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PREDICTION OF SOIL RESISTANCE

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The resistance of soil, affecting the emergence of crop seedlings, was found to increase linearly with its density at different moistures and decreased with its moisture following a quadrate relationship at different densities under nondrying conditions. It was further found to increase with the area of the penetrating device (used to measure soil resistance) and drying time.

A general prediction equation was developed employing Housel's approach to describe the penetration resistance of soil within the measured ranges and was given by :

$$F = Ar\,(0.0586M^2 - 2.778M + 37.122) + Ad\,(5.66r + 11.578M - 194.1)$$

Where F is penetration resistance of soil (lb), A is area of the penetrating device (in^2), M is initial moisture of soil (%), d is drying time (days) and r is unit weight of soil minus unit weight of water (lb/cft). The first term represents the resistance under nondrying conditions and the second term incorporates the effect of air drying. This equation was least accurate for low moisture contents and low density of soil, and the measured and predicted values for the most part did not lie within 95% confidence bands. However, the error of prediction ranged from about 0.68% to 35% (with a mean of 5.6%) excluding low moisture—low density data.

INTRODUCTION

The resistance of soil greatly affects the germination, emergence and growth of crop seedlings. Tillage operations are mainly performed to reduce the resistance of soil in order to maximize its yield. The prediction of soil resistance has, therefore, become a matter of great importance to engineers.

In this study, an effort was made to predict the penetration resistance of soil employing Housel's approach, as reported in soil mechanics literature.

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With this approach, a general prediction equation was developed to describe the penetration resistance of soil within the measured ranges. The predicted resistance was found to be a function of initial moisture content and bulk density of soil, area of penetrating device, and drying time.

MATERIALS AND METHODS

(a) Description of soil. The soil used for determining the penetration resistance of soil had the following mechanical composition by weight:

Sand	25.9 per cent	(0.050 to 2.00 mm)
Silt	41.3 per cent	(0.002 to 0.50 mm)
Clay	32.8 per cent	(0.002 mm)

The above air dried soil passed through a nine mesh (0.078-inch opening) sieve was weighed and mixed with the necessary amount of moisture by means of an electric sprayer. It was then transferred to plasstic boxes (3 11/16 inch diameter and 5 1/2 inch deep) and compacted to a height of 2 inches.

(b) Measurement of soil resistance. The resistance of soil was measured with the help of a conical shaped penetrometer which could be moved vertically up or down manually or by means of an electric motor and gearing arrangement. The penetrating tool was attached to a proving ring employing a four strain gage bridge circuit for sensing the resistance of soil. The bridge circuit was connected by means of an input coupler to Offner dynograph fitted with amplifiers, writer element, recording paper operated by a revolving drum, and a regulated power supply unit The resistance of the soil experienced by the penetrometer when moved through the soil box could be measured with the help of the dynograph at a desired amplifier sensitivity.

(c) Prediction of soil resistance. Housel as reported by spangler (1960) considers the resistance to penetration of a plate moving in soil as the sum of two components, one an area component proportional to the plate diameter squared and the other a perimeter shear component, proportional to the diameter :

$$F = An + Pm$$

$$\text{or} \quad F = \frac{\pi}{4} D^2 n + \pi Dm \qquad (1)$$

Where :

F = penetration resistance of soil (lb)

A = area of plate (in^2)

D = diameter of plate or footing (in)

P = length of perimeter (in)

n = compressive stress on soil column directly beneath the plate (psi)

m = perimeter shear (lb/linear in)

RESULTS AND DISCUSSION

(a) Effect of penetrometer size. Table 1 shows the values of force measured with different sizes of penetrometers moving through soil boxes of two-inch depth having initial moisture content of 12% and compacted to different densities. Nondrying conditions were maintained by keeping the boxes covered except during the test. The penetrometer used were of 0.115, 0.238, 0.364 and 0.490 inch in diameter. The analysis of the data shown in the table yielded the following regression equations at 95% significance level :

$$F = 24.01\ D^2 \qquad (70\ lb/cft) \qquad (2)$$
$$F = 76.82\ D^2 \qquad (80\ lb/cft) \qquad (3)$$
$$F = 12.64\ D + 137.18\ D^2 \qquad (90\ lb/cft) \qquad (4)$$

Where :

F = estimated force or penetration resistance (lb)

D = diameter of penetrometer (in)

TABLE 1 : *Effect of penetrometer size (12% soil moisture)*

Density (lb/cft)	Diameter of penetrometer (in)	Measured force (lb)		
		Box 1	Box 2	Box 3
70	0.111	0.534	0.634	0.60
	0.238	1.60	1.70	1.60
	0.364	2.60	2.80	3.00
	0.490	5.70	5.90	5.20
80	0.115	1.867	1.800	1.834
	0.238	5.00	5.50	4.75
	0.364	9.00	8.50	9.50
	0.490	18.25	87.50	17.50
90	0.115	4.267	4.267	4.133
	0.238	11.00	11.50	12.00
	0.264	22.00	23.00	21.50
	0.490	41.50	39.00	41.00

The above equations reveal that the force (soil resistance) exerted by the penetrometer is a function of its diameter squared or the area. It will be observed that the above data derived equations agree in form with Housel's Equation No. 1. The coefficients m and n respectively were obtained by dividing the coefficients of D^2 with $\pi/4$ and those of D with π in equations 2, 3 and 4 and are given below :

w(lb/cft)	70	80	90
m	0	0	4.02
n	30.6	97.8	174.7

From this analysis, the end area resistance (An) seems most important, the perimeter shear term (Pm) contributing only for higher density soil.

(b) Effect of density (nondried soil). Table 2 shows the maximum values of force measured by a conical shaped penetrometer having a diameter of 0.115 inch and a cone angle of 60 degrees, when moved through a two inch depth of nondried soil kept at a constant temperature room of 20°C. Each value of the force recorded in the table is the average of three values obtained on each of the three soil boxes (replications).

Since the range of soil density in the experiments varied from 70 lb/cft to 100 lb/cft, a variable r = w — 62.4 (where w = unit weight of soil, minus unit weight of water and w — 62.4 refers to sumerged unit weight of soil) was selected so as draw the data close to the origin and facilitate its statistical regression analysis. It was decided to perform the regression of force F (lb) on r (lb/cft), where the coefficient of variation for the former was greater or equal to that of the latter. The regression of F on r and vice versa was carried out when the coefficient of variation for the former was found lower. The regression equations thus determined from the Table 2 are given below at 95% significance level for different moisture contents -

$F = 0.127r$	(12% moisture)	(5)
$F = 0.105r$	(14% moisture)	(6)
$F = 0.073r$	(16% moisture)	(7)
$F = 0.067r$	(18% moisture)	(8)
$F = 0.033 + 0.038r$	(20% moisture)	(9a)
$r = 6.682 + 24.74\ F$	(20% moisture)	(9b)
$F = 0.279 + 0.035r$	(22% moisture)	(10a)
$r = 6.23 + 27.045F$	(22% moisture)	(10b)
$F = 0.314 + 0.029r$	(24% moisture)	(11a)
$r = 7.9 + 31.55F$	(24% moisture)	(11b)

Where :

F = estimated force for nondried soil (lb)
r = density of soil — density of water = w-62.4 (lb/cft)

(e) Prediction using Housel'approach. Equations 5 to 8 may be used to determine Housel's values by assuming m = 0 corresponding to zero intercepts and dividing F by the penetrometer end area, 0.0104 square inch, giving :

Moisture content %	12	14	16	18
n/r	12.2	10.1	7.02	6.44

The intercepts at higher moisture contents given by Equations 9b, 10b, and 11b suggest that r should be defined as approximately w - 56 for the regressions to include the origin. For example, Equation 9b can be written as w-62.4 = 24.74 F–6.882, or w = 55.7 = 24.74 F. Denoting w - 55.7 by r, the equation can be rewritten as r = 24.74 F. An approximate method, however, is to assume that the regressions do pass through the origin, which gives n values based on slopes (y/x) as follows :

moisture content (%)	20	22	24
n/r	5.03	4.55	4.11

As the moisture content becomes sufficiently high, n/r will approach zero because the soil will become liquid.

A second order quadratic equation was found to describe the data.

$$n/r = 0.0586\ M^2 - 2.778\ M + 27.122 \quad (12)$$

Equation 12 can be written as follows :

$$n = r\,(0.586\ M^2 - 2.778\ M + 37.122) \quad (13)$$

Using F = A n = 0.0104 n, where A = 0.0104 square inch

$$F = 0.0104r\ [(0.0586\ M^2 - 2.778\ M + 37.122)] \quad (14)$$

Equation 14 has the disadvantage the extroapolation to higher moisture contents will increase n/r, whereas logically it should decrease. However, within the bounds of the experimental conditions, it is sufficiently pricise, and the form is advantageous for calculation.

A comparison between the measured values and those predicted from equation 14 is presented in Table 2. The percentage difference between the measured values and those predicted from Equation 14 range from 0.33 to 64% The mean value of all the percentage differences was, however, computed as -4.3%, the negative sign indicating overprediction by Equation 14. The mean absolute difference was determined as 0.513 pound.

TABLE 2. *Values of measured and predicted force for nondrying condition*

Moisture %	Density lb/cft	Measured force (lb)	Predictedforce (lb)
12	70	0.534	0.965
		0.600	
		0.634	
	80	1.800	2.239
		1.834	
		1.867	
	90	4.133	3.512
		4.267	
		4 267	
	100	4.667	4.784
		4.800	
		4.933	
16	70	0.600	0.608
		0.600	
		0.633	
	80	1.067	1.408
		1.133	
		1 334	
	90	2.133	2.208
		2.133	
		2.333	
20	100	2.533	3.008
		2.634	
		2.667	
	70	0.500	0.397
		0.533	
		0.567	
	80	1.000	0.920
		1.067	
		1.067	
	90	1.467	1.442
		1.533	
		1.557	
24	100	1.600	1.965
		1.633	
		1.667	
	70	0.433	0.335
		0.433	
		0 467	
	80	0.867	0.775
		0.900	
		0.933	
	90	1.200	1.215
		1.233	
		1.233	
	100	1.233	1.655
		1.300	
		1.367	

Effect of moisture (nondried soil) : The regression analysis of the data on moisture and force (penetration resitance) recorded in Table 2 yielded the following results at 95% level of significance for different bulk densities of soil :

$$F = 0.818 - 0.15\ M\ (70\ lb/cft) \quad (15)$$

$$F = 14.31 - 1.14\ M - 0.025\ M^2\ 90\ lb/cft) \quad (16)$$

$$F = 4.97 - 0.35 + 0.035\ M^2\ (80\ lb/cft) \quad (17)$$

$$F = 15.07 - 1.137\ M + 0.024\ M^2\ (100\ lb/cft) \quad (18)$$

Where :

F = estimated force for nondried soil (lb)

M = mosture content of soil (%)

Figure 1 shows diagramatically the effect of initial moisture on the resistance of soil with bulk density of 80 lb/cft. The general prediction Equation 14 has been added to the figure and is represented by the dotted line. The decrease in force with moisture as indicated by the diagram and Equations 15 to 18 may be attributed to the decrease in strength and viscosity of soil.

Effect of drying. Table 3 shows the values of force measured by the penetrometer of 0.115 inch in diameter on different days when boxes were kept uncovered in a constant temperature room of 20° C. One reading of force was taken from each box. The regression of analysis of the data shows in the Table produced the following equations :

12% inital moisture :

$$F_d = 0.58 + 0.121\ d \quad (70\ lb/cft) \quad (19)$$

$$F_d = 1.667 + 0.348\ d \quad (80\ lb/cft) \quad (20)$$

$$F_d = 3.737 + 0.980\ d \quad (90\ lb/cft) \quad (21)$$

16% intitial moisture :

$$F_d = 0.686 + 0.257\ d \quad (70\ lb/cft) \quad (22)$$

$$F_d = 0.927 + 0.727\ d \quad (80\ lb/cft) \quad (23)$$

$$F_d = 1.960 + 1.733\ d \quad (50\ lb/cft) \quad (24)$$

20% initial moisture :

$$F_d = 0.90\ d \quad (70\ lb/cft) \quad (25)$$

$$F_d = 1.338\ d \quad (80\ lb/cft) \quad (26)$$

$$F_d = 1.17 + 2.098\ d \quad (90\ lb/cft) \quad (27)$$

80 lb/cft

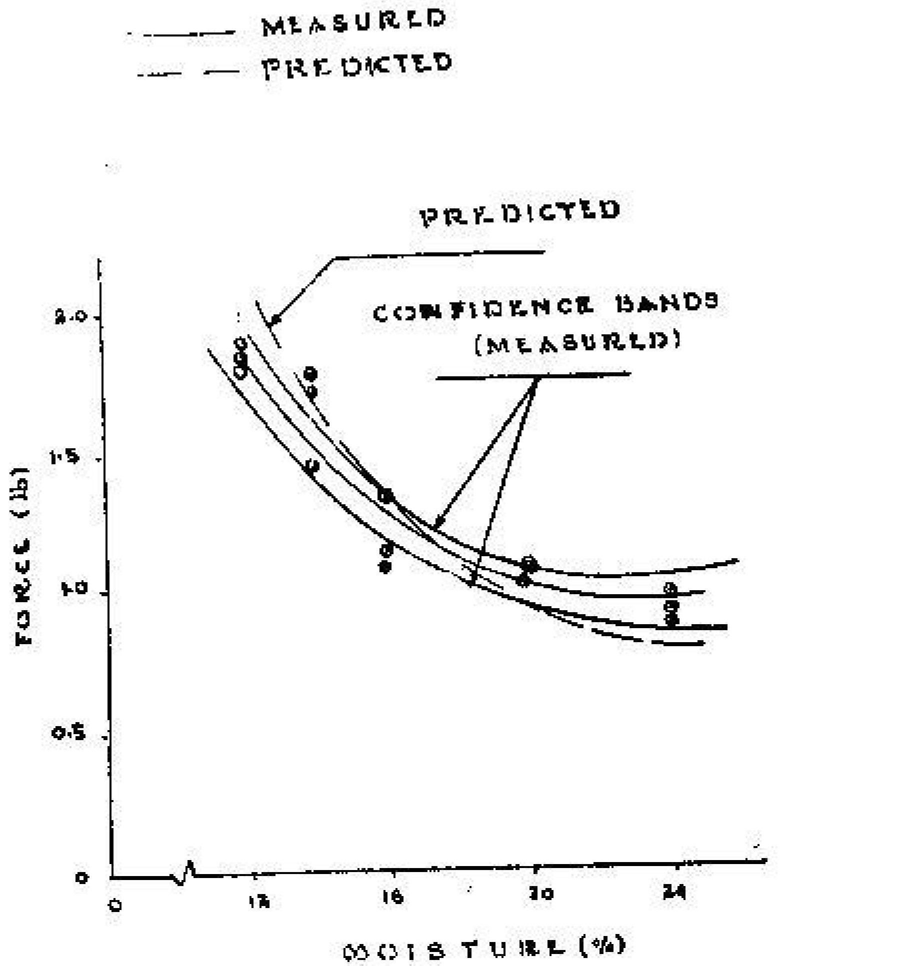

FIG. 1 EFFECT OF MOISTURE ON FORCE AT 80lb/cft

Equations 19 to 27 were used to include the effect of drying in Equation 13, used to determine Housel's n values. Considering only the slopes in these equations and dividing them by the area (0.0104 square inch) of the penetrometer, Housel's n as a function of drying time (d) was obtained. The ratio n/d thus obtained from Equations 19 to 27 was evaluated and has been shown below for different soil moistures and densities :

Moisture (%)	r = w–62.4 (lb/cft)	n/d = slope/area = slope/0.0104
12	7.6	11.63
	17.6	33.50
	27.6	94.0
16	7.6	24.7
	17.6	69.5
	27.6	166.6
20	7.6	86.5
	16.6	128.5
	27.6	202.0

The multiple regression of the above values gave the following equation :

$$n/d = 5.661\ r + 11.578\ M - 194.124$$

$$n = d\ (5.661\ r + 11.578\ M - 194.124) \qquad (28)$$

The function given by equation 28 was added to equation 13 in order to account for the effect of drying. This resulted in the following equation:

$$n = r\ (0.0586\ M^2 - 2.778\ M + 37.122) + Ad\ (5.661\ r + 11.578\ M - 194.124) \qquad (29)$$

Since $F = A\ n$, where A is the end area of the penetrometer

$$F = A\ r\ (0.0586\ M^2 - 2.778\ M + 37.122) + A\ d\ (5.661 - 11.578M - 194.124) \qquad (30)$$

Figure 2 shows a graphical comparison of the measured and predicted force at different days for 16% moisture and 90 lb/cft. The predicted line shown dotted represents Equation 30.

The predicted values of force, as obtained from Equation 30 have been entered in Table 3. The difference between the measured and predicted values, as shown in the Table, range from 0.68 to 45% excluding the low

16% MOISTURE

90 lb/cft

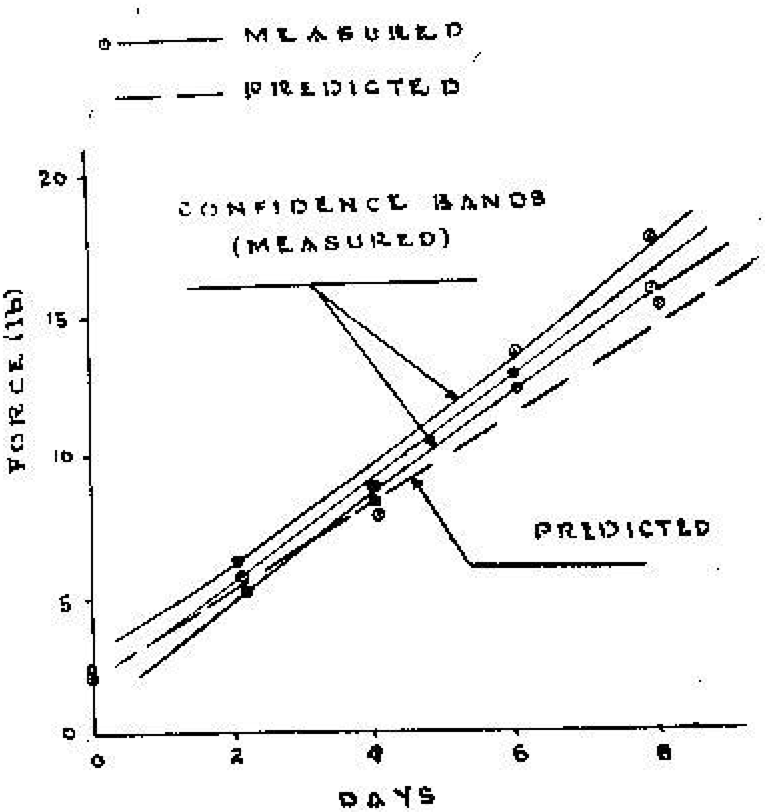

FIG. 2. EFFECT OF DRYING TIME ON FORCE AT 16% MOISTURE AND 90 lb/cft

TABLE 3. *Measured and predicted forces for drying conditions.*

Moisture (%)	Density (lb/cft)	Days of drying	Measured force (lb)				Predicted force (lb)	Differences measured —predicted (lb)	Per cent difference
			Box 1	Box 2	Box 3	Mean			
12	70	0	0.534	0.634	0.60	0.589	0.967	—0.378	—64.17
		2	0.8	0.9	0.8	0.833	0.714	—0.119	—14.28
		4	1.0	1.1	1.0	1.033	0.461	—0.572	—55.37
		6	1.4	1.3	1.2	1.300	0.208	—1.092	—84.00
		8	1.4	1.6	1.7	1.567	—0.04	—1.607	—102.55
	80	0	1.867	1.8	1.834	2.239	0.405	—0.405	—22.08
		2	2.2	2.5	2.3	2.333	3.164	—0.831	—35.61
		4	3.0	2.8	2.7	2.833	4.088	—1.255	—44.29
		6	3.9	3.6	3.4	3.633	5.013	—1.380	—37.98
		8	5.0	4.8	4.2	4.667	5.934	—1.267	—27.14
	90	0	4.267	4.267	4.133	4.222	3.512	—0.708	—16.76
		2	5.8	5.4	5.2	5.433	5.614	—0.181	— 3.33
		4	7.5	7.0	7.25	7.250	7.716	—0.466	— 6.46
		6	8.5	9.0	10.0	9.107	9.817	—0.657	— 7.17
		8	12.0	12.0	12.5	12.167	11.919	—10.248	— 2.03
16	70	0	0.60	0.60	0.633	2.611	0.601	-0.010	— 1.63
		2	1.1	1.2	1.2	1.167	1.312	-0.145	—12.42
		4	2.0	1.8	2.0	1.933	2.025	0.090	— 4.65
		6	2.4	2.0	2.2	2.200	2.734	-0.534	-24.27
		8	2.4	2.8	2.8	2.667	3.444	—0.777	-29.13
	80	0	1.133	1.067	1.334	1.178	1.393	-0.215	18.25
		2	2.0	2.4	2.8	2.400	3.281	—0.881	—36.70
		4	3.2	3.4	3.8	3.467	5.188	—1.701	—49.06
		6	5.0	4.6	5.0	4.866	7.056	—2.190	—45.00
		8	6.5	7.0	8.0	7.166	8.943	—1.777	—24.79

Moisture (%)	Density (lb/cft)	Days of drying	Measured force (lb) Box 1	Box 2	Box 3	Mean	Predicted force (lb)	Difference = measured -predicted (lb)	Per cent difference
	90	0	2.133	2.133	2.333	2.119	2.184	—0.015	— 0.68
		2	5.4	6.2	5.2	5.600	2.249	—0.351	— 6.26
		4	8.5	7.5	8.0	8.30	8.314	—0.314	— 3.90
		6	12.0	13.5	12.51	2.667	11.375	—1.292	—10.19
		8	15.0	17.5	15.5	16.30	14.445	—1.555	— 9.71
20	70	0	0.533	0.567	0.500	0.533	0.397	+0.136	+25.51
		2	2.0	2.0	2.0	2.000	2.070	—0.070	—33.50
		4	3.4	3.4	3.6	3.466	3.744	—0.278	— 8.02
		6	5.0	5.2	4.8	5.000	5.417	—0.417	— 8.34
		8	8.0	7.0	7.5	7.500	7.091	+0.409	+ 5.45
	80	0	1.067	1.000	1.067	1.645	0.920	+0.125	+11.96
		2	4.0	4.0	4.0	4.000	3.771	+0.229	+ 5.72
		4	4.7	4.6	3.4	4.567	4.622	—2.055	—44.99
		6	8.0	7.0	7.5	7.500	4.473	—1.973	—26.30
		8	10.0	12.5	11.0	11.111	12.324	—1.213	—10.91
	90	0	1.467	1.533	1.567	1.522	1.422	+0.080	+ 5.35
		2	5.0	4.5	4.0	4.500	5.470	—0.97	—21.55
		4	8.5	11.3	11.0	10.111	2.499	+0.612	+ 6.05
		6	12.5	13.5	15.5	13.834	13.527	+0.307	+ 2.21
		8	18.5	16.0	19.0	17.833	17.556	+0.277	+ 1.55

moisture (12%) and low density (70 lb/cft) data. The mean of all the percentage differences was computed as —5.62% of the measured values, the negative sign indicating overprediction by Equation 30. The absolute value of the mean difference was determined as 0.712 pound.

Effect of different variables on resistance. The method of multiple regression was employed to estimate the penetration resistance of soil considering the effects of moisture, density, days of drying, and the interaction between them. The equation developed from the values of measured force shown in Table 3 is presented below, based upon the highest multiple correlation coefficient and the least standard error of the estimated value:

$$F_d = 0.134\,w - 0.802\,M - 0.033\,M^2 - 5.46\,d - 0.005\,M\,w + 0.1\,M\,d + 0.06\,w\,d \qquad (31)$$

Where :

F_d = estimated force (lb)
w = unit weight or density of soil (lb/cft)
M = moisture of soil (%)
d = days of drying

The multiple correlation coefficient was computed as 0.976 and the standard error of the estimate 0·975. The value of t for testing the regression coefficient of each variable and the associated standard error is given in Table 4.

TABLE 4. *Values of t and standard error for the regression coefficient associated with different variables affecting resistance*

Variable	Standard error	t value (d.f. = 127)
density = w	0.02	6.617
moisture = M	0.388	-2.07
(moisture)^2 = M^2	0.013	2.493
day = d	0.322	-16.962
moisture x density = M x w	0.001	-4.781
moisture x day = M x d	0.008	11.86
density x day = w x d	0.004	16.444

Table 4 suggests that the drying time (day) has a clear effect on the resistance of soil, since the absolute value of t-statistic for the regression coefficient associated with the time (day) variable is very high. Similarly, the initial moisture content of soil may have less effect since the corresponding absolute value of t-statistic is the lower.

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