ADJUSTMENT OF FLAT-TIPPED PENETROMETER RESISTANCE DATA TO A COMMON WATER CONTENT

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ABSTRACT

Soil penetration resistance readings that need to be compared are often taken at different soil water contents. Because soil water can significantly effect penetration resistance, it is often difficult to determine whether penetration resistance differences are caused by water content or treatment. Empirical equations that relate soil penetration resistances from a 5-mm diameter, flat-tipped probe to soil water content were evaluated. The purpose of these equations was to adjust soil penetration resistance with changes in soil water content from plot to plot or time to time in the same plot. Several relationships were developed statistically for United States Southeastern Coastal Plain Ultisols from Norfolk loamy sand data and verified by other data of that soil and other soils. Penetration resistance (PR) was related to water content (WC) and bulk density for laboratory samples with R^2 ranging from 0.86 to 0.96. When the ratio of functions of water contents was related to the ratio of the penetration resistances, in most cases bulk density cancelled out and R^2 ranged from 0.44 to 0.99. The R^2 for the field samples ranged from 0.78 to 0.90, with one value at 0.25 for the relationship between penetration resistance and water content and bulk density, and 0.53 to 0.80 for the ratios. Some of the best relationships were developed from equations that considered boundary conditions of PR = 0 for WC = saturation and PR = ∞ for WC = 0. These fit the data as well as or better than more empirical relationships but used fewer parameters.

INTRODUCTION

Soil strength, as measured by penetration resistance, varies with a number of soil properties such as bulk density (or volume weight) and soil water content or tension (Mirreh and Ketcheson, 1972; Taylor and Gardner, 1963; Camp and Lund, 1968; Perumpral, 1987) and soil texture and organic matter (Gerard et al., 1982; Gupta and Larson, 1982; Spivey et al., 1986). Soil water content and, therefore, soil penetration resistance can vary rapidly with significant differences possible on a daily basis. This can mask the differences in penetration resistance caused by tillage treatments. To be able to compare penetration resistance readings, it would be advantageous to adjust them for differences caused by water content changes from different plots or from time to time in the same plot.

Penetration resistance differences based on bulk density changes have been measured by Camp and Lund (1968) for Norfolk sandy loam. They measured cone indices of near 3 to 14 MPa at wilting point for bulk densities of 1.4 to 1.7 Mg/m^3 on Norfolk fine sandy loam. Cassel (1982) recommended taking bulk density and water content samples along with penetration resistance data. However, there is no standard water content and/or bulk density at which penetration resistances are consistently measured. Furthermore, there is no one accepted method for adjusting readings not taken at those standard conditions. This leads to confusion. For example, if a dryer soil has greater penetration resistance, it is often not clear whether this is due to a treatment difference or a water content difference.

Relationships between water content and penetration resistance have been developed by Mirreh and Ketcheson (1972), Ayers and Perumpral (1982), and Busscher and Sojka (1987). Perumpral (1987) reviewed others. It is the purpose of this article to use these already developed relationships to adjust penetration resistance for changes in soil water content assuming a constant bulk density and to develop other relationships.

MATERIALS AND METHODS

Samples of A_p horizons were collected from Coastal Plain soils of South Carolina, Georgia, and Alabama. The soils and their classifications are shown in Table 1. Each

TABLE 1. Series, texture, and taxonomic classification for soils used in the study

Escambia fine sandy loam	coarse loamy, siliceous Plinthaquic Plaeudult
Exum sandy loam	fine, loamy, siliceous, thermic Typic Paledult
Lahaina* silty clay loam	clayey, kaolinitic, isohyperthermic Tropeptic Haplustox
Lucy sand	loamy, siliceous, thermic Arenic Paleudult
Norfolk loamy sand	fine, loamy, siliceous, thermic Typic Paleudult
Red Bay loamy sand	fine, loamy, siliceous thermic Rhodic Paleudult
Tifton fine sandy loam	fine, siliceous, thermic Plinthic paleudult

* This soil is from Oahu, HI

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soil had one set of samples except for Norfolk which had four sets of samples taken from farms located within ten miles of the Coastal Plains Research Center, Florence, South Carolina. The soils are non-swelling.

Samples of Escambia, Lahaina, Lucy, Norfolk sets 1 and 2, Red Bay, and Tifton were prepared for analysis following the methodology of Spivey et al. (1986). Samples were crushed by hand to pass a 2 mm sieve and were mechanically compacted into 76-mm diameter aluminum sleeves using a hand operated hydraulic press and trimmed on both top and bottom to 25-mm thickness. Densities ranged from 1.3 to 1.8 Mg/m^3 at 0.1 Mg/m^3 intervals for Norfolk sample set 1 and at 0.05 Mg/m^3 intervals for the others. The cores were moistened by placing them on a sand bed with a water table 13 mm below the surface. They were then brought to equilibria on standard ceramic pressure plates at 0.0, 0.01, 0.03, 0.05, 0.08, and 0.10 MPa for Norfolk set 1 and 0.03, 0.05, and 0.10 MPa for the others.

Field samples were taken at the end of the growing season just before or after harvest or at the beginning of the season before any land preparation. For Norfolk sets 3 and 4 and Exum, samples were taken with a locally-built sampler. It also used a 76-mm diameter, 25-mm deep aluminum cylinder to hold the core. The cylinder was driven into the soil behind a beveled driving tip through a cylindrical guide which was mounted on a rectangular metal plate. The plate was stabilized into position by 50-mm pins at its corners.

For Norfolk sets 3 and 4, samples were moistened in the same manner as lab samples. They were brought to equilibrium at 0.005, 0.01, 0.03, 0.07, and 0.1 MPa for set 3 and 0.01, 0.03, 0.08, and 0.20 MPa for set 4.

Core penetration resistance for all data sets except Exum was measured with a stainless steel, 5-mm diameter, flat-tipped probe. The probe was attached to a strain gauge and a motor geared to penetrate at a rate of 0.28 mm/s. Penetration resistance was continuously recorded as a function of depth of penetration. The value used was obtained at a depth of about 5 mm where the penetration resistance reached a constant value. Three measurements were made on each side of each core and averaged to give one penetration resistance. This was was subsequently treated as a single reading for the core as seen in Spivey et al. (1986). This procedure helped eliminate extraneous readings. For example, fracturing of the sample could be identified from breaks in the core or a sudden drop in penetration resistance on the recorded trace. These traces were excluded.

Penetration resistance for Exum was measured with a flat-tipped, 5-mm diameter, hand-held penetrometer pushed into the side of a pit. The soil sampler was then used to obtain a 76-mm diameter, 25-mm deep sample at the depths of the measurements. These samples were used to measure soil water content and soil bulk density.

Bulk density, soil water content on a weight or volume basis, soil matric tension, and penetration resistance measurements were used for all sets except Exum. Exum did not have tension measurements.

Regression equations relating soil penetration resistance, bulk density, and water content or soil matric tension were developed from Norfolk set 1, and verified using Norfolk sets 2 to 4, in various formulations of the parameters shown in equations 1 to 8. They were then applied to the other soils for further verification.

Gravimetric samples can be easily and routinely taken at the point of the penetration resistance reading. Therefore, emphasis was placed on development of the penetration resistance versus water content on a weight basis (to adjust the penetration resistance for changes in water content).

For each of the equations, the ratio of penetration resistances at different water contents or tensions having the same bulk density was also tested. This ratio was developed by dividing the equation by itself for different water contents obtaining the ratio of the penetration resistances on the left hand side of the equation and the ratio of the regressions on the right. This was used to simulate an adjustment in penetration resistance for water content changes at the same bulk density. Since many of the cores in the study were compacted in the laboratory or taken under similar field conditions, there were many cores with the same bulk density after values were rounded off to two decimal places. A logarithmic transformation of the ratios was taken before analysis.

The penetration resistance and its ratios were first calculated from equations that have been reported in the literature (Mirreh and Ketcheson, 1972):

$$PR = A + B\,BD + C\,BD^2 + D\,TEN + E\,TEN^2 + F\,BD\,TEN \tag{1}$$

where PR is soil penetration resistance in MPa, BD is bulk density in Mg/m^3, TEN is matric tension in MPa, and A through F are statistically determined parameters. The second equation was reported by Ayers and Perumpral (1982):

$$PR = (A\,BD^B) / (C + (WC - D)^2) \tag{2}$$

where WC is water content. The third equation was used by Busscher and Sojka (1987):

$$PR = A\,BD^B\,WC^C \tag{3}$$

All three of these relationships were developed for penetration resistance measured by cone tips: a 1.6-mm diameter, 60 °; a 20-mm diameter, 30 °; and a 13-mm diameter, 30 °, respectively. For eq. 1, the analysis of the ratio of penetration resistances versus water contents requires a knowledge of bulk density; for eqs. 2 and 3, the bulk density term drops out.

Other equations that were considered are shown in Table 2. Equation 4 was a relationship between penetration

TABLE 2. Equations* used to adjust strength to a constant water content

$PR = A\,BD^B\,TEN^C$	(4)
$PR = A\,BD^B\,EXP(C\,(D - E\,WC))$	(5)
$PR = A\,BD^B\,((SAT-WC) / WC)^C$	(6)
$PR = A\,BD^B\,(SEC(\pi/2(WC/SAT-1)-1-1)^C$	(7)
$PR/20 = A\,(BD-BD_o) / (BD_m-BD_o)^B * (WC-SAT) / (-SAT)^C + D$	(8)

* PR is penetration resistance in MPa, BD is bulk density in MG/m^3, TEN is soil water tension in MPa, WC is water content in kg/kg, SAT is the water content of the soil at saturation, and A, B, C, D, and E are statistically determined parameters.

resistance and soil water tension rather than soil water content. The tension in eq. 4 was estimated from the characteristic curve TEN = EXP(0.9432 - 0.3046 WC) developed from data set 1 ($R^2 = 0.93$) to give eq. 5.

Equation 8 developed unitless parameters out of penetration resistance, bulk density, and water content. Maximum penetration resistance was taken as 20 MPa. It is approximately the largest value measured in the field at this research site over the past 10 years. Zero was the minimum penetration resistance value. BD_m and BD_o were maximum and minimum bulk densities. They were assumed to be equal to 2.65 and 1.0 Mg/m^3, respectively. The minimum value was the bulk density of sieved soil poured loosely into a sampling cylinder. SAT is the water content at saturation, the maximum water content attainable. One trial used SAT as 0.387, calculated from 1.64 Mg/m^3, a mid-range bulk density, assuming a solid particle density of 2.65 Mg/m^3. Another trial used SAT = 1 - BD/2.65. Minimum water contents were assumed to be zero.

Equations 6 and 7 were developed using boundary conditions which consisted of wet soil having no penetration resistance and dry soil being essentially impenetrable. These were a result of field experiences where the probe will not register a penetration resistance if the field is wet and will go off scale if it is dry. At WC = SAT, penetration resistance equals zero (PR = 0). At WC = 0, penetration resistance equals infinity (PR = ∞). Though penetration resistance may never actually equal infinity, it can get large enough to be essentially off scale. Bulk density was also given boundary conditions of BD = 0 Mg/m^3, PR = 0 MPa, and BD = 2.65 Mg/m^3, PR = ∞.

The number of data points were 159, 111, 53, and 76 for sets 1 through 4 of Norfolk, respectively, for penetration resistance data. For ratios, data were sorted by bulk density. If the bulk density of one data point differed by more than 0.01 Mg/m3, the ratio of that data point with the next one was discarded. The numbers of data points used for the ratios were 138, 76, 30, and 53 for data sets 1 to 4, respectively. The numbers of data points for the ratios of other soils are shown in Table 3.

For each of the equations, general linear models procedure of SAS was used to determine the parameters A to F, if they were linear, and the multivariate secant method of the nonlinear regression procedure was used, if they were nonlinear (SAS Institute Inc., 1985). Before comparison, penetration resistance was log transformed as recommended by Cassel and Nelson (1979).

TABLE 3. Coefficient of determination for ratios from a variety of soils for the equations that use water content as a variable*

Soil Name	No. of data points	Equation Number 2	3	5	6	7	7A	8	8A
Escambia	22	0.98	0.98	0.99	0.98	0.99	0.99	0.99	0.98
Exum	29	0.67	0.64	0.70	0.68	0.69	0.69	0.72	0.69
Lahania	28	0.92	0.92	0.91	0.85	0.83	0.83	0.82	0.84
Lucy	19	0.44	0.73	0.70	0.72	0.72	0.72	0.69	0.69
Red Bay	17	0.92	0.93	0.93	0.93	0.93	0.93	0.93	0.91
Tifton	5	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.96

* Ratios are calculated at different water contents and the same bulk density.

RESULTS AND DISCUSSION

Coefficients of determination for the above equations for the four sets of Norfolk soil are shown in Table 4 for soil penetration resistance and Table 5 for the ratio of the penetration resistances. Values of R^2 ranged from 0.80 to 0.96 for the penetration resistances, except for one value at 0.25. For ratios of the penetration resistances with equal bulk densities, R^2 values ranged from 0.53 to 0.93 with 78 % of the values $\geq$ 0.60. When ratios of the penetration resistances are compared for other soil types, they give values from 0.64 to 0.99 except for one value at 0.44, as shown in Table 3. All of the analyses which produced the values in the tables were statistically significant at the 5% level or better (Little and Hills, 1978).

In Table 4, the R^2 values for sets 1 and 2 of Norfolk are greater than for sets 3 and 4. This is reasonable since the equation parameters were developed using set 1 data and the soil in both set 1 and set 2 data were compacted and measured in the laboratory using the same equipment. Sets 3 and 4 were field samples. The same trend is seen in Table 3 where the larger R^2 values are calculated for the laboratory data sets, and the smaller ones for the Exum soil, which was measured in the field. In Table 5, which shows the results for the ratios of the four sets of Norfolk data, the R^2 is greater for set 1 than for the others; however, the differences between lab and field samples is not as evident.

Equation 4 has the highest R^2 values in Tables 4 and 5. It uses tension rather than water content in the equation for penetration resistance and in the ratio of penetration resistances. Substitution of water content into the equation by use of the characteristic curve (eq. 5) gives a slightly lower coefficient of determination. Despite the fact that this uses more parameters to fit the curves, the lower coefficient is reasonable since the water retention vs. tension curve had an $R^2 = 0.93$.

Other forms of the above equations were tried in an attempt to improve the fit of the data of set 1 and be verifiable by the other sets of Norfolk data and the data from the other soils. Equations 3 to 7 were also tested with $BD_a = (BD/(2.65 - BD))$ replacing BD. This satisfied the boundary conditions mentioned above. It did not improve

TABLE 4. Coefficients of determination for penetration resistance data as a function of bulk density and soil water content or tension for the four sets of Norfolk soil

Equation	R^2 for Set 1	2	3	4	Parameters
1	0.90	0.93	0.78	0.25	6
2	0.90	0.91	0.85	0.83	4
3	0.87	0.93	0.80	0.90	3
4	0.92	0.96	0.88	0.87	3
5	0.90	0.93	0.82	0.89	3+2*
6	0.88	0.93	0.80	0.90	3
7	0.88	0.93	0.80	0.90	3
7A	0.86	0.93	0.84	0.89	2
8	0.90	0.92	0.81	0.87	4
8A	0.90	0.92	0.81	0.87	4

* Number of parameters determined statistically from the penetration resistance equation plus the number determined from the water retention curve.

TABLE 5. Coefficients of determination for the ratio of penetration resistances as a function of the ratio of the equations at different water contents and the same bulk density for the four sets of Norfolk soil

Equation	R^2 for Set 1	2	3	4	Statistical Parameters
1	0.75	0.58	0.67	0.62	6
2	0.91	0.65	0.53	0.76	2
3	0.85	0.60	0.58	0.78	1
4	0.93	0.82	0.79	0.82	1
5	0.91	0.63	0.55	0.80	1+1*
6	0.88	0.60	0.57	0.79	1
7	0.89	0.60	0.57	0.79	1
7A	0.89	0.60	0.57	0.79	0
8	0.93	0.63	0.53	0.80	1
8A	0.92	0.63	0.58	0.80	1

* Number of parameters statistically determined from the penetration resistance equation plus the number determined from the water retention curve.

the fit of the curves. Sigmoid relationships of the form $(TAN(\pi/2\ BD/2.65))^C$, $(SEC(\pi/2\ BD/2.65))^C$, and $(COT((\pi/2)\ (WC/SAT)))$ which satisfied the boundary conditions were also attempted. These did not improve the fit either.

Equation 7A is the same as eq. 7 except that C = 1. There is one less parameter to fit the data. This modified form of eq. 7 predicted about the same R^2 value for the penetration resistance, Table 4, and ratio of the penetration resistances, Tables 3 and 5. Equation 7A in Table 5 has no parameters in the ratio. It shows that a reasonable fit for the ratio can be obtained from the boundary conditions of the water contents alone.

The R^2 values of about 0.40 were obtained for penetration resistance as a function of bulk density and water content if B = 1 and C = 1 of eq. 7 even if a sigmoid relationship was used for the bulk density. Equation 6 which used a non-sigmoid relationship to satisfy the water content boundary conditions had about the same coefficient of determination as eq. 7.

Despite the high R^2 values and statistical significance, there was scatter in the penetration resistance data for all equations, see Tables 6 and 7. This was also seen in figures 1 to 3 where calculated penetration resistance was plotted as a function of the measured values for eq. 1, a commonly quoted equation; eq. 4, the best of the R^2 values; and eq. 7A, respectively. (Figure 1 shows eq. 1 without 10 data points from set 4 that were calculated out of range. Inclusion of these ten data points gave the low R^2 value shown in Table 4.) In all three cases, calculated values for field data fell below the 1:1 ratio line except for set 1 of the Norfolk data which was used to develop the relationships. None of the other equations had visually or statistically better fit to the data than those shown.

For the ratios, a high R^2 denoted a relationship that fell along a line but not necessarily the 1:1 ratio line shown in the graphs. In fact, most of the relationships do not follow the 1:1 line. Rather they look much like figure 4 which are the calculated ratios from eq. 7 vs. the measured ratios for sets 2, 3, and 4. The one notable exception to this was eq. 7A, which is shown in figure 5 for sets 2, 3, and 4 of Norfolk and in figure 6 for the other soils.

TABLE 6. Mean and standard error for the four sets of Norfolk soil for equations 1 to 8 and the ratios of the equations calculated at different water contents and the same bulk density

	Non-Ratios								Ratios							
	Data Set															
	1		2		3		4		1		2		3		4	
Equation	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
	MPa		MPa		MPa		MPa									
1	1.31	0.06	1.65	0.12	0.75	0.09	0.57	0.12	0.99	0.05	0.96	0.05	1.25	0.10	1.49	0.09
2	1.31	0.06	1.49	0.10	0.82	0.09	0.94	0.05	0.94	0.06	0.99	0.01	1.27	0.08	1.17	0.06
3	1.32	0.05	1.59	0.11	0.76	0.07	0.98	0.07	1.01	0.04	0.99	0.02	1.20	0.05	1.19	0.06
4	1.31	0.06	1.65	0.13	0.80	0.09	1.12	0.08	0.94	0.05	0.93	0.05	1.17	0.07	1.23	0.06
5	1.32	0.06	1.56	0.11	0.79	0.08	0.97	0.06	0.96	0.05	0.99	0.02	1.22	0.06	1.18	0.06
6	1.32	0.06	1.58	0.11	0.77	0.08	0.98	0.06	0.99	0.04	0.99	0.02	1.20	0.05	1.19	0.06
7	1.32	0.06	1.58	0.11	0.78	0.08	0.98	0.06	0.98	0.05	0.99	0.02	1.20	0.06	1.19	0.06
7A	1.26	0.06	1.67	0.12	0.59	0.07	0.96	0.08	0.97	0.08	0.98	0.04	1.36	0.09	1.33	0.10
8	1.33	0.06	1.51	0.10	0.82	0.09	0.98	0.06	0.93	0.05	0.99	0.01	1.18	0.05	1.14	0.05
8A	1.33	0.06	1.49	0.11	0.83	0.09	0.99	0.06	0.95	0.04	1.00	0.01	1.14	0.04	1.13	0.04

TABLE 7. Mean and standard error from the analysis of the log transformed ratios for a variety of soils using the equations that contain water content as a variable

	Equation															
	2		3		5		5		7		7A		8		8A	
Soil	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Escambia	0.63	0.14	0.82	0.06	0.70	0.11	0.78	0.07	0.77	0.08	0.64	0.14	0.70	0.11	0.74	0.08
Exum	0.91	0.11	0.97	0.04	0.91	0.09	0.94	0.06	0.93	0.07	0.88	0.11	0.87	0.10	0.92	0.07
Lahania	1.00	0.04	1.00	0.02	0.99	0.06	0.99	0.06	0.98	0.08	0.96	0.14	0.95	0.19	1.01	0.05
Lucy	0.96	0.02	0.87	0.07	0.90	0.05	0.88	0.07	0.88	0.06	0.81	0.11	0.93	0.04	0.94	0.03
Red Bay	0.96	0.02	0.96	0.02	0.96	0.02	0.96	0.02	0.96	0.02	0.93	0.03	0.97	0.02	0.97	0.01
Tifton	1.03	0.06	1.03	0.07	1.03	0.06	1.03	0.07	1.03	0.07	1.05	0.11	1.02	0.05	1.02	0.04

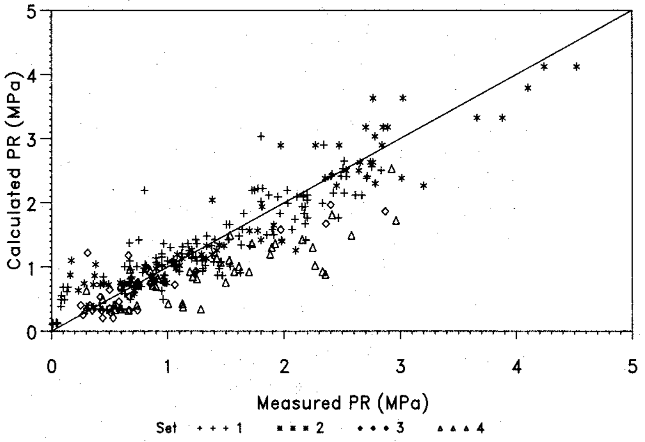

Figure 1–Measured vs. calculated values of penetration resistance for eq. 1 using the four data sets for Norfolk soil. The line represents a one-to-one relationship.

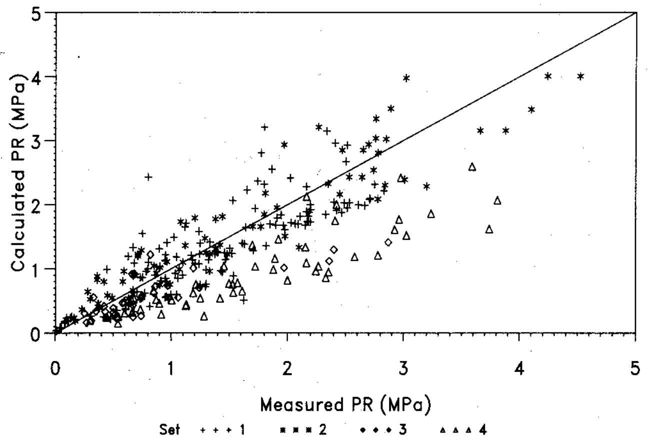

Figure 3–Measured vs. calculated values of penetration resistance for eq. 7A using the four data sets for Norfolk soil. The line represents a one-to-one relationship.

CONCLUSIONS

Soil penetration resistances can be adjusted for changes in water content to aid in the comparison of treatments based on equal water content. Methods were developed for a 5-mm, flat-tipped probe. The method did not extend to the more standard cone-tipped probe presumably because it measures soil penetration resistance in a different manner.

Although the relationships gave high R^2 values, there was scatter in the data. It is probable that including other factors such as organic matter or texture could reduce the scatter.

All equations shown did accurately relate predicted to measured penetration resistances. An increase in the number of parameters did not necessarily increase the fit of the data. However, one of the ratios of penetration resistances versus a function of water contents, eq. 7A, was developed solely from boundary conditions based on field observations. It required no statistical parameters and gave one of the better fits to the data. Its predicted penetration resistances fell closer to the 1:1 ratio line on graphs with measured values than the other equations.

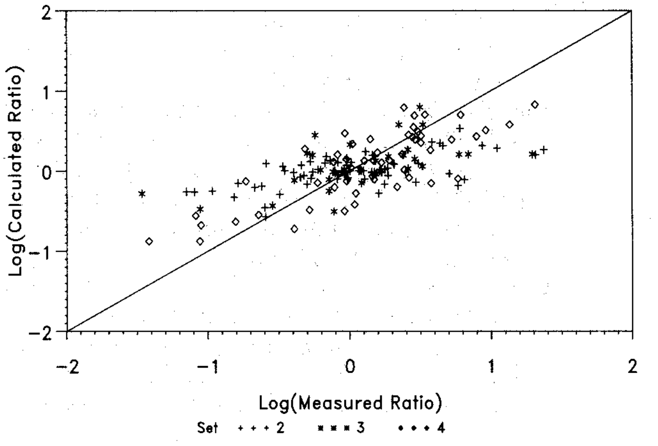

Figure 4–The natural logarithms of the calculated vs. measured ratios of the penetration resistances for eq. 7 using data sets 2, 3, and 4 for the Norfolk soil. The line represents a one-to-one relationship.

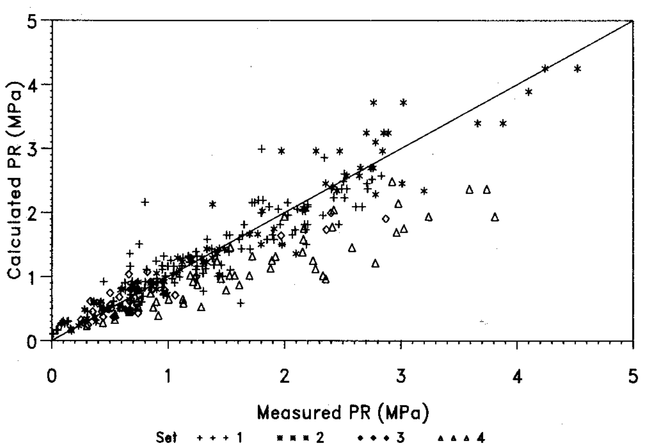

Figure 2–Measured vs. calculated values of penetration resistance for eq. 4 using the four data sets for Norfolk soil. The line represents a one-to-one relationship.

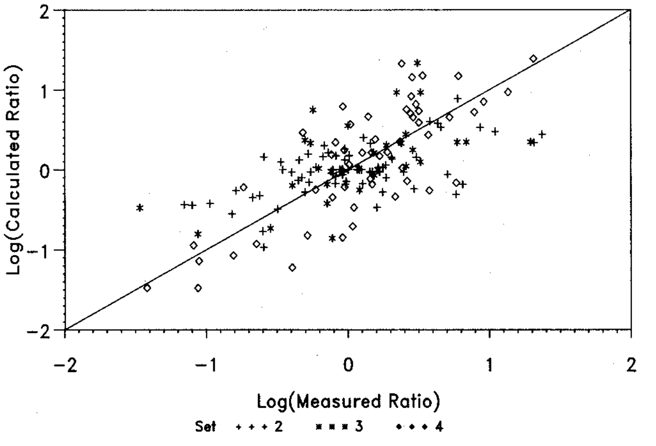

Figure 5–The natural logarithms of the calculated vs. measured ratios of the penetration resistances for eq. 7A using data sets 2, 3, and 4 for the Norfolk soil. The line represents a one-to-one relationship.

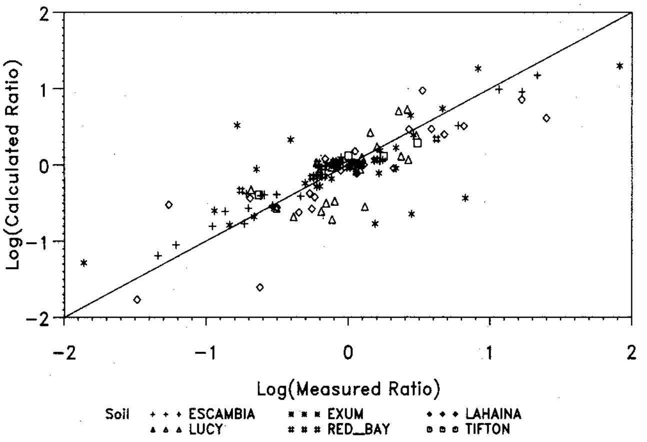

Figure 6–The natural logarithms of the calculated vs. measured ratios of the penetration resistances for eq. 7A using data sets from the soil shown in Table 3. The line represents a one-to-one relationship.

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