REVIEW PAPER

USE OF PENETROMETERS IN AGRICULTURE: A REVIEW

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ABSTRACT: Soil physical quality can be easily and quickly evaluated by using simple equipment to identify levels of soil compaction. Hence, it is necessary to know the variables responsible for changes in the soil penetration resistance (SPR). The aim of this review is to identify the main factors related to the various equipment used for assessing SPR as a soil physical quality indicator in agriculture. This literature review describes the different types of equipment used and its relationship with SPR. A wide range of procedures, devices, and equipments are available. Much of variability in SPR results is related to the equipment model, cone angle and diameter, and penetration rate. Usually, restrictions to root growth are correlated with SPR values above 2-3 MPa. However, comparisons of SPR values obtained under different soil moisture regimes in the same soil type have provided conflicting results of difficult interpretation. In order to minimize these problems, there is a need for standardization of measurement procedures and interpretation, and/or correction of SPR values according to a soil water content of reference.

KEYWORDS: soil compaction, soil physics, physical quality, penetrometry.

UTILIZAÇÃO DE PENETRÔMETROS NA AGRICULTURA: UMA REVISÃO

RESUMO: A qualidade física dos solos pode ser fácil e rapidamente avaliada com o uso de equipamento simples para a identificação do nível de compactação do solo. Para isso, é necessário o conhecimento das variáveis responsáveis por alterações da resistência do solo à penetração (RP). O objetivo desta revisão é identificar os principais fatores relacionados com os equipamentos utilizados para a avaliação da RP como indicador da qualidade física do solo na agricultura. Essa revisão bibliográfica descreve os tipos de equipamentos utilizados e sua relação com a RP. Existe disponível uma grande variabilidade de equipamentos, dispositivos e procedimentos. Grande parte da variabilidade dos resultados de valores de RP está relacionada com os modelos de equipamentos, diâmetro e ângulo de cone e taxa de penetração. Usualmente, as restrições ao crescimento radicular, estão correlacionadas com valores de RP acima de 2 a 3 MPa. Porém, comparações entre valores de RP obtidos sob diferentes conteúdos de água no solo, em áreas com mesmo tipo de solo, proporcionaram resultados conflitantes e de difícil interpretação. Para reduzir esses problemas, recomenda-se uma normatização no procedimento de medida e interpretação e/ou correção dos valores de RP para um conteúdo de água do solo de referência.

PALAVRAS-CHAVE: compactação do solo, física do solo, qualidade física, penetrometria.

INTRODUCTION

Soil compaction is a limiting factor in agricultural production (DIAS JUNIOR & PIERCE, 1996) that is known and accepted as the factor that most negatively alters soil structure (FIGUEIREDO et al., 2011). This effect is directly associated with the reduction in the availability of water in the soil, soil aeration, and nutrients to plants, along with the increase of soil resistance to root growth (LETEY, 1985; MEDEIROS et al., 2010). Among various methods to determine the state of soil compaction and physical quality, the evaluation of soil penetration resistance (SPR) has

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been commonly used in experimental studies, not only related to precision agriculture (SILVA et al., 2004; BOTTEGA et al., 2011; CHERUBIN et al., 2011; DALCHIAVON et al., 2011; GIRARDELLO et al., 2011) but also to assessments of management conditions of agricultural areas (GOEDERT et al., 2002; NEIRO et al., 2003; FREDDI et al., 2007; SILVA et al., 2009; CALONEGO & ROSOLEM, 2011; OTTO et al., 2011) and forests (SEIXAS & SOUZA, 2007; SINNETT et al., 2008).

The SPR values may be affected by several factors related to soil (SILVA et al., 2000a; 2000b), determination method and, obviously, measuring instruments (ROBOREDO et al., 2010). Detailed knowledge of the influence of these factors on the results observed at field level is critical for obtaining structural indicators of soil quality. The probable low consistency among SPR values, when compared to the pressure exerted by roots, may be attributed to the different penetrometer models, procedure used by the operator, physical differences between the path of the penetrometer rod and roots in the soil, soil type, and studied plant species (TORRES & SARAIVA, 1999).

The objective of this review is to identify the major factors related to the lack of standardization of the instruments used for the assessment of SPR values as indicators of soil physical quality in agriculture, describing the main used equipment types and their relation to the determination of SPR values.

REVIEW

Penetrometry

Penetrometry is an appropriate measure for assessing SPR values and is obtained by the use of devices called penetrometers. A penetrometer consists of a rod, or a shaft, with a cone tip (LOWERY & MORRISON, 2002). The SPR values of a cone are determined while it penetrates the soil by means of the vertical force applied to the cone divided by its basal area (BRADFORD, 1986). However, according to this same author, the determination of the SPR values of the rod friction is equal to the vertical force applied to the rod divided by its surface area.

Among the main factors affecting the determination of SPR values, the cone angle, diameter and roughness, and the penetration rate of the penetrometer may be cited (BRADFORD, 1986). Besides these factors, the determination of SPR values depends on soil bulk density (Db) (OTTO et al., 2011), water content in the soil (ASSIS et al., 2009; FIGUEIREDO et al., 2011; MORAES et al., 2012), soil pore-water pressure (FREUDLUND et al., 1978; KIM et al., 2008), particle size distribution (VAZ et al., 2011), clay content (MOLIN et al., 2006), soil type (SILVA et al., 2004), soil compressibility (SILVA et al., 2002), and soil-metal friction (DEXTER et al., 2007).

The main rules for the determination of SPR values are standardized by the American Society of Agricultural and Biological Engineers (ASABE) via EP542 (ASABE, 2006a) and S313.3 (ASABE, 2006b) standards. In this sense, for comparisons of SPR values, the main mechanisms involved in this determination must be known. The use of different cone types (angle and diameter) and penetration rates from those suggested by the ASABE standards (ASABE, 2006b) results, in most cases, in completely different SPR values, what hinders their analysis and interpretation.

Penetrometry allows the characterization, in third dimension, of a soil layer by means of a penetrometer insertion into the soil at different angles (LOWERY & MORRISON, 2002). In this sense, the evaluation and monitoring of soil layers of mechanical impediment for root development are important tools to characterize the evolution of agricultural management systems (TORRES & SARAIVA, 1999; SECCO et al., 2009).

Penetrometer models and their qualities

Penetrometers are based on two principles of penetration: (i) static penetrometer or penetrograph: in the operation, the whole set is pressed against the soil and, (ii) dynamic or impact penetrometer (Figure 1): in the operation, the rod penetrates the soil according to the impact of a weight falling from a constant height, in freefall (STOLF, 1991; STOLF et al., 1998). Static definition is due to the fact that these devices require constant penetration rate (SÁ & SANTOS JUNIOR, 2007).

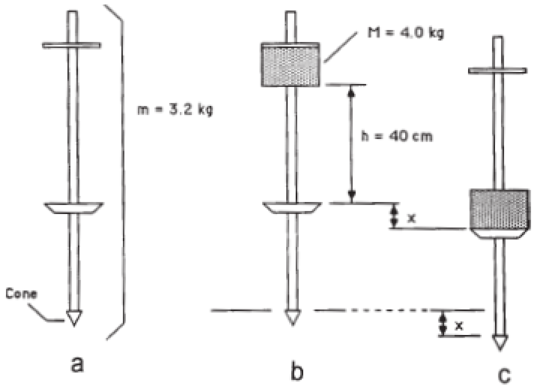

FIGURE 1. Impact penetrometer, model IAA/Planalsucar-Stolf (a); before impact (b); after impact (c) (Source: STOLF et al., 1998).

Static penetrometers, or penetrographs, are basically constituted of a probe, often conical, which is slowly introduced into the soil by means of a graduated rod (LEITE et al., 2010). Penetrometers are devices that allow ad hoc assessments of SPR values while penetrographs continuously record, in graphs, SPR values throughout the soil profile (SÁ & SANTOS JUNIOR, 2005).

The dynamometer pocket penetrometer (Figure 2a) is used to describe SPR values of a soil profile. When it is pressured against the soil, a helical spring of linear compression indicates the SPR values (CAPPELLI et al., 2001). Also, it may be used with a digital data storage system, obtaining point readings every 1.0, 2.5, or 5.0 cm penetration (Figure 2b).

There are also penetrometers of the semi-automatic type (Figure 2c) (CAMARGO & ALLEONI, 2006) or with digital data storage system (Figure 2d) (SILVA et al., 2000b; BIANCHINI et al., 2002; CHERUBIN et al., 2011). However, results obtained by the manual operation of the equipment depend on the operator’s experience and skill due to the uncertainty of maintaining a constant penetration rate during determination (BIANCHINI et al., 2002).

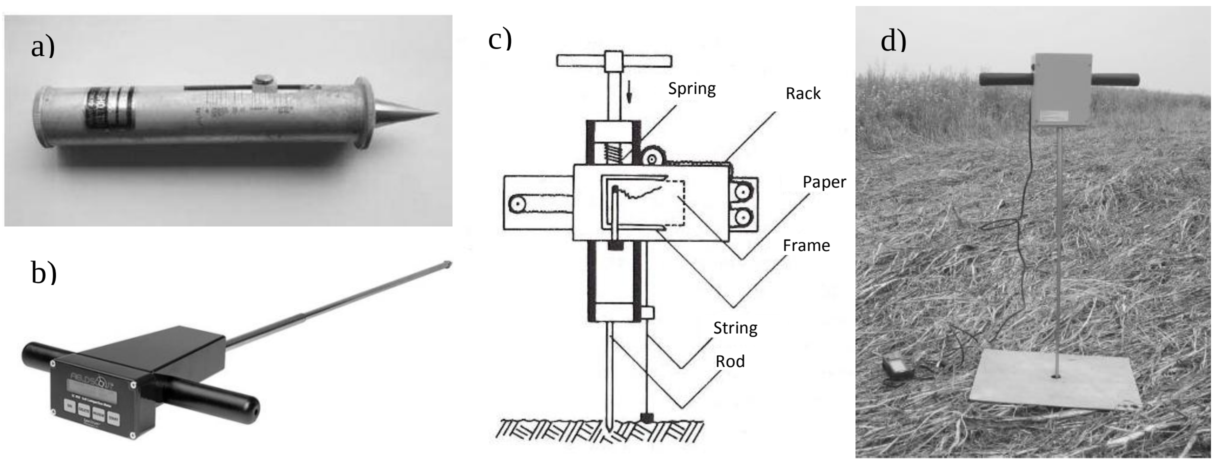

FIGURE 2. Static equipment for determination of the soil penetration resistance. (a) dynamometer pocket penetrometer (SÁ & SANTOS JUNIOR, 2005); (b) digital static penetrometer, model Field Scout TM SC 900 (SPECTRUM TECHNOLOGIES, 2009); (c) Scheme of a semi-automatic mechanical penetrometer of springs (CAMARGO & ALLEONI, 2006); and (d) digital static penetrometer, model PentroLOG (CHERUBIN et al., 2011).

The determination of SPR values in undisturbed soil samples can be performed with the use of a bench top electromechanical penetrometer (Figure 3a) (TORMENA et al., 1998; SERAFIM et al., 2008; LIMA et al., 2009; CALONEGO & ROSOLEM, 2011) or a bench top dynamic mini cone penetrometer (Figure 3b) (SÁ et al., 2007). In these cases, it is possible to control the water content of soil samples, with greater accuracy, during analysis (SÁ & SANTOS JUNIOR, 2005). Using this equipment, soil physical and water quality may also be evaluated via the determination of the least limiting water range (TORMENA et al., 1998). However, unlike other equipment used for the determination of SPR values in the field, there are no standards or regulations for these instruments regarding cone size and diameter, and penetration rate.

Virtually, all devices have smaller rod diameters than the cone base, so that the frictional component of the axis can be reduced (BENGOUGH & MULLINS, 1990), favoring observation of, only, the effects of SPR values in a standardized conical tip (ASABE, 2006b). However, rod use, with either the presence or absence of a cone on the tip with the same rod diameter (Figure 3c), indicates that the determined values are relative to the friction that the rod provides when it is inserted into the soil (BRADFORD, 1986; CHI & TESSIER, 1995). According to ASABE (2006b), these values cannot be defined as SPR values. As an example, there is the penetrometer described by BRADFORD (1986), with 3.74 mm diameter and 60° angle (Figura3c).

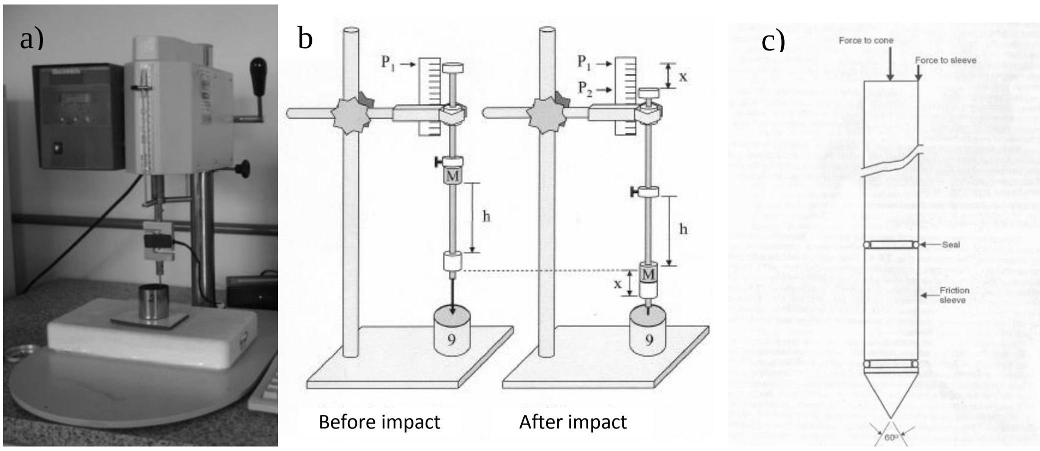

FIGURE 3. Equipment for determination of the penetration resistance in undisturbed soil samples. (a) bench top electronic penetrograph, model MA-933; (b) Scheme of the dynamic mini penetrometer described by SÁ et al. (2007) (Source: SÁ et al., 2007); and (c) Rod of the bench top static penetrometer of rod-soil friction, developed by BRADFORD (1986) (Source: LOWERY & MORRISON, 2002).

The determination of SPR values is highly influenced by the soil water content (CONTE et al., 2008; MORAES et al., 2012), when small reductions in the value of this parameter provide a large increase in the readings of SPR values (SECCO et al., 2009). Such increase due to the reduction of soil water content may be explained by theories that relate the pressure of water and air in the soil pores with the soil shear strength (FREUDLUND et al., 1978). These authors describe the behavior of the shear strength of saturated and unsaturated soils, and the results show that the decrease in water pressure in the soil pores increases the soil frictional resistance. This exponential increase of the SPR values according to the soil water content restricts comparisons among same soils with different moisture contents; this occurs because a small decrease or increase in this parameter results in a large increase or decrease in SPR values (VAZ et al., 2011), resulting in under or overestimation of the soil compaction state (MORAES et al., 2012). In order to overcome this problem, MORAES et al. (2012) suggest the correction of the SPR values according to a water content of the reference soil.

Since penetrometers is limited in the SPR readings, the soil least limiting water ranges must be observed for the determination of SPR values according to the different used equipment.

Dynamic penetrometers are those with the greatest ranges of readings for the evaluation of SPR values in the field, varying from zero to more than 20 MPa (VAZ et al., 2011; MORAES et al., 2012). Static penetrometers and penetrographs of manual insertion provide field measurements of SPR values up to 5 MPa (ASABE, 2006b). Meanwhile, bench top electronic penetrometers enable a wide determination of SPR values in undisturbed soil samples up to 19.6 MPa.

Static equipment presents some advantages over dynamic (or impact) ones, among these, the procedure standardization for determination (ASABE, 2006b). However, the use of impact penetrometers is appropriate for all applications indicated for static ones, and it is recommended when the constancy of the static penetrometer operation is questionable (HERRICK & JONES, 2002).

When comparing SPR results determined with both dynamic and static penetrometers, it is possible to observe that the largest differences are found in soils with high clay contents (STOLF, 1991) and Db (BEUTLER et al., 2007b). The correlation coefficient among SPR readings provided by both devices in an Oxisol of medium texture was approximately 0.80 (ROQUE et al., 2003). However, for a clayey Oxisol (450 g kg^{-1} clay), this coefficient was 0.74 (ROBOREDO et al., 2010). The main measurement differences obtained for these devices may be attributed to the fact that dynamic devices record the maximum SPR values per unit of depth, while the static ones determine the values per unit area (HERRICK & JONES, 2002). In this sense, these authors do not recommend comparisons between these two types because different parameters are evaluated: static penetrometers generate a “cone index”, representing a force per unit area, while dynamic penetrometers determine the "real resistance" in terms of force per unit of depth.

The identification of compacted soil layers may be performed with both devices (dynamic and static). This is due to the fact that the pattern of soil resistance is not affected by the instrument type (BAVER et al., 1972). However, there are differences in the correlation of SPR values, determined using dynamic and/or static penetrometers, and Db values, as ROBOREDO et al. (2010) found that the best correlation between SPR and Db values was obtained with the use of dynamic penetrometers (r = 0.91). This indicates, therefore, that dynamic penetrometers may be more sensitive to diagnose more compacted soil layers.

Relationship between cone diameter and base area, and penetration resistance

Most penetrometers used in agriculture have cone diameters ranging from 2.15 mm, in laboratory equipment (MISRA & Li, 1996), to 20.27 mm in models used for determinations in the field (ASABE, 2006b). Penetration rods with diameters similar to a needle (0.5-1.0 mm) may also be used (BENGOUGH & MULLINS, 1990, 1991; SCHIMITD et al., 2013). In this sense, the cone is a variation source of SPR values as, depending on the model, there are distinct basal areas and angles (TORRES & SARAIVA, 1999). However, MISRA & LI (1996) stated that SPR values do not depend on the cone diameter when the latter is larger than 2 mm.

In devices with manual trigger, the standard diameter recommended for determination of SPR values is of 20.27 mm in soils that do not exceed SPR values of 2 MPa (soft soils) and 12.83 mm in locations with SPR values up to 5 MPa (hard soils) (Figure 4) (ASABE, 2006b). These same regulations determine that the maximum allowed wear must be 3% in relation to the standard cone diameter.

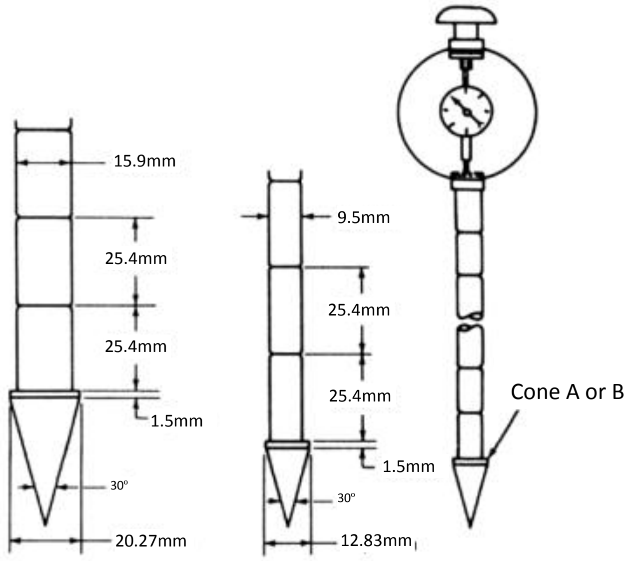

FIGURE 4. Cone standards for penetrometers according to ASABE S.313.3 (Source: ASABE, 2006b).

The determination of SPR values in undisturbed soil samples may be affected by some problems. In undisturbed soil samples collected in rigid cylinders, the insertion of the penetration rod in the soil promotes soil confinement on the cylinder walls, what may alter the SPR values (BENGOUGH & MULLINS, 1990). Therefore, in order to avoid overestimation of SPR values, values of the maximum cone diameter in relation to the diameter of undisturbed samples should be observed. This soil confinement caused by the cone insertion affects SPR values especially in soils with high clay content and/or Db. In compressible soils (low density), this confinement effect is smaller because both rod and penetration cone volumes may be accommodated by the compression of a small soil amount (BENGOUGH & MULLINS, 1990). Moreover, the presence of structural discontinuity (root or biological pores) and/or fragments of materials with different compressive characteristics (stones) favors changes in SPR values (MISRA & LI, 1996). For the solution of these problems, the distance between the measuring location of the SPR values and the structural discontinuity (biological pores, stone fragments, and others) should be at least eight times larger than the cone diameter (MISRA & LI, 1996). These authors mentioned that, for the use of a cone with 4 mm diameter, the undisturbed soil sample should present at least 32 mm diameter. In this context, it is important to use the correct cone diameter in undisturbed soil samples so that it allows achievement of correct SPR values.

Relationship between cone angle and penetration resistance

Penetrometers used to obtain SPR values in agriculture have different cone angles that, most commonly, vary from 30 to 60° (SERAFIM et al., 2008). The ASABE standards (ASABE, 2006b) for the use of penetrometers determine that the cone angle must be 30°. This standardization is due to the fact that SPR values depend on the cone angle (Bradford, 1986). This author states that cone angles of 30° determine the lowest SPR values in relation to either greater or lower angles. However, readings obtained from cone angles of 60°, associated with smaller diameters (approximately 4 mm), have provided better correlations with plant root growth (SERAFIM et al., 2008).

The determination of SPR values in undisturbed soil samples is determined using bench top penetrometers (TORMENA et al., 1998; SÁ et al., 2007; CALONEGO & ROSOLEM, 2011). A more detailed description was presented by BRADFORD (1986) and, later, refined by TORMENA et al. (1998), who used cones of 60° angle. However, due to the small volume of soil samples usually used (cylinders of 5 cm diameter and 5 cm height), the use of cones indicated by ASABE (2006) is inappropriate. This is because ASABE standards (ASABE, 2006b) indicate that cones of 12.83 mm diameter and 30° angle must be used. The utilization of these cone dimensions for the determination of SPR values, in undisturbed soil samples of 5 cm diameter, results in a higher SPR value due to the reduced space for soil containment and passage of the penetrometer cone and rod (BENGOUGH & MULLINS, 1990; MISRA & LI, 1996). In this sense, the determination of SPR values in undisturbed soil samples, with base area of about 5 cm, should be standardized and determined via the use of penetrometers with a rod, which tip presents a 4 mm diameter cone of 60° angle, as described by TORMENA et al. (1998). Furthermore, the diameter of the penetration rod must be smaller than the cone diameter, what avoids rod-soil friction (BRADFORD, 1986; ASABE, 2006b).

Relationship between penetration rate and penetration resistance

An appropriate value for the penetration rate in a soil with high water content is important because there is an effect of water movement through soil pores, which favors changes in SPR values (BENGOUGH & MULLINS, 1991). A problem that is usually observed from the comparison of several studies in the literature is the disuniformity among the adopted penetration rates. However, it is known that it is very difficult to establish a penetration rate to be used in all conditions because the rate increase may raise, reduce, and/or not influence SPR values, depending on soil properties and moisture conditions of the profile (BRADFORD, 1986).

The ASABE, by means of the EP542 standard, describes technical standards for the achievement of SPR values with cone penetrometers (ASABE, 2006a), aiming to reduce problems with very high penetration rates. This standard indicates, as the penetration rate limit, the uniform value of 30 mm s^{-1}, with readings at depth intervals of less than 0.05 m. However, for field readings, the best results have been obtained with the use of rates of less than 8.3 mm s^{-1}(LOWERY & MORRISON, 2002). According to SARAIVA & TORRES (1999), the higher the insertion rate is, the lower the recorded SPR values are. This same evidence was obtained by KIM et al. (2008), who observed a reduction in SPR values from 3.14 to 0.91 MPa, with an increase in penetration rate from 0.02 to 0.25 mm s^{-1}. When the same authors applied a penetration rate of 8 mm s^{-1}, SPR values reduced to 0.7 MPa, demonstrating that the change in SPR values is not constant according to penetration, as it is related to soil pore-water pressure. In this sense, impact penetrometers and/or penetrometers of constant penetration rate tend to minimize this problem (TORRES & SARAIVA, 1999). Based on parameters of constant rod penetration rate into the soil profile, REINERT et al. (2007) developed a penetrometer, to be used in the field, with both cone angle and diameter in accordance with ASABE standards (ASABE, 2006b). The authors state that the equipment was effective in the acquisition and subsequent interpretation of the SPR values according to the soil profile depth.

A bench top electronic penetrograph was developed by TORMENA et al. (1998), which was composed of an electric linear actuator with stepper motor, used for the determination of SPR values in undisturbed soil samples collected in cylinders. The developed equipment was based on the penetrometer designed by BRADFORD (1986), and enables the achievement of SPR values under a constant soil penetration rate. According to the authors, when this penetrometer model is used, SPR values determined in the sample surface layer, of up to 1 cm depth, should be discarded. This is because, in a homogeneous undisturbed soil sample, SPR values increase until full cone penetration into the soil and, then, tend to be constant. However, bench top electronic penetrometers do not have standards of operation and functioning. The most observed penetration rates in the literature are 0.033 s^{-1} mm (2 mm min^{-1}) (SILVA et al., 1994; BETZ et al., 1998), 0.17 mm s^{-1} (10 mm min^{-1}) (TORMENA et al., 1998; OLIBONE et al., 2010), 0.33 mm s^{-1} (20 mm min^{-1}) (Silva et al., 2006), and 1 mm s^{-1} (60 mm min^{-1}) (KUNZ, 2010).

Relationship between root growth and penetration resistance

The SPR, aeration, temperature, and water content are soil physical factors that directly affect crop growth, development, and yield (LETEY, 1985). When using SPR values that directly affect plant root growth, the soil water content has been used as reference when the SPR values reach 2 MPa (COLLARES et al., 2006). However, there are differences among the SPR limiting values for root growth, as they depend on the studied plant species. For the cotton crop, root growth was restricted when SPR values reached 3.5 MPa (ROQUE et al., 2003). For beans, this restriction occurred with SPR values close to 3 MPa (KAISER et al., 2009). The growth of soybean plants was also affected, when cultivated under both rainfed and irrigated systems, to SPR values between 1.30 and 1.64 MPa (BEUTLER et al., 2007a).

Differences in the SPR limiting values for each studied species may occur in accordance with the lubrication mechanism of the root zone, which is exerted by roots (SCHIMIDT et al., 2013). These authors observed that lupine plants support a greater mechanical impediment to root growth than maize. This is due to the fact that the lupine root system has a lubrication of the mucilage and cells attached to the edge of the entire root elongation region, unlike the maize root system, which mainly lubricates the root cap (SCHIMIDT et al., 2013). The SPR values determined by penetrometers may be six times, or more, greater than the maximum axial pressure values that plant roots can exert in the soil (BENGOUGH & MULLINS, 1990). However, unlike penetrometers, roots are flexible organs that can extract water and excrete mucilage around their edges, growing along tortuous soil pores, which facilitates root penetration (BENGOUGH & MULLINS, 1990).

The effect of soil texture, as indicated above, should also be taken into consideration. In a medium textured Oxisol, the critical SPR value for rice plants, cultivated under the rainfed system, was 2.38 MPa (BEUTLER & CENTURION, 2004). However, in a clayey Oxisol, the critical SPR value for the same plants was reduced to 2.07 MPa. Maize decreased yield when SPR values were higher than 1.65 MPa; however, SPR values of 5.69 MPa caused changes in the root system morphology of that same crop, but did not prevent root from growing (FREDDI et al., 2007). Negative effects on the root morphology of maize plants grown in a compacted soil were observed by BERGAMIN et al. (2010), what was directly related to SPR values.

The United States Department of Agriculture - USDA (USDA, 1993), based on a penetrometer described by BRADFORD (1986), with a 6.4 mm diameter cone of 60° angle, that operates at a constant penetration rate of 6.4 mm s^{-1}, classifies the SPR values into three main classes: small, intermediate, and large (Table 1). It is important to mention that the USDA, in this publication, recommends that the SPR values should be presented with the description of the determination conditions in the field. Among these recommendations, the importance of describing the soil water content, axis orientation, and penetration rate is highlighted.

TABLE 1. Penetration resistance classes according to the United States Department of Agriculture (Source: USDA, 1993).

Classes	Penetration resistance (MPa)
Small	< 0.10
Extremely low	< 0.01
Very low	0.01 – 0.10
Intermediate	0.10 – 2.00
Low	0.10 – 1.00
Moderate	1.00 – 2.00
Large	> 2.00
High	2.00 – 4.00
Very high	4.00 – 8.00
Extremely high	> 8.00

Another indication of the limits for classes of SPR values were presented by CANARACHE (1990) (Table 2). This class separation was determined by the author with the use of a penetrometer with a 7 mm diameter cone of 0.785 cm^2 and 45° base angle of penetration. This author believes that SPR values between 2.6 and 5 MPa present moderate root growth constraints that start to restrict root growth. However, higher SPR values than 5.1 MPa are considered critical for root growth. CAMARGO & ALLEONI (2006) suggested that SPR values measured in the field should be compared to those determined under natural conditions (native forest or field) of the same region, so that agricultural cultivation systems could be evaluated. Following this procedure, it is possible to identify, more easily, the existence of soil layers with a higher compaction degree caused by the adoption of the current soil management system.

TABLE 2. Limits for penetration resistance classes according to CANARACHE (1990) (Source: adapted from CANARACHE, 1990).

Penetration resistance classes	Limits (MPa)	Limitations for root growth
Very low	≤1.0	No limitations
Low	1.1-2.5	Weak limitations
Medium	2.6-5.0	Moderate restrictions
High	5.1-10.0	Critical restrictions
Very high	10.1-15.0	Virtually no root growth
Extremely high	>15.0	No root growth

Using mathematical models, CANARACHE (1990) described the behavior of the SPR values for a range of clay contents (0 to 70%) and Db (0.86 to 1.81 Mg m^{-3}), demonstrating the variation of the soil water content at field capacity (10 kPa tension) (Figure 5a) and permanent wilting point (1,500 kPa tension) (Figure 5b). It is observed that these two physical and water variables (clay content and bulk density) do influence the results of SPR values. The critical SPR values (2.6 to 5 MPa) in the water content referring to field capacity (Figure 5a) were dependent on the soil clay content and Db (CANERACHE, 1990). For the same Db, the increase in the soil clay content promoted raises in SPR values. As expected, SPR values raised with the increase of Db values, what allowed the identification of the appropriate Db range for each soil clay content according to the critical SPR values.

Determinations of SPR values depend on the soil water content at the evaluation time, as there are exponential increments in SPR values due to the reduction of the soil water content (VAZ et al., 2011; MORAES et al., 2012). Differences in soil compaction may also be masked due to variations of the soil water content (MORAES et al., 2012). These authors observed that the SPR values that were determined with the soil water content at field capacity were not suitable to act as indicators of the traffic and soil management effects on the soil compaction state. In order to solve the problem of the soil water content effect on SPR values, MORAES et al. (2012) developed mathematical models for the correction of SPR values to a reference value of gravimetric water content. These authors concluded that the application of pedotransfer functions allows the observation of differences in the soil compaction state among treatments, which were not detected before due to variations in the soil water content.

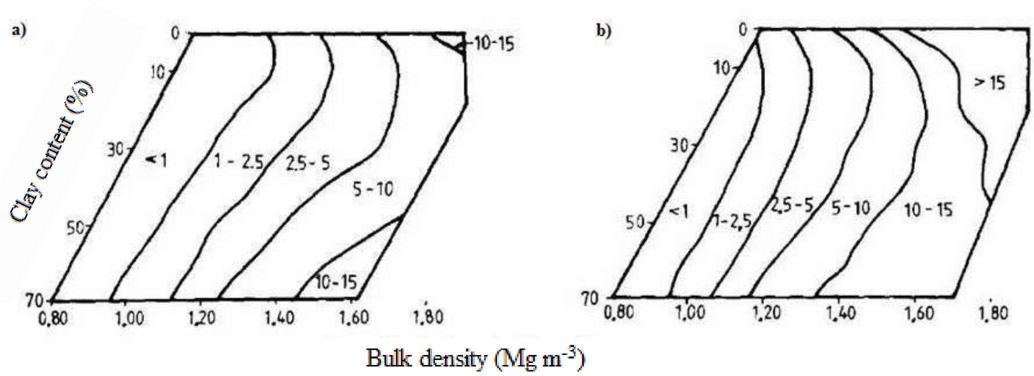

FIGURA 5. Limits of penetration resistance according to clay content and bulk density variations, (a) in the soil water content at field capacity (10 kPa tension); and (b) in the soil water content at permanent wilting point (1,500 kPa tension) (Source: Adapted from CANARACHE, 1990).

REICHERT et al. (2003) and REICHERT et al. (2007), when using data from critical Db defined by values of the least limiting water range equal to zero, presented critical Db values according to textural classes, which ranged from 1.25 to 1.30 Mg m^{-3} (clayey) up to 1.70 to 1.80 Mg m^{-3} (sandy loam). Results obtained by CANARACHE (1990) indicate that the reduction in the soil water content close to the permanent wilting point increases the SPR values, thus increasing the physical limitations imposed on plants. In this sense, REICHERT et al. (2007) recommend that it is essential for the basis of the results that the evaluation of the SPR values be combined with other field assessments, such as Db or root trenching.

FINAL CONSIDERATIONS

The penetration resistance is an important property used to evaluate the physical quality of cultivated soils, as it indicates the occurrence of problems related to compaction. However, sometimes it becomes difficult to compare the results observed in the field with the data found in the literature due to the lack of standardization of equipment, measurement procedures, and result interpretation. This can result in erroneous recommendations for management practices, unnecessary interventions, or even the recommendation of a technical procedure to minimize the negative effects of soil compaction, what results in unnecessary costs and environmental risks.

The determination of the penetration resistance in dry soil conditions results in high levels of penetration resistance; however, these values cannot be directly used to indicate problems of soil physical quality.

The recommendation for determining the penetration resistance with the soil water content close to field capacity might be used with serious restrictions due to the fact that, for some soil types, the effect of the soil water content hampers the identification of the real soil compaction state. Penetration resistance values should be corrected to a reference soil water content in order to reduce problems of result interpretations referring to the different compression levels obtained under varied conditions of soil management.

The required standardization of equipment and measurement procedures for all determination conditions, both in the field and laboratory, is essential to provide a better understanding of the observed values, what facilitates their comparison with other crop conditions, soil types, etc. Soil friability aspects must be taken into consideration and, above all, the moisture condition of the soil profile should be described, indicating the values of the soil water content at the time of the penetration resistance determination. In the case that it is measured under different moisture conditions of the same soils, standardization and/or correction of the penetration resistance values to a known water content should be performed.

Studies on penetration resistance are performed according to international standards and/or rules; however, regulations for the manufacture and operation of bench top electronic penetrometers are not yet available in the literature.

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