USE OF CONE PENETROMETER DATA TO EVALUATE PRIME FARMLAND ROOTING MEDIA[1]

Robert E. Dunker, Scott L. Vance, Charles L. Hooks, and Robert G. Darmody[2]

Abstract: Reclamation of prime farmlands after mining includes various methods of excavation, transportation, and placement affecting the physical properties of the reconstructed soil. Poor soil physical condition has proved to be the most severe and difficult limiting factor in the reclamation of prime soils. Deep tillage has become a practice accepted by the mining industry as a final step in the reclamation process for row-crop acreage. The penetrometer can be an important management tool for the mine operator to assess levels of soil compaction resulting from soil reconstruction and to evaluate the effectiveness and depth of deep tillage operations. Soil strength measurement with the deep profile penetrometer is shown to be a viable method in assessing long term yield potential of mined land when chemical and plant nutritional variables are not yield limiting.

Additional Key Words: soil strength, mine reclamation.

Introduction

Soil horizon replacement required by Illinois law (Illinois Dep. of Mines and Minerals 62 Ill. Adm. Code Part 1823) mandates the excavation of the natural topsoil and subsoil or suitable rooting material prior to the mining operations. The soil horizons are successively replaced to a total depth of 122 cm (48 in) over the graded mine spoil. The physical condition of a reconstructed soil will vary due to both the pre-mine soils used for construction and to the methods of excavation and placement (Vance et al. 1987). Poor soil physical condition has been identified as the major limiting factor affecting crop performance on mined land in Illinois (Dunker et al. 1992a, Hooks et al. 1992). The Illinois Department of Mines & Minerals (IDMM) allows the use of deep tillage to ameliorate subsoil compaction created in mine soil reconstruction and has become an accepted practice by the industry in the Illinois coal basin. IDMMM classifies deep tillage as any tillage to a depth below 45 cm (18 in) and since it is a non-standard agricultural tillage practice, it can be applied only once before the mandatory productivity testing period. If deep tillage is to be a viable method for achieving productivity restoration standards for mined land, effects must be immediately measurable and permanent. Yield effects of tillage depth and persistence of tillage effects has been studied (Dunker et al. 1992b, Dunker et. al. 1993) using soil strength measured with a deep profile cone penetrometer as the parameter by which tillage depth, effectiveness, and longevity is evaluated. Soil strength averaged over 23 to 112 cm (9 to 44 in) soil depth was significantly correlated with six year mean corn yields (-0.97**) and four year mean soybean yields (-0.92**).

Parameters commonly used to relate the mechanical impedance of soil to root growth are bulk density and penetrometer resistance. Cone penetrometers have been used to measure soil strength in agricultural and engineering applications for many years. Soil penetrability is a measure of the ease with which an object can be pushed or driven into the soil. Soil factors influencing penetration resistance are matric potential (water content), bulk density, soil compressibility, soil strength parameters, soil structure, and soil texture (Bradford 1986).

Soil bulk density, the ratio of the mass of dry solids to the bulk volume of soil, is commonly used to characterize soil compaction and soil structure. Since bulk density relates to the combined volumes of the solids and pore spaces, any factor that influences soil pore space (such as compaction) will affect bulk density. Fine-textured soils such as silt loams, clays, and clay loams generally have lower bulk densities than sandy soils. The fine-textured

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[1] Paper presented at the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29, 1994.

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Proceedings America Society of Mining and Reclamation, 1994 pp 38-47
DOI: 10.21000/JASMR94030038

https://doi.org/10.21000/JASMR94030038

soils tend to be organized in porous structural units (peds), resulting in high total pore space and a low bulk density. Sandy soil particles may pack closely together, which results in higher bulk densities.

Some studies have supported the concept of a critical bulk density beyond which roots cannot penetrate as the physical parameter that will best characterize root growth (Veihmeyer and Hendrickson 1948, Zimmerman and Kardos 1961). Other research (Taylor and Gardner 1963, Taylor and Burnett 1964) has suggested that penetrometer resistance, not bulk density, may be a better predictor of root system performance. This may be especially true for mine soils because during the reclamation process, large blocks of naturally compacted soil may remain undisturbed when replaced. High traffic reclamation systems will cause additional compaction effects on these soil materials, resulting in a high strength, low porosity soil. In ameliorating this compaction with deep tillage, shearing action creates large void spaces within the compacted blocks. Bulk density, which gives a very good estimate of porosity within a measured soil unit, may tend to underestimate the effects of large voids on root system performance. Uhland cores, a method that extracts small soil units to estimate bulk density, may not contain the large voids in proportion to the total soil volume. Soil strength, as measured by a penetrometer, may more accurately reflect resistance encountered by roots.

Numerous studies have described the effects of mechanical impedance on root growth and crop yield (Taylor 1971, Russell 1977, Kahnt et al. 1986, Boone and Veen 1982, Shierlaw and Alston 1984). Taylor and Gardner (1963) and Taylor and Burnett (1964) have reported that penetrometer resistance values greater than 2 MPa (290 psi) may result in severe root impedance, and at 2.6 MPa (380 psi) root elongation will be severely restricted.

Development of Cone Penetrometer for Mined Land

The cone penetrometer was originally developed by the U.S. Army Corps of Engineers and was designed for hand operation (Bradford 1986). Hand-operated penetrometers will work well for measuring resistance at near surface depths. However, accuracy is limited by the ability of the operator to maintain constant pressure, and the applied force is limited by the strength of the operator. Most hand-operated penetrometers utilize a proving ring and dial gauge requiring a second person to read the dial at the operators vocal command. Electronic load-measuring recording devices have been developed to replace the proving ring with either a linear displacement transducer or a strain-gauge load cell (Prather et al. 1970, Anderson et al. 1980). Vehicle-mounted systems were developed and used by Williford et al. (1972), Cassel et al. (1978), and Smith and Dumas (1978). These vehicle systems were designed to measure near-surface tillage effects on natural soils.

A constant rate deep profile recording penetrometer was developed to serve the need to quantify physical properties of reconstructed soils (Hooks and Jansen 1986). This device, capable of recording soil strength to a depth of 112 cm (44 in), utilizes a modified tractor-mounted hydraulic (Giddings) coring machine. This system uses a 645 mm^2 (1 in^2) 0.525 rad (30 degree) right circular cone and operates at a constant penetration rate of 3 cm sec^{-1} (1.2 in sec^{-1}) (ASAE Std 313.2).

A modification of the original device is currently under development and testing. It incorporates two penetrometer masts center mounted on a small low ground pressure articulated tractor (Hooks et al. 1993). The electrohydraulic operating system is remotely controlled by a laptop computer in the tractor cab. Data from two samples taken to a depth of 122 cm (48 in) can be simultaneously collected and displayed to the operator. This system has reduced manpower requirements while increasing productivity of data collection over the previous system.

Cone penetrometer data of minesoils is taken in the spring, when soils are uniformly moist and near field capacity. This minimizes the effects of variable soil moisture on soil penetration resistance. Sampling at each location consists of paired samples taken to a depth of 112 cm (44 in). The data are typically recorded as average penetrometer resistance of a given depth segment. In University of Illinois studies on soil strength effects on crop yields, five, 23 cm (9 in) depth segments are used for data analysis (Vance et al. 1992).The first segment (0 to 23 cm) is not used in the data analysis. This segment is easily altered by tillage and its moisture content may be highly variable due to differences in surface topography.

From an engineering or physical approach, soil strength is a real and true value that should be predictable within given values of moisture content, texture, density, etc. In evaluating reclamation treatments, soil strength may be approached as a relative value that is a composite of the effects of moisture content, texture, density, etc. Moisture content, particularly when below field capacity, is a major factor in soil strength. However, when penetrometer data is collected in the spring when soils are most uniformly moist, we consider minor differences in soil moisture between adjacent reclamation treatments to be a reflection of the soil/environment interaction and a valid part of the composite value "soil strength."

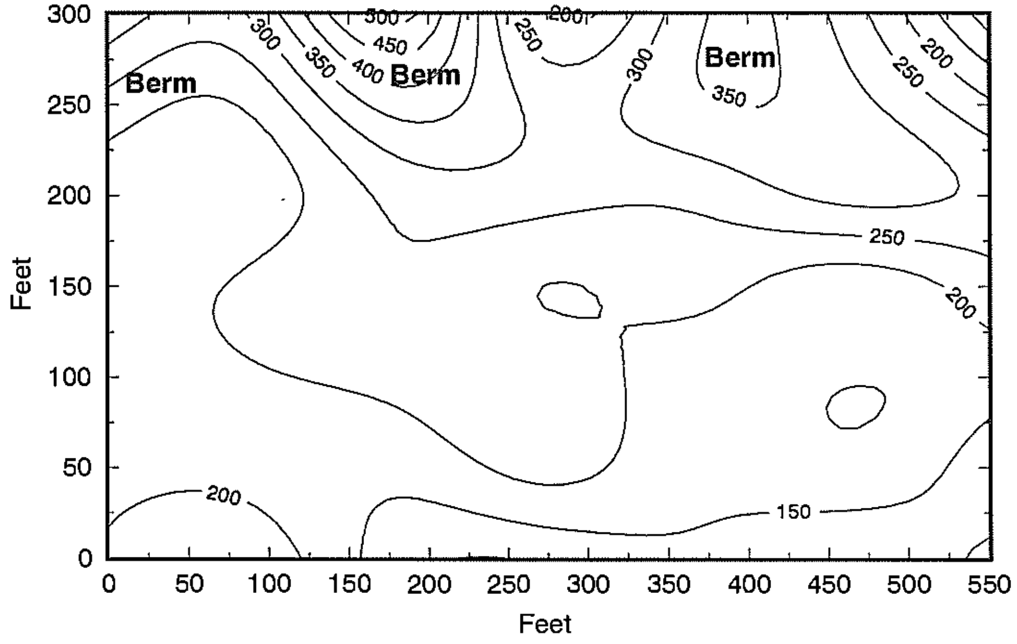
Application as a Management Tool

Soil strength data are an excellent parameter for use in reclamation planning and evaluation. Use of a deep profile recording penetrometer is a relatively fast and nondestructive method of assessing compaction effects of reclamation operations. For example, the reclamation plan at one mine in Illinois specifies moving topsoil with a cross-pit wheel to create topsoil storage berms on the graded rooting media. This mine had previously used a scraper haul system to transport and replace topsoil, but unacceptable compaction resulted from excessive wheel traffic. The topsoil berm system eliminates or reduces wheel traffic by use of low ground pressure dozers to push topsoil from the berms. The operator was still concerned about the effects of placing large topsoil berms on the graded rooting media. To assess compaction beneath the berms, soil strength levels were measured with a cone penetrometer to a depth of 112 cm (44 in) on a 15 by 15 m (50 by 50 ft) grid where berms had been located before topsoil was replaced. Profile data were segmented by depth and contour plotted to provide a series of maps of the area (figs 1-2). Investigation of aerial photography revealed that part of three berms had been located along the north (top) area of the tract, and a small one may have extended into the southeast (bottom left) of the area. The effects of the large berms are evident on every depth segment map. However, the effect of the smaller berm is detected only in the 45 to 68 cm(18 to 27 in) and 68 to 91 cm (27 to 36 in) depth segments. Penetrometer data in this format allows the operator to locate compaction problems and to make decisions on the number and size of berms placed in an area.

One of the most significant advances in reclamation of prime farmland soils in the Midwest has been the development of deep tillage technology. The degree and depth of compaction in mine soils vary with the reclamation practices used in soil reconstruction (Vance et al. 1987). Because of the need for deep soils in the corn belt, compaction is a serious problem when rooting is limiting above 122 cm (48 in). Deep-tillage equipment now exists that will ameliorate compaction to a depth of 122 cm (48 in). Intermediate-depth tillage equipment that can effectively disrupt soil to a depth of 91 to 96 cm (36 to 38 in) has been refined and is commonly used where severe compaction is limited to that depth. Dunker et al. (1992b) evaluated the effects of six deep-tillage treatments ranging in effective depth from 23 to 122 cm (9 to 48 in) on a severely compacted scraper-placed soil in southern Illinois. Corn yield increased with increasing tillage depth within and across the 4 yr studied. Post tillage penetrometer data indicated that amelioration effects of tillage remain at least 4 yr after application of tillage treatments. Subsequent study (Dunker et al. 1993) shows these effects persist into the sixth year and suggests that unless the soil is recompacted by mismanagement, effects of deep tillage to depths of 91 to 122 cm (36 to 48 in) should be permanent.

Application of deep tillage on mined land in Illinois is an expensive operation costing between $140 and $180 per hectare ($350 to $450 per acre). Penetrometer measurement can be a valuable method the operator can use to verify tillage effectiveness and depth since many operators are specifying tillage depth as part of the agreement with

9 to 18 in Average Penetrometer Resistance, PSI



18 to 27 in Average Penetrometer Resistance, PSI

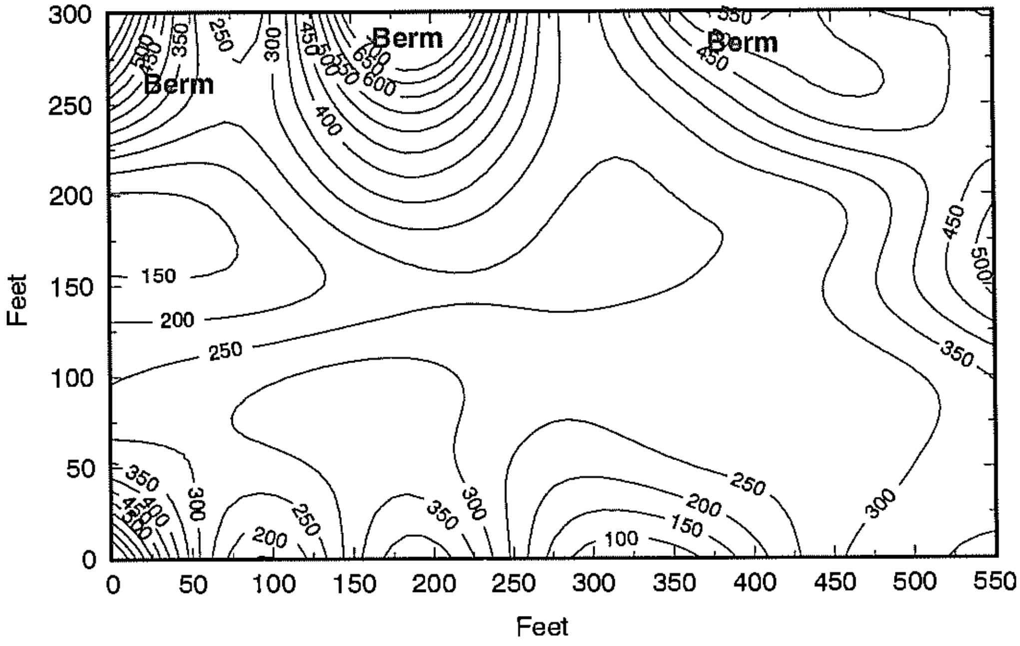
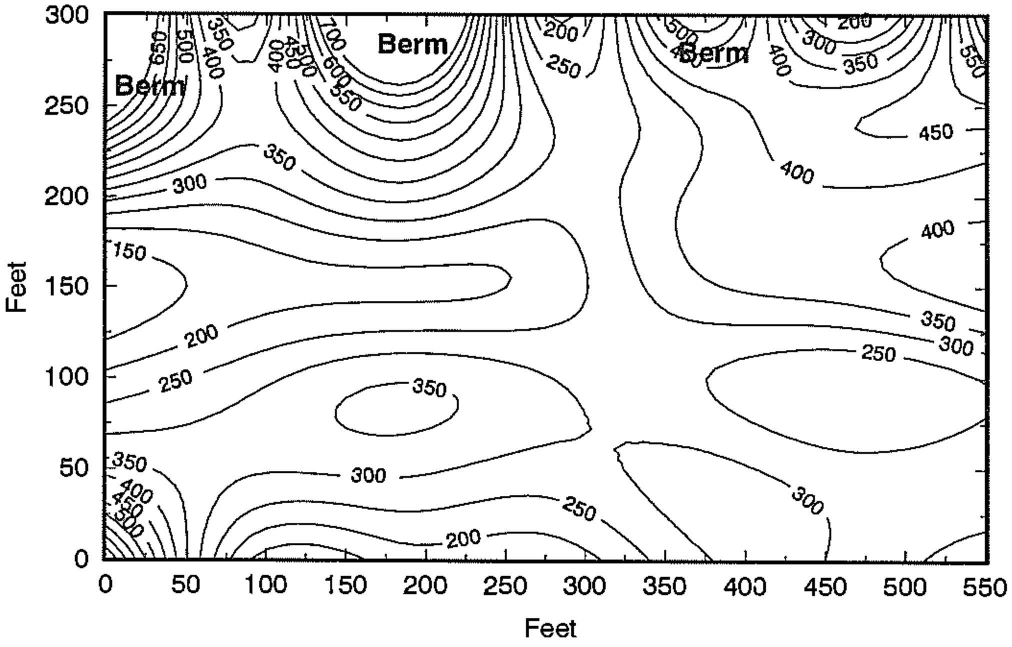
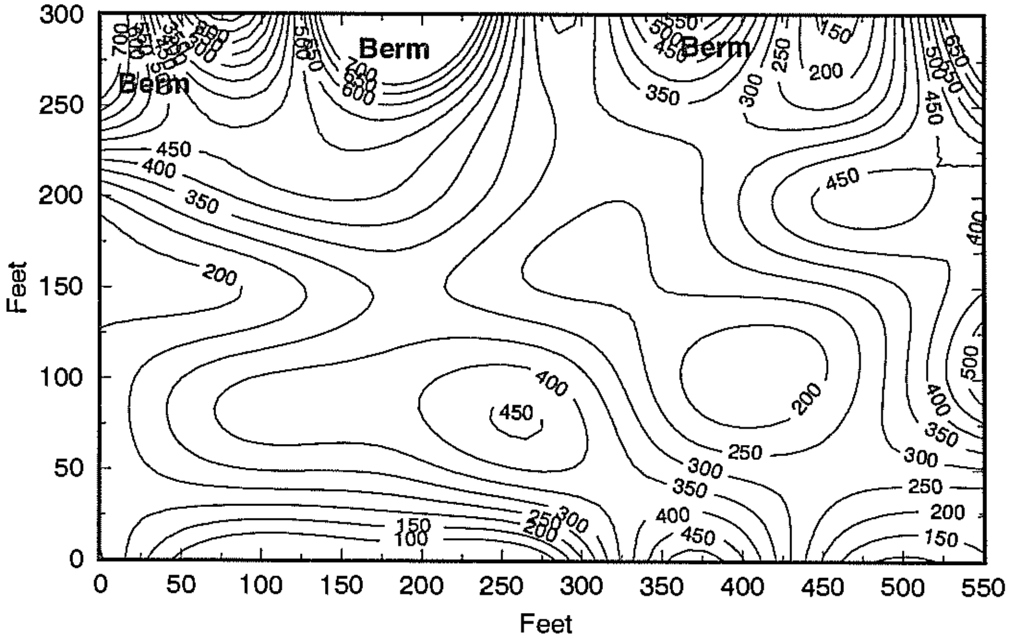


Figure 1. Soil strength contour maps of 9 to 18 in and 18 to 27 in depth segments in topsoil berm area.



27 to 36 in Average Penetrometer Resistance, PSI



36 to 44 in Average Penetrometer Resistance, PSI

Figure 2. Soil strength contour maps of 27 to 36 in and 36 to 44 in depth segments in topsoil berm area.

the deep tillage contractor. Figure 3 shows two methods by which soil strength data can be used for this purpose. The contour map presents data from an area where the north half was deep tilled to 122 cm (48 in). The mine operator can look at these data and be assured that the tillage was effective in ameliorating compaction and is uniformly applied. The lower graph (fig. 3) presents the average profiles of the treatments and gives the mine operator an indication of treatment differences. If needed by the mine operator, profiles for specific sample points can be generated to analyze problem areas.

To evaluate persistence of tillage treatment effects and repeatability of penetrometer readings, soil strength measurements were taken in 1988, 1989, 1991, and 1993 on a deep-tilled scraper placed mine soil in southern Illinois (Dunker et al. 1993). Figure 4 presents profile data of two of these tillage treatments. The TLG-12 treatment (Kaeble Gmeinder TLG-12) utilizes a cut-lift operation to shatter the soil to a depth of approximately 80 to 91 cm (32 to 36 in). The DMI treatment (DMI, Inc. prototype deep plow) utilizes a two-lift solid winged shank ripper and has an effective tillage depth of 122 cm (48 in). Penetrometer profile data presented in figure 4 show that effects of these treatments remain unchanged over the 6 yr period (treatments were applied in 1987) and that soil strength data measured with the penetrometer is repeatable over time.

Application for Regulatory Use

Penetrometer measurements on reclaimed mined land vary widely. These are associated with wide ranging values in crop yield. Prime farmland reclamation areas with high soil strength levels have had the lowest crop yields, and low soil strength soils have had the highest yields. Vance et al. (1992) reported significant correlation of 23 to 112 cm (9 to 44 in) average penetrometer resistance with 6 year mean corn yield (-0.98**) and six year mean soybean yields (-.0.99**) in a study evaluating several methods of reclamation.

Illinois performance standards for prime farmland require measuring yields of reclaimed areas and comparing them to a predetermined target yield. Target yields are based on productivity indexes of premine soils with a weighted productivity index calculated for each permit. The Illinois Department of Agriculture has developed the Agricultural Lands Productivity Formula (a crop yield based system) to provide a calculated standard yield to be used for mined land comparison to determine if productivity has been restored (Giordano 1992). This formula includes a countywide-based weather adjustment factor to account for weather effects. It is based on USDA Agricultural Statistics Service information and adjusted for harvest loss. If the mine operator can produce crops equal (based on a 90% confidence interval) to the target yield for 3 yr within a 10 yr period, productivity is deemed restored.

Figure 5 presents the relationship of mean corn yields expressed as a percent of the prime farmland target yield for each treatment to 23 to 112 cm (9 to 44 in) average penetrometer resistance. This database represents corn yields collected at numerous locations with various soil reconstruction methods in Illinois over a 15 yr period. This relationship of soil strength and yield is curvilinear. This would be expected because as soil strength decreases, yield can only increase to a certain potential level. In contrast, as soil strength increases to a level that prohibits root penetration by mechanical impedance, any additional increase in soil strength would have little or no effect.

Section 515 (b) (7) of the Surface Mining Control and Reclamation Act (Public Law 95-87) specifies regulations for soil removal, storage, replacement, and reconstruction. It states that the root zone material of prime farmland must be replaced with proper compaction and uniform depth over the regraded spoil material. This compaction requirement is yet to be quantified by the Office of Surface Mining in rule making. There has been considerable interest in recent years in the development of a soil-based model to evaluate mine soil productivity. A soil-based productivity index based on the premise that root growth is a function of the sufficiency of the soil could be a suitable method to evaluate mine soils if it is based on long-term mined land yields. Neill (1979) identified five soil properties (potential available water storage capacity, bulk density, soil pH, electrical conductivity, and aeration)

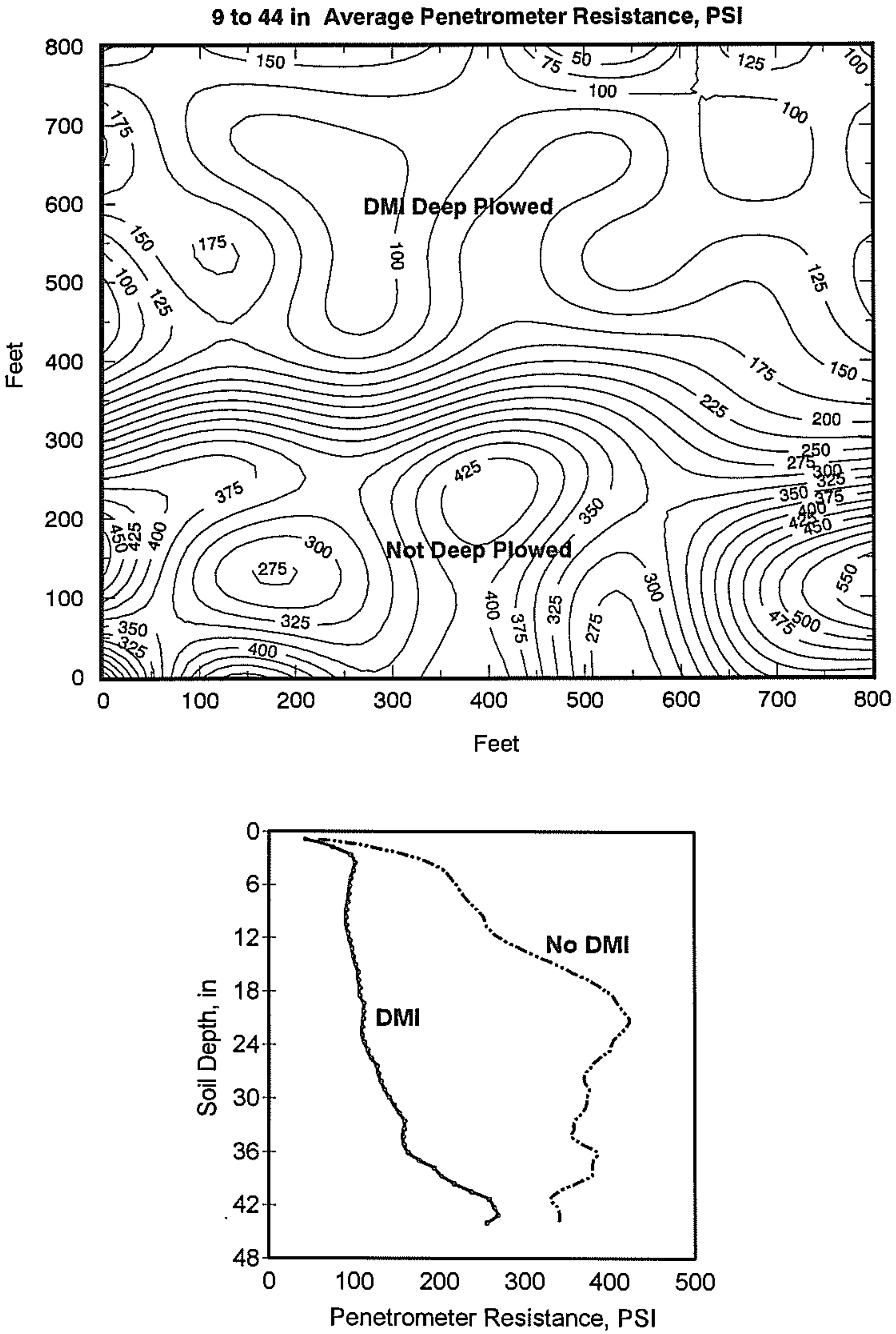


Figure 3. Soil strength contour map (top) of DMI deep-tillage (48 in) area and mean soil strength profiles (bottom) for the tilled and nontilled areas.

as being easily measured soil parameters that predict root growth. Cone penetrometer readings could be introduced to the productivity index model as a potentially efficient alternative to bulk density as a measure of soil compaction (Barnhisel et al. 1992). Soil strength measurement with the deep profile penetrometer is a viable method for assessing long term yield potential of mined land when chemical and plant nutritional variables are not yield limiting factors. While yield variation among years is associated more closely to weather variables than to soil factors, soil strength is closely correlated to mean yields averaged over multiple years.

Development of a compaction standard for prime farmland rooting media will enhance the success of a crop-based performance system. Requiring that rooting media meet a sufficiency level of compaction as a measure of quality control will prevent severely compacted mine soils from entering the crop performance testing stage. This will assure that only high quality mine soils will be allowed to pass through the bond release system.

Summary

The penetrometer can be an important management tool for the mine operator to assess levels of soil compaction created during soil reconstruction and to evaluate the effectiveness and depth of deep-tillage operations. Soil strength measurements with the deep profile penetrometer appear to be a viable method of assessing long term yield potential of mined prime farmland of the midwestern corn belt when chemical and plant nutritional variables are not yield limiting. The inclusion of a penetrometer resistance measurement as a surrogate for a compaction standard will improve the success of surface mine reclamation.

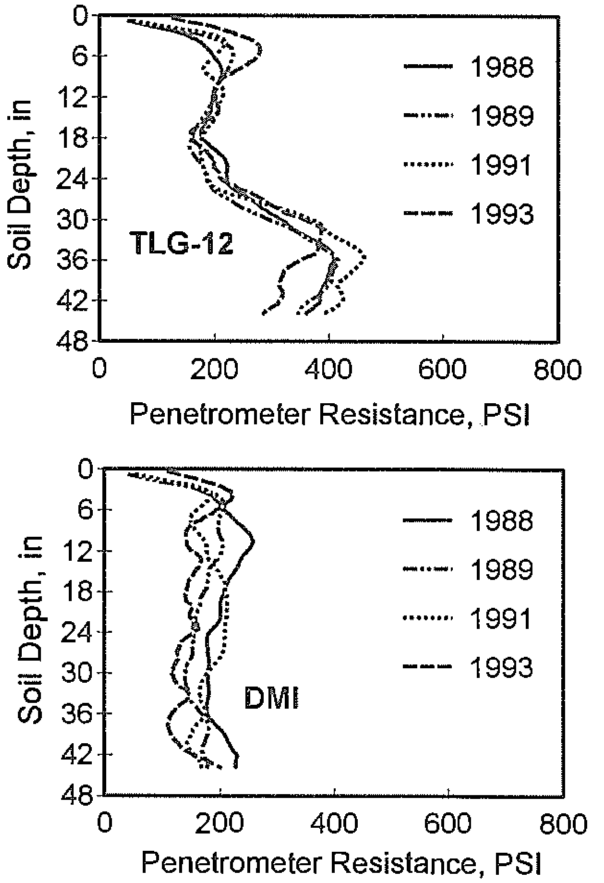


Figure 4. Mean penetrometer profiles for deep-tillage treatments over a 6 yr period, 1988-93.

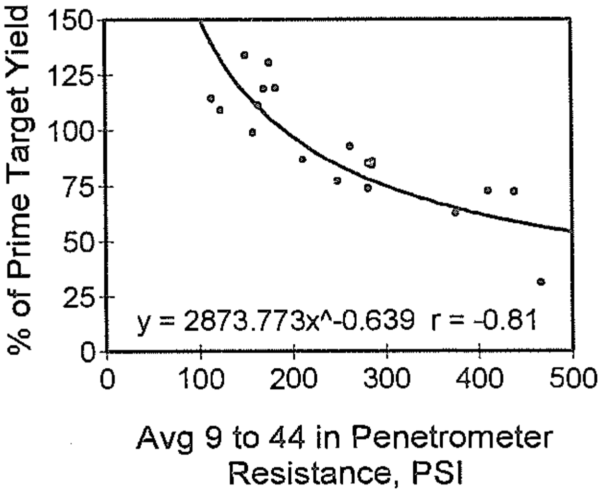


Figure 5. Regression of corn yield expressed as % of prime target yield to average penetrometer resistance for 18 reclamation treatments.

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