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# *IN SITU* STRENGTH, BULK DENSITY, AND WATER CONTENT RELATIONSHIPS OF A *DURINODIC XERIC HAPLOCALCID* SOIL

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**Compaction significantly reduces yield, quality, and profitability of irrigated crops in the US Pacific Northwest (PNW). Compaction assessment is usually done via bulk density measurement, even though crops respond negatively to excessive compaction largely because of root penetration (soil strength) limitations, not because of bulk density *per se*. For most soils, strength is thought to depend primarily on the interaction of water content and bulk density. We hypothesized that the soil strength (expressed as cone index) of an important PNW soil, Portneuf silt loam (*Durinodic Xeric Haplocalcid*), could be predicted for a given bulk density or water content and that it would increase with increasing bulk density and decreasing water content. To test this, the *in situ* cone index, the bulk density and water content profile of a 1.5-ha field was intensively sampled three times over a 2-year period, producing 688 data triplets. These data were used to produce soil water strength-bulk density response surface relationships using robust curve fitting. Cone index relationships were poor when derived from full-profile data sets but improved when data were segregated by depths. When grouped by depth intervals, cone indices of individual layers were always correlated strongly with soil water content, but not always with bulk density. The high calcium carbonate content of this soil was thought to have produced cementation effects on the cone index that varied with prolonged wetting versus prolonged drying. Variability among *in situ* strength penetrations and bulk density cores was also thought to reduce model accuracy. The difficulties inherent in developing the comprehensive relationships of soil strength to bulk density, and the overriding dependency of strength on the dynamic variable of water content, suggest great uncertainty when using bulk density sampling for realistic assessment of overall soil status affecting root restriction or crop performance unless sampling is extensive and the relationships between strength, bulk density, and water content have been intensively documented for an individual soil. (Soil Science 2001;166: 520–529)**

**Key Words: Compaction, bulk density, cone index, penetration resistance, penetrometer, soil quality.**

ALTHOUGH *in situ* soil strength is a very important determinant of crop growth and yield potential (Campbell et al., 1988; Cassel and Nelson, 1979; Grecu et al., 1988; Perumperal, 1987; Sojka et al., 1991), published relationships to bulk density and water content have seldom, if ever, been determined from *in situ* measurements. Reductions in soil strength have led to increased plant growth (Young et al., 1997), improved tilth leading to better soil conditions for growth (Tapela and Colvin, 1998; Sojka et al., 1997), and increased crop yield and quality (Raper et al., 1998; Sojka et al., 1990, 1991, 1997).

Soil characterization and compaction evaluation cannot be regarded as complete without quantification of soil strength. Yet, it is increasingly clear that the relationships between soil

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strength and other soil parameters are not fully understood (Busscher et al., 1997). The situation is complicated by the variability in soil strength and the number of soil properties found to affect it (Cassel et al., 1978; Tsegaye and Hill, 1998). Soil properties affecting strength include texture and organic matter content (Spivey et al., 1986), water content (Ayers and Perumperal, 1982; Busscher et al., 1997; Lehrsch et al., 1982), bulk density (Taylor and Gardner, 1963; Camp and Lund, 1968; Mirreh and Ketcheson, 1972), cementation (Poch and Verplancke, 1997), and profile soil property variation (Cassel et al., 1978).

Sojka et al. (1991) found a strong correlation between mean profile soil strength and corn (*Zea mays* L.) yield on Norfolk loamy sand, a southeastern Coastal Plain Paleudult. On similar Coastal Plain soils, Sene et al. (1985) found no correlation between corn yield and soil strength *per se,* but where subsoiling resulted in ped mean weight-diameters less than 6 mm, yield was improved. Of the various dynamic soil properties, water content causes the most rapid temporal and spatial changes in soil strength because of rainfall or irrigation, infiltration, plant water uptake, evaporation, drainage, and the interaction of water content with other soil parameters.

As a result of these difficulties, few of the published relationships of soil strength to other basic soil properties, such as water content, texture, or bulk density, have been derived from *in situ* measurements. Most studies have relied on measurements using soil cores prepared or manipulated under laboratory conditions (Spivey et al., 1986; Bengough et al., 1997) or undisturbed cores brought into the laboratory from the field (Poch and Verplancke, 1997; Becher, 1998) to relate strength measured on the cores to other soil properties. These reports have used various measures of soil strength.

The most common *in situ* measure of soil strength, and one that is often related to crop performance, is cone index (CI), the ratio of the force required to push a metal cone through the soil to the cone's basal area (Davidson, 1965). *In situ* CI measurements are commonly made using various types of recording ASAE standard cone penetrometers (ASAE, 1996). Nevertheless, soil strength is rarely reported with soil water content at the time of measurement or with calibration to or assessment of the influence of other *in situ* properties such as bulk density or other soil characterization parameters. We hypothesized that *in situ*-determined soil strength, as determined by recording penetrometer assessment of profile cone index, would increase with increasing bulk density and decreasing water content; we also postulated that these field-derived properties could be used to develop a mathematical relationship that would predict soil strength (cone index) from bulk density and water content and would reflect field soil property interactions.

No *in situ*-determined relationships of soil strength (cone index) to bulk density and water content were available for *Durinodic Xeric Haplocalcid* soils. These soils occupy large areas of the US Pacific Northwest. They are highly productive, but they are prone to compaction, which can be exacerbated by cementation effects during prolonged drying. To relate cone index to bulk density and water content, we sampled a 1.5-ha field of Portneuf silt loam intensively at three sampling times during a 2-year period and tested our hypothesis. We were also interested in determining whether that relationship differed with soil depth.

## MATERIALS AND METHODS

The experiment was conducted from 1988 through 1990 on a 1.5-ha field of Portneuf silt loam (coarse silty, mixed, superactive, mesic *Durinodic Xeric Haplocalcid*) at 42° 33′ N latitude and 114° 21′ W longitude, elevation 1210 m, 1.2 km northeast of Kimberly, Idaho. The experimental site had a uniform 1% southerly slope with no east-west slope. The Portneuf soil formed in loess covering a fractured basalt plain. It has a calcium carbonate- and silica-enriched B horizon. Profile distribution of soil properties is presented in Table 1, after McDole and Maxwell (1987), with relevant profile structural descriptions from their publication below:

**AP–0 to 0.28 m**–Silt loam; weak fine granular structure; slightly hard when dry, friable when moist, slightly sticky and slightly plastic when wet; few very fine to medium roots; many fine tubular pores; 12% $CaCO_3$; moderately alkaline; abrupt smooth boundary.

**Bkq1–0.28 to 0.66 m**–Silt loam; massive; extremely hard when dry, very firm when moist, nonsticky, and nonplastic when wet; 45% durinodes 12 to 25 mm diameter, which are very hard when dry, very firm when moist; few very fine roots matting on ped surfaces 0.28 to 0.38 m; 18% calcium carbonate; moderately alkaline; clear smooth boundary.

**Bkq2–0.66 to 0.94 m**–Silt loam; massive; slightly hard when dry, friable when moist, nonsticky and nonplastic when wet; 20% oblong durin-

TABLE 1

Portneuf silt loam properties sampled 290 m from study site (McDole and Maxwell, 1987)

| Horizon | Depth | Particle size distribution Sand | Silt | Clay | Bulk density | Organic C | CEC | Soil 1:1 Water | EC | $CaCO_3$ Equiv. |
|---|---|---|---|---|---|---|---|---|---|---|
| | m | % | % | % | Mg $m^{-3}$ | g $kg^{-1}$ | $cmol_c$ $kg^{-1}$ | pH | S $m^{-1}$ | % |
| Ap | 0–0.28 | 14 | 66 | 20 | 1.48 | 10 | 18.6 | 8.0 | 0.07 | 2 |
| Bk | 0.28–0.58 | 8 | 71 | 21 | 1.45 | 6 | 13.7 | 8.4 | 0.05 | 24 |
| Bkq1 | 0.58–1.02 | 16 | 80 | 4 | 1.43 | 4 | 11.7 | 8.5 | 0.05 | 21 |
| Bkq2 | 1.02–1.37 | 18 | 81 | 1 | 1.42 | 2 | 12.7 | 8.5 | 0.05 | 16 |

odes 12 to 25 mm diameter, which are very hard when dry, very firm when moist; few microtubular pores; 15% $CaCO_3$; moderately alkaline; clear smooth boundary.

**C1–0.94 to 1.98 m**–Very fine sandy loam; weak, medium subangular blocky structure; soft when dry, friable when moist, nonsticky and nonplastic when wet; few microtubular pores; strongly alkaline; 8% $CaCO_3$.

The mineralogy of this site was described by Lewis et al. (1991). Their analysis of the coarse clay fraction showed that the proportion of smectites in the A horizon varied from 0 to 14%, and in the Bw, Bk, and C1 horizons the proportion varied from 15 to 23%. Illite in the A horizon varied from 57 to 68%, and in the Bw, Bk, and C1 horizons it varied from 44 to 56%. Kaolinite varied from 0 to 15% in the A and Bw horizons, and from 16 to 22% in the Bk and C1 horizons. Vermiculite was not found in the A horizon, and it's content varied from 1 to 15% in remaining horizons.

The field had an approximately 80-year history of irrigated continuous cropping in rotations that frequently included small grains, corn, and dry beans (*Phaseolus vulgaris*) and with annual fall plowing and spring disking. In 1986 and 1987, the west half of the study site (Blocks 1 and 2) was cropped to corn and the east half (Blocks 3 and 4) to sugar beet (*Beta vulgaris* L.). In 1988 and 1989, the site was completely in corn. Natural variation at the time of sampling provided the range in water content among samples subsequently removed from the field.

To encompass a reasonably wide range of soil conditions, bulk density and penetration resistance were measured three times under varying field conditions. The first sampling was from April 26 to May 9, 1988, after fall moldboard plowing and spring secondary tillage. The second sampling was October 25–28, 1988, after corn harvest but before fall tillage. The third sampling was April 9–12, 1990, on ground undisturbed over winter from the preceding 1989 corn crop (amid stover). Data from these three samplings were combined to determine relationships among soil bulk density, water content, and strength.

In Spring 1988, a 54-mm-diameter hand coring tool was used to take volumetric soil samples at depths of 0 to 60 mm at each sampling site. In Fall 1988 and Spring 1990, volumetric samples were taken from 0 to 35-mm depths using a 51-mm-diameter hand coring tool. At each site, subsoil samples were obtained from one core using a tractor-mounted, hydraulically driven soil probe 32 mm in diameter. Surface samples were taken in triplicate at each sampling site, separating subsamples by a minimum of 0.15 m to avoid compaction from neighboring corings. All surface and subsoil samples were taken between the wheel tracks of the tractor-mounted soil corer. Subsoil corings were also offset from surface sampling areas to avoid measurement artifacts of the surface procedure.

In Spring 1988, 48 cores were taken from the subsoil at 2.9-m spacing along each of two east-west transects across the site. At the same time, eight cores were also taken about 4.1 m apart from each of four north-south transects across the site. Twelve additional cores were taken at pre-selected locations along the previously sampled transects in the field. In Fall 1988, 20 cores were taken from pre-selected locations along each of the two east-west transects sampled earlier that spring.

In Spring 1990, 12 cores were taken from pre-selected locations along each of the two east-west transects. Also at that time, four cores, 8.1 m apart, were taken from each of the four north-south transects sampled in Spring 1988. This identical protocol was followed during each of the three seasonal samplings. In each case, the sampling transects were offset about 2 m to avoid previous corings. All subsoil cores were taken as continuous cores, separating depth increments from the continuous core. Each continuous core was examined to ensure that core length corresponded to core depth to avoid using cores compacted by insertion of the core-sampler. Cores compacted more than 6 mm by the sampler were discarded, and a new coring was done in close proximity to obtain a core not measurably compacted by the sampling process.

Subsoil samples were taken at depths of 0.15 to 0.30 m, 0.30 to 0.45 m, and 0.45 to 0.60 m. Once cores were removed from the profile, the remaining holes were loosely filled with surface soil to minimize effects on subsequent field observations. Soil samples were weighed, oven-dried at 105 °C, and weighed again to determine bulk density and water content.

For the surface (i.e., uppermost depth increment) of each sampling site, the measured soil strength was matched with the average bulk density, and water content was measured on the three surface soil samples.

Immediately after each coring, the soil profile's penetration resistance was measured using a hand-operated, Carter-type ASAE standard recording cone penetrometer with a 13-mm-diameter, 30° solid angle cone-tipped probe (Carter, 1967). This device records analogue penetration data on index cards. Three penetrations were made in the vicinity of (0.15 to 0.20 m away from) each extracted core. The penetrometer recorded resistance down to 0.60-m depths. Three probings were made in each plot along the nonwheel-track mid row. Data from each probing were digitized into a computer using the method of Busscher et al.(1985). Analogue resistance tracings were digitized at 0.05-m-depth increments for each of the three traces and averaged to give a single value. Soil water contents, taken at 0.15-m-depth intervals, were associated with the corresponding cone index readings at that depth.

Soil strength data were means of three penetration resistances for a given depth increment at a given transect location. Mean strength parameters were regressed against the mean bulk density and/or gravimetric water content for all depths together and for each depth increment.

We interpreted the data by performing regression analyses using TableCurve 2D version 3.05 and TableCurve 3D version 1.0 (software marketed by Jandel Scientific of SPSS Inc., Chicago, IL). TableCurve 2D fits data to approximately 3500 equations. TableCurve 3D fits data to more than 453 million linear equations and 170 nonlinear equations. The equation forms examined for best fit included higher powers of $x$ and $y$ and use of log and semi-log relationships. Obviously, most equations did not reasonably fit the data. To select appropriate equations, we placed emphasis on fits with high correlation coefficients and those that were accomplished using simple and physically reasonable curve forms. Some curves fit the data but had little or no physical basis and were merely a tortuous adaptation to the data. Such solutions were ignored. Data were analyzed both as a whole and as segregated by depth. Examination of individual data points was performed to eliminate questionable data and outliers that were regarded as physically impossible. Of a total of 688 data triplets, only 35 were excluded, of which 25 were excluded because of off-scale, high strength values that could not be interpreted. The residuals of the equations retained were examined for normal distribution to satisfy the assumptions of regression analysis using the SAS routine Proc Univariate. All the equations retained and presented in tables met the assumption of normally distributed residuals. This same protocol was used to examine a variety of two-dimensional relationships with volumetric water content and strength. These relationships produced poorer fits than for gravimetric water content. Volumetric water content cannot be used to produce three dimensional relationships with bulk density inasmuch as bulk density is represented both as a separate parameter and as part of the water content variable.

## RESULTS AND DISCUSSION

Mean soil bulk densities, strengths (as cone index), and water contents as a function of depth (Table 2) show that wide ranges of compaction and field water status were encountered among sampling times and depths. No attempt was made to assume a single appropriate curve form or model to fit the data, but rather all equations producing reasonably good fits of the data were considered and then further screened, eliminating complicated tortuous curve fits that were unlikely to relate to physical reality. This generally left only a few simple curve forms that adequately fit the data. If $R^2$ values were similar among curve forms, the mathematically simplest curve form was chosen to represent the data. If curve forms were similar in mathematical complexity but varied in $R^2$ value, the form with the highest $R^2$ value was chosen to represent the data.

TABLE 2

Mean and standard deviations (SD) for bulk densities (BD), water contents (WC), and soil strengths (CI) for the various dates of measurement.

April 1988

| *Depth* | *BD* | *SD* | *WC* | *SD* | *CI* | *SD* |
|---|---|---|---|---|---|---|
| *m* | *Mg m$^{-3}$* | | *kg kg$^{-1}$* | | *MPa* | |
| 0–.08 | 1.15 | 0.06 | 0.122 | 0.023 | 0.19 | 0.21 |
| 0.15–0.30 | 1.32 | 0.08 | 0.176 | 0.017 | 0.87 | 0.54 |
| 0.30–0.45 | 1.53 | 0.06 | 0.183 | 0.024 | 4.96 | 1.47 |
| 0.45–0.60 | 1.57 | 0.05 | 0.160 | 0.026 | 4.05 | 3.07 |

October 1988

| *Depth* | *BD* | *SD* | *WC* | *SD* | *CI* | *SD* |
|---|---|---|---|---|---|---|
| *m* | *Mg m$^{-3}$* | | *kg kg$^{-1}$* | | *MPa* | |
| 0–.08 | 1.24 | 0.06 | 0.073 | 0.013 | 0.62 | 0.57 |
| 0.15–0.30 | 1.33 | 0.08 | 0.117 | 0.020 | 3.58 | 0.71 |
| 0.30–0.45 | 1.50 | 0.04 | 0.118 | 0.038 | 7.55 | 1.55 |
| 0.45–0.60 | 1.53 | 0.05 | 0.107 | 0.036 | 8.51 | 0.52 |

April 1990

| *Depth* | *BD* | *SD* | *WC* | *SD* | *Avg* | *SD* |
|---|---|---|---|---|---|---|
| *m* | *Mg m$^{-3}$* | | *kg kg$^{-1}$* | | *MPa* | |
| 0–.08 | 1.15 | 0.07 | 0.070 | 0.012 | 0.22 | 0.10 |
| 0.15–0.30 | 1.44 | 0.16 | 0.148 | 0.009 | 0.75 | 0.28 |
| 0.30–0.45 | 1.55 | 0.20 | 0.192 | 0.017 | 3.91 | 1.35 |
| 0.45–0.60 | 1.53 | 0.05 | 0.178 | 0.020 | 8.06 | 1.51 |

At times, analysis was complicated by penetration resistance measurements in small portions of the profile that did not reasonably reflect adjacent soil matrix penetration resistance values. For example, if the recording penetrometer encountered a macropore, weakness zone, or root channel, it penetrated otherwise hard soil for a short depth increment without registering a cone resistance representative of passing through the soil mass. When these midprofile ultra-low readings were identified, they were eliminated from further analysis. Similarly, when cone indices spiked abruptly, indicating an encounter with a stone or other nontypical midprofile ultra-high strength feature, the readings were eliminated from further analysis.

Mean soil strengths for all bulk density sampling intervals were initially regressed against water content and bulk density, using all values from all depths (Table 3). The relatively low $R^2$ of 0.45 prompted further regression analyses by individual depth increments, which are also presented in Table 3. Further analysis (discussed below) examines various groupings of depth increments.

TABLE 3

Evaluation of fit of three dimensional and two dimensional regressions with regression coefficient ($R^2$) and standard error (Se). Three dimensional fits regress mean soil strength (MPa) against both water content (kg kg$^{-1}$) and bulk density (Mgm$^{-3}$). Two dimensional fits regress soil strength against water content

| | Mean strength (MPa) | | | | | |
|---|---|---|---|---|---|---|
| | Three dimensional | | | Two dimensional | | |
| Depth (m) | $R^2$ | SE | n | $R^2$ | SE | n |
| 0–0.08 | 0.05 | 0.23 | 174 | 0.05 | 0.28 | 174 |
| 0.15–0.30 | 0.60 | 0.59 | 170 | 0.68 | 0.53 | 170 |
| 0.30–0.45 | 0.42 | 0.98 | 144 | 0.38 | 1.00 | 144 |
| 0.45–0.60 | 0.09 | 3.06 | 165 | 0.03 | 3.17 | 165 |
| All depths | 0.45 | 2.14 | 653 | 0.10 | 2.73 | 653 |

The regression of soil strength, bulk density, and water content using all data triplets (Fig. 1, Table 4) showed a strong increase in cone index with increasing bulk density but only a small decrease of cone index with water content. This is indicated by the differences between slopes in Fig. 1, where soil strength in MPa decreased with an increase of water content, expressed as kg of water per kg of soil, with a slope of −0.11, while soil strength increased with an increase of bulk density, as Mg $m^{-3}$, with a value of 10.9.

Because the Portneuf soil often has only a shallow Ap horizon and pronounced zones of high bulk density below it, we felt that it was appropriate to segregate the data into groups by depth intervals. Bulk density was determined separately for the 0–0.08, 0.15–0.30, 0.30–0.45, and 0.45–0.60-m depth intervals. Data from each interval were subjected to the same regression analysis of mean soil strength against bulk density and water content as was used for the complete profile. The relationships for the 0.15–0.30 and 0.30–0.45-m depth intervals were as good as or better than the overall profile (Table 3). However, the relationships for 0–0.08 m and 0.45–0.60 m showed almost no cone index dependence on either bulk density or water content.

For the surface samples, the low bulk densities in April 1988 and April 1990 (Table 2) may have prevented the kinds of matrix effects necessary to produce water content- or bulk density-related changes in strength (i.e., surface soil was loose, unconsolidated, and without a cohesive matrix). Water-mediated changes in interaggregate and interparticle bonding and cohesion account largely for water content effects on soil strength. In loose, freshly tilled soils, the aggregates are separated and do not interact significantly, even with changes in water content or further reductions in bulk density. Thus, variation of water content at such low mean bulk density values or further reductions in bulk density below some threshold value show little or no effect on soil strength. Bulk densities of the surface samples were largely on the asymptotic portion of an idealized soil strength response curve, where, at some critical bulk density, strength approaches zero.

At the lowest depth, some insensitivity arises from the inability of the penetrometer to penetrate smoothly the hard subsoil of the Portneuf series. The penetrometer frequently reached its maximum recordable value. The B horizon of Portneuf soil commonly contains 20% calcium carbonate equivalent, and in some places it has areas of partial cementation that develop high strength when dry and do not soften immediately when wetted. In a gypsum-rich soil, Poch and Verplancke (1997) found, through multiple regression analysis, that although the degree of gypsum cementation did not significantly affect soil strength as a separate factor, it was positively correlated with penetration resistance, along with water content and bulk density. Determination of soil strength in the Portneuf soil using a recording cone penetrometer may be confounded, in part, by calcium carbonate cementation, possibly in a hysteretically variable fashion. This may occur where the degree of cementation at a given water content differs in relation to whether the soil has been dry and only recently become wet or if the soil has been wet long enough to partially dissolve the calcium carbonate cementation.

Although bulk density was a greater determinant of soil strength than was water content, when analyzing the entire profile as a single data set (Fig. 1), this did not hold true when analyzing the data by depth interval. When the 0.15–0.30 and 0.30–0.45-m depths were analyzed as discreet layers, soil water content alone often explained as much, or even more, variation in cone index than did the combination of bulk density and water content (Table 3). This is likely because the variation of bulk density at a given depth was relatively small (with low standard deviations) compared with the variation of water content.

For the 0.15–0.30-m depth, the best three-dimensional fit of mean soil strength (regressed against water content and bulk density) produced an $R^2$ of 0.60 (Table 3). Although this was an improvement over the three-dimensional equation

TABLE 4

Equations used for the regression calculations. Equation forms and constants used to produce the data in Table 2, where z = cone index (MPa), x = water content (kg $kg^{-1}$), and y = bulk density (Mg $m^{-3}$)

| *Depth (m)* | Three dimensional | | | | Two dimensional | | |
|---|---|---|---|---|---|---|---|
| | *Equation* | a | b | c | *Equation* | a | b |
| 0.15–0.30 | $z = a+bx^{-1}+cy$ | −2.29 | 66.6 | −0.56 | $z = ax^b$ | 0.0003 | −3.16 |
| 0.30–0.45 | $z = a+bx^{-1}+cy$ | −1.44 | 117 | −0.42 | $z = a+bx$ | 11.8 | −0.37 |
| All depths | $z = a+bx+cy$ | −12.1 | −0.11 | 10.9 | $z = a+bx$ | 0.78 | 0.23 |

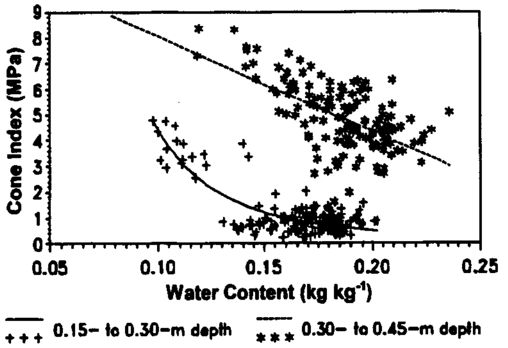

Fig. 1. Soil Strengths (cone indices) for all depth intervals as a function of water content and bulk density.

for the full profile data set, an $R^2$ of 0.68 was obtained for mean soil strength as a function of water content only, using a simple power function (Table 4). Figure 2 presents the two-dimensional scatter and best fit regression lines for cone index and water content at the 0.15–0.30 and 0.30–0.45-m depths. These plots show that reasonably good prediction of strength can be accomplished with water content alone, especially if discreet relationships for a given depth increment are used. These plots also demonstrate that bulk densities would have had to include values at a far more compact (higher) range to discriminate the bulk density role adequately in determining strength in this soil, and that portion of the bulk density range is simply not encountered in normal field cropping situations on the Portneuf soil. On this calcareous soil, over this range of bulk densities (which is representative of that found in cropping situations), water content alone can predict soil strength well.

For the 0.30–0.45-m depth, the best three-dimensional fit of mean soil strength produced an $R^2$ value of 0.42 (Table 3). The same form of simple two-dimensional power function used in the 0.30–0.4-m data produced an $R^2$ of 0.38. The addition of bulk density to the regression did not improve it substantially.

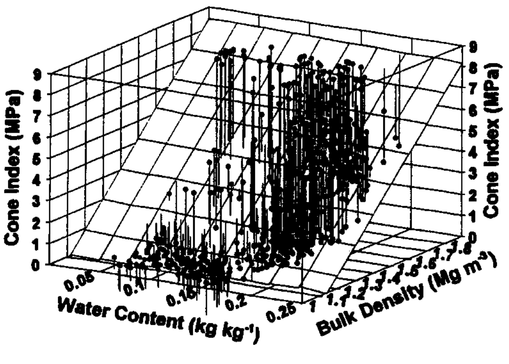

Fig. 2. Soil Strengths (cone indices) for depth intervals 0.15 to 0.30 m and 0.30 to 0.45 m as functions of water contents.

The extremely low $R^2$ values for the 0.45–0.60-m depth interval relate to the failure of the penetrometer to separate high strength values adequately. In the very high strength range (>6 MPa), the ability to maintain uniform insertion speed and force using a hand held penetrometer is greatly diminished, as is, possibly, instrument sensitivity. Furthermore, the analogue recordings of "spikes" of strengths, approaching a similar high value across a range of water contents and bulk densities, may have included artifacts that should have registered much higher values than the instrument was capable of recording. We attempted to identify the data points affected by this artifact of the measurement process by eliminating all the nearly identical high values that were indicative of instrument pegging. However, it is difficult to know when values close to the limit are also being affected. If there was some amplitude in the cone indexes near the upper limit of the maximum strength data, we did not delete those data points. However, it is apparent that our attempts to intervene objectively in the data were not able to unmask those out-of-range data points consistently for all depth increments.

Cassel et al. (1978) noted that water content is a strong determinant of cone index and that individual soil depths also influence interpretation of soil strength. Their study focused on maximum strength values encountered in each penetration, rationalizing that this criteria paralleled the difficulty encountered by roots penetrating a soil profile. The logic of this approach is strongly supported for direct field assessment of soil strength status and field treatment effects at a point in time and space affecting a crop. However, it does not seem to overcome consistently the challenge of empirically modeling the relationship of strength to bulk density and water content using *in situ* measurements, where variability among sampling points likely affects each data triplet differently. In this scenario, water content variation over short distances is probably small, on average, especially in a field at rest after or before a growing crop. Much larger variation is possible in bulk density, where traffic and tillage effects can greatly change bulk density in a few centimeters of lateral displacement. This is in addition to the possible variation in the relationship between bulk density and strength *per se*. Correlation also improved in our study when data were segregated by horizon, which likely reflects a number of soil property changes collateral with horizonation. Taken together, these variations reflect the large scale field variation in natural and tillage-induced soil structural relationships, water content history (hysteresis), and cementation status dominant on a given sampling date for a particular depth, and they may explain why the prediction of soil strength from water content alone was more consistently reliable.

As a final attempt to improve the correlations between bulk density, water content, and strength, we combined triplets from the various combinations of depth increments. For three-dimensional correlations, combining the first three depth increments yielded an $R^2$ of 0.56; however, this relationship showed strength increasing slightly with water content, which did not seem reasonable and may have been an artifact of other soil property differences among the layers affecting strength that were coincidental, in this data subset, with water content at the time of sampling. Combining data from the second two depth increments (0.15 to 0.30 and 0.30 to 0.45 m) produced an $R^2$ of 0.41. In this case, however, the model produces negative strength values at low bulk densities. Water content alone, on a layer by layer basis, still provided a better prediction of soil strength.

Similar groupings were also compared for a two-dimensional analysis of water content effects on strength. Combining the surface three horizons produced an $R^2$ of 0.25 with an equation that predicted an exponential strength increase with increasing water content, the opposite of what might be reasonable. Combining the second and third depth increments had a still poorer $R^2$ of $<0.01$ and also showed increased strength with increasing water content, though less pronounced than for the three top depth increments combined. The individual regressions of these depth increments and their scatter, presented in Fig. 2, make it clear why combining the layers would give an erroneous prediction of strength dependence on water content and make a strong case for development of individual regressions specific to a given depth increment. In this calcareous soil, water content is a good predictor of soil strength in the range of bulk densities likely to be encountered in a field cropping situation if the calibration of water content to strength is specific to specific soil depth increments (and likely related to horizonation).

## CONCLUSIONS

Portions of these data, when segregated by depth, show sensitivity of soil strength to the combined influence of water content and bulk density. However, despite this manifestation in portions of the data set, *in situ*-determined soil strength as CI was usually far more sensitive to water content alone. Some of these results may be because these data were derived from field bulk density cores and *in situ* continuous recording penetration resistance determinations. It may not be possible to detect the dependency of the *in situ*-determined cone index on bulk density with greater sensitivity using soil cores extracted from a soil profile because of structural and pore variability affecting both penetration resistance and water retention. The relationship of strength to bulk density is affected by the precision of the bulk density measurement. It is difficult to measure bulk density with the same degree of precision and discrimination as is possible for soil strength, even when samples are taken with great care. The bulk density sample also integrates a soil volume that differs from the one which is the effective matrix actually affecting the strength measurement. Furthermore, the bulk density measurement for *in situ* sampling, is, of necessity, slightly displaced laterally from the point of penetration. Bulk density can vary abruptly over short distances of a few centimeters as a result, for example, of traffic, tillage, or irrigation-furrow consolidation. These variations could easily impair the accurate correlation of bulk density with *in situ*-determined strength. *In situ* water content is less likely to vary as much over short lateral distances as bulk density, particularly in a resting field between active crop growth (and irrigation) seasons. Thus, *in situ* measurements of strength are more likely than bulk density to be sensitive to nearby measurement of water content.

Data from this study reflect characteristics similar to other reported findings (Campbell et al.,1988; Busscher et al., 1997) on taxonomically different soils (Ultisols). It should be recognized that these data from a *Durinodic Xeric Haplocalcid* also represent a situation where calcium carbonate and cementation may play a significant role in determining soil strength. The determination of water content *per se* may not be enough to describe adequately the effect of water on soil strength because of the interaction of the duration of wetness and/or hysteresis effects.

The number of samples in this study was very large. We are unaware of a larger published data set, especially for *in situ*-derived soil strengths. However, robust correlations were difficult and sometimes impossible to obtain. This should serve as a caution against using relatively sparse numbers of field determinations of either bulk density or soil strength, especially without detailed examination of their interrelationships, for interpretation of soil status (or so-called "soil quality") based on penetration resistance, cone index, bulk density or other compaction indices. Our study shows that these relationships may be ambiguous, particularly on soils where chemical cementation may affect strength. Furthermore, our study at least suggests that cementation may affect soil strength differently if measured on a wetting cycle (particularly following prolonged drying) versus a drying cycle.

Many soils and cropping systems could be managed better if the relationship between soil strength and water content and bulk density was well quantified. However, our data suggest that labor, cost, and time requirements for sufficient samples needed to characterize this interrelationship adequately may be prohibitive if it is to be accomplished with precision adequate to characterize the peculiarity of specific individual soils. This limitation would be compounded by the need to spatially characterize and map variations in the relationship on production-sized fields for use in management. Our study shows that even when sufficient data are collected to produce the many data points, considerable judgment is needed to interpret relationships from such a data set. This raises the question whether the simpler strength-bulk density-water content relationships that appear in the literature, derived from sparse measurements on disturbed cores or packed cores, represent accurately the nature of the relationships *in situ*. Our data marks a beginning of such characterization for the Portneuf soil, but it points to the need for further investigation to help resolve the quandaries our paper has raised.

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