinkage values predicted by Upadhyaya model (z_{upadhyaya}) the polynomial regression model $z_{test} = -30.28 z_{upadhyaya}^2 + 3.375 z_{upadhyaya} + 0.009$ with $R^2 = 0.986$ can be proposed.

REFERENCES