

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

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**Abstract:** Soil stiffness constants govern the soil sinkage and the pressure-sinkage behaviour of the soil under load. To determine soil stiffness constants in Upadhyaya 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 Upadhyaya model were determined from five sets of soil pressure-sinkage tests using five rectangular plates that have the same contact area and different aspect ratio. The determined soil stiffness constants ( $k_1$ ,  $k_2$  and  $n$ ) for the experimental site were 222.3 kPa, 3635 kPa/m 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, assessment of Upadhyaya 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 • Upadhyaya 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 like that. 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. In addition, 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 Upadhyaya 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<sup>n</sup>
- $z$  = 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]. Upadhyaya combined the two concepts and 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 2 [11, 12, 17]:

$$P = (k_1 + k_2 b)(z/b)^n \quad (2)$$

Where:

$k_1$  and  $k_2$  = 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 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 may be risky to attempt the measurement of soil stiffness constants with tests that use only two plates, especially if they are small plates [3]. It has been shown that the variation in soil stiffness constants 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 soil stiffness constants, the variation in soil stiffness constants are reduced dramatically [13]. 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  $k_1$  and  $k_2$  are the intercept and slope of this line, respectively [15].

**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 determine soil stiffness constants under field conditions, a tractor mounted pressure-sinkage test apparatus was designed and constructed (Fig. 2). The test apparatus had five different rectangular plates (Fig. 3). The dimensions of five plates 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

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

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



Fig. 1: Selected field for conducting multiplate penetration tests



Fig. 2: Tractor mounted pressure-sinkage test apparatus



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



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

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

Plate number	Length (m)	Width (m)	Area (m <sup>2</sup> )	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

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  $k_1$  and  $k_2$  by using the data from Table 3, regression analysis was applied to the soil stiffness constant ( $k$ ) and the plate width ( $b$ ). From the linear regression results,  $k_1$  and  $k_2$  are the intercept and slope of the regression line, respectively. Our attempts to relate  $k$  to  $b$  using equation 2 resulted in very good agreements ( $R^2 = 0.986$ ). The determined soil stiffness constants ( $k_1$ ,  $k_2$  and  $n$ ) for the experimental site are given in Table 4. As well known, 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 good agreements may attract the trust of any scientist on the soil stiffness constants in Upadhyaya model under field

Table 3: Determined soil stiffness constants k and n for each sinkage plates

Plate number	k (kPa/m <sup>2</sup> )	n (non-dimensional)	R <sup>2</sup>
1	758.5	0.448	0.827
2	609.4	0.488	0.855
3	492.8	0.472	0.879
4	419.6	0.543	0.868
5	412.7	0.407	0.775

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

k <sub>1</sub> (kPa)	k <sub>2</sub> (kPa/m)	n (non-dimensional)	R <sup>2</sup>
222.3	3635	0.472	0.986

conditions. These results may be in line with the results reported by McKyes and Fan [18] that it 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 be in agreement with those of Rashidi and Seyfi [15] who reported that Upadhyaya 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, assessment of Upadhyaya 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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