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Comparative Evaluation of Penetrometers with Conical and Cylindrical Tips

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Abstract

To assess the growing conditions of agricultural crops, select soil treatment methods, and so on, soil strength is often used as a characteristic. Penetrometers, which differ in the shape of their tip (deformer), are used to measure it. The most common penetrometers use cylindrical or conical deformers. The parameters of the latter (the cone base radius and the apex angle) are standardized. However, even with different cone parameters and loading rates, cone penetrometers yield different measured strength values for the same soil. Given this, measurements taken with cone and cylindrical penetrometers are even more different. To accurately compare data from these instruments, an appropriate methodology is needed. Currently, such a methodology is lacking. Therefore, this article aims to develop and test a method for accurately comparing soil strength data obtained using penetrometers with cylindrical and conical tips (deformers). Research has shown that to obtain accurate soil strength data, the penetration depth of the penetrometer's cylindrical tip should not exceed 15 cm. It has been experimentally established that soil strength measurements obtained with penetrometers using conical and cylindrical deformers of equal base radii can be compared when immersed in soil to a depth of no more than 5 cm. This publication proposes a proven analytical equation for establishing a relationship between the radii of cylindrical and conical penetrometer tips, enabling the acquisition of comparable, accurate soil strength data to depths of up to 15 cm. The penetrometer with a conical tip is the decisive factor in this regard; its parameters, unlike those of the cylindrical penetrometer, are standardized.

Soil penetration resistance is a key indicator used to evaluate soil physical conditions, root growth environments, and the suitability of tillage practices. However, measurements obtained with penetrometers equipped with conical and cylindrical tips are not directly comparable because the mechanisms of soil deformation generated by these deformers differ substantially. This study aimed to develop and validate a methodology for harmonizing penetration-resistance measurements obtained using cylindrical and standardized conical penetrometers. A theoretical framework describing soil deformation during cylindrical and conical penetration was developed using soil bearing capacity, volumetric compression, and soil–steel friction relationships. Analytical equations were derived to determine the permissible penetration depth of a cylindrical deformer and to establish an equivalence relationship between the radii of cylindrical and conical penetrometer tips. The proposed methodology was validated through field experiments using a standardized LAN-M penetrometer fitted with interchangeable conical and cylindrical tips. The results demonstrated that reliable penetration-resistance measurements obtained with a cylindrical tip require limiting penetration depth to 0.15 m. An experimental comparison of deformers with identical diameters showed that measurements remain statistically comparable only within the upper 0.05 m of soil depth. At greater depths, significant discrepancies arise because of different soil-penetration mechanisms. A new analytical relationship between cylindrical and conical tip radii was developed and experimentally verified. The proposed equation enables the selection of geometrically equivalent deformers, yielding statistically comparable penetration resistance values across the investigated 0–0.15 m soil layer. The findings support the standardization and cross-comparison

of soil-strength datasets obtained using different penetrometer designs. Future research should validate the proposed methodology across wider ranges of soil textures, moisture conditions, bulk densities, and penetration rates, and integrate the developed relationships into digital soil-monitoring and precision-agriculture systems.

Key words: Soil strength, Soil deformation, Volumetric compression coefficient, Deformation depth, Deformation stress

Introduction

Crop yields are primarily determined by soil fertility, which is characterized by its physical and mechanical properties. One such property is soil strength. Knowing the value of this parameter allows us to assess the environment in which crop roots thrive, select a method, and evaluate the quality of soil cultivation [1].

Penetrometers are used to measure soil strength. Their deformed (tips) come in various designs: cylindrical, conical, conical concave, conical convex, and spherical [2]. The most widely used of these are penetrometers with cylindrical and conical deformed [3].

The practice of using a pocket penetrometer with a cylindrical tip is described in the article [4]. During the research, its penetration depth into the soil did not exceed ¼ inch. However, if necessary, this penetrometer can be used to take measurements to a depth of 10 cm [5]. Moreover, for working in soft soils, this penetrometer features a 1-inch-diameter tip.

When using a cylindrical penetrometer, it is proposed to calculate the soil penetration resistance (H , N·m⁻²) using the formula [2]:

$$H = \frac{R}{2a \cdot h},$$

where R – force (N) for pressing (immersion insertion) the penetrometer into the soil to a depth h (m); $2a$ – diameter of the penetrometer tip (m).

Numerous attempts to use penetrometers with a cylindrical deformed in industry are well known in the study of patterns of change in the chemical composition and structure of metals and their alloys under the influence of various external factors [6–9].

Along with measuring penetration resistance, penetrometers with a cylindrical deformed allow one to determine the value of the soil volumetric compression coefficient (k , N·m⁻³) [10]:

$$k = \frac{P}{S \cdot h},$$

where P – force acting on a cylindrical deformed, N; S – cylindrical tip's area, m²; h – cylindrical deformed immersion depth into the soil, m. The problem lies in determining the limiting value of the h parameter. This value determines the cylindrical deformed penetration depth into the soil at which the correct values of soil penetration resistance are achieved.

The practical application of penetrometers with conical tips is more representative. A fundamental study [11] describes the types of penetrometers with conical deformed. Researchers note that using them with different tip angles and diameters can yield different soil penetration resistance readings. The same result occurs with different penetration speeds of the conical deformed into the soil. To address this shortcoming, the design parameters of cone penetrometers have been standardized (ASAE standard S313.3) [12–14].

Standardized cone penetrometers are primarily used to study the physical and mechanical properties of soil [15–18]. The results of using these penetrometers to study tire-soil interactions are presented in [19–23]. Moreover, this applies to both conventional crop cultivation technologies and the well-known Controlled Traffic Farming (CTF) system [25].

Of particular interest are studies [26], in which cone penetrometer results are interpreted using pedotransfer functions. The desire to provide greater convenience in measuring soil penetration resistance led to the development of an electromechanical penetrometer with a conical tip [27–28].

As noted above, even the use of standardized cone penetrometers with different cone parameters yields different measured penetration resistance values for the same soil. Therefore, it follows that measurements taken with cone and cylindrical penetrometers will be even more distinct. To accurately compare data from these instruments, an appropriate methodology is needed. However, as a review of the literature shows, such a methodology is currently lacking.

Taking this into account, the aims of this article are: a) to determine the maximum value of the penetrometer's cylindrical tip depth immersion into the soil to obtain correct values of its penetration

resistance; b) to develop and test a method for the correct comparison of data on soil penetration resistance obtained using penetrometers with cylindrical and conical tips (deformers).

Theoretical premises

In the first phase, the penetrometer's cylindrical deformer (CD) compacts the soil vertically as it penetrates. The relationship between the depth of CD penetration and the force acting on it is nearly linear. The nature of this process is satisfactorily described by the relationship proposed [10]:

$$\sigma = \sigma_o \cdot \tanh\left(\frac{k}{\sigma_o} \cdot h\right), \quad (1)$$

where σ – soil compressive (deformation) stress, Pa; σ_o – ultimate bearing capacity of soil, Pa; k – soil volumetric compression coefficient, $\text{N} \cdot \text{m}^{-3}$; h – soil depth compressive (deformation), m.

Formula (1) is quite applicable for practical calculations for the following reasons. First, the constants σ_o and k are generally recognized as soil characteristics. Their values are given in various literature references. Second, relationship (1) allows for multiple transformations based on known relationships between hyperbolic functions, analogous to trigonometric ones.

In the second phase, a compacted soil core begins to form beneath the CD. Like a wedge, it moves downward along with the CD, continuing to compact the soil.

In the third phase, the compacted core begins to push the soil layers laterally. It is at this stage that the CD penetration should be stopped. The depth achieved during this phase is fairly accurately characterized, in terms of soil volumetric compression, by the corresponding coefficient. When the soil is displaced laterally by the CD, the value of this coefficient is distorted and no longer reflects reality. This occurs because when the soil is displaced laterally, it is not contained within the calculated volume. A particular portion of it is left from the compacted volume.

As for the cone penetrometer, the process of penetrating its tip into the soil is different. Let's imagine that the cone penetrometer is inserted into the soil under the action of a vertically applied P_k force (Fig. 1). This force, in turn, causes a soil reaction force Ns , which is directed perpendicular to the side surface of the steel cone. The movement of the steel cone in the soil creates a frictional force F . The result is:

$$P_k = Ns \cdot \sin\alpha + F \cdot \cos\alpha, \quad (2)$$

where α – half the value of the angle at the apex of the penetrometer cone (Fig. 1)

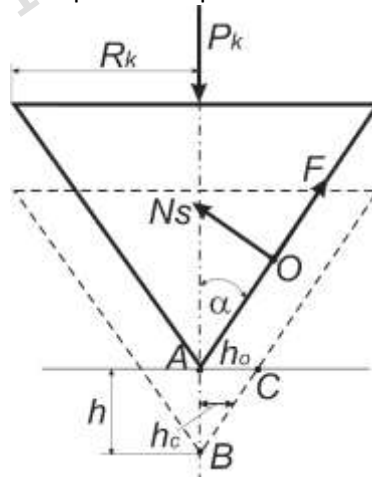


Fig. 1. Scheme of conical deformer penetration into soil

If we take into account that $F = f \cdot Ns$ (where f is the friction coefficient of the soil on steel), then equation (2) is transformed to the form:

$$P_k = Ns \cdot (\sin\alpha + f \cdot \cos\alpha). \quad (3)$$

The Ns force can be represented as the product of the soil deformation stress σ (Pa) on the lateral surface of the conical deformer:

$$S = \frac{\pi \cdot R_k^2}{\sin\alpha},$$

where R_k – base radius of the conical deformer, m. As a result, we get:

$$Ns = \sigma \cdot \pi \cdot \frac{R_k^2}{\sin \alpha}. \quad (4)$$

As noted above, soil deformation can be presented by relationship (1). As the cone is driven into the soil to a depth of $h = AB$, this deformation along line AC occurs by a value of h_o . At point B, this deformation is zero. As a result, the soil is deformed by the cone deformer by a h_c value, which is equal to:

$$h_c = \frac{h}{2} \cdot \tan \alpha. \quad (5)$$

Taking into account dependencies (1), (4)-(5), equation (3) will finally be transformed to the following form:

$$P_k = (f \cdot \cot \alpha + 1) \cdot \pi R_k^2 \cdot \sigma_o \cdot \tanh \left(\frac{k}{\sigma_o} \cdot \frac{h}{2} \cdot \tan \alpha \right). \quad (6)$$

Equation (6) allows us to calculate the force that must be applied to the penetrometer cone when it is inserted into the soil to a depth of h . For a cylindrical deformer with a base radius of R_c , the equation for determining the force acting on it will be different:

$$P_c = \pi R_c^2 \cdot \sigma_o \cdot \tanh \left(\frac{k}{\sigma_o} \cdot h \right). \quad (7)$$

Let's consider the case where $P_k = P_c$. In this case, equating the right-hand sides of equations (6) and (7), we obtain:

$$\frac{R_c}{R_k} = \sqrt{\frac{(f \cdot \cot \alpha + 1) \cdot \tanh \left(\frac{k}{\sigma_o} \cdot \frac{h}{2} \cdot \tan \alpha \right)}{\tanh \left(\frac{k}{\sigma_o} \cdot h \right)}}. \quad (8)$$

Relationship (8) allows us to determine the ratio of the cylindrical and conical deformers' radii to ensure $P_k = P_c$. This allows us to determine the value of the second radius by specifying the value of one. The penetration resistance values obtained by both penetrometers can then be compared correctly.

Material and Methods

Methodology for conducting theoretical studies

To determine the permissible depth of the cylindrical deformer penetration into the soil (h), equation (1) was considered as a function $\sigma = f(h)$. The established limit value of the h parameter was used to calculate the P_k and P_c forces [equations (6) and (7)], as well as the ratio between the tip radii R_k and R_c from equation (8).

During the calculations, it was assumed that the angle at the apex of the penetrometer cone was 30° , from which it follows that the angle $\alpha = 15^\circ$. The values of the constants k , σ_o and k were adopted in accordance with the recommendations set out in [10]. The calculations were performed in Mathcad 15.0.

Methodology for conducting experimental studies

The field study instrument was a Lan-M penetrometer (Ukraine) that complies with ASAE S313.3 (Fig. 2).



Fig. 2. LAN-M penetrometer

Field experiments were conducted in two stages. In the first, the penetrometer was used with conical (Fig. 3a) and cylindrical (Fig. 3b) tips of the same diameter, 12.7 mm. In the second stage, the conical and cylindrical tips had different diameters.



Fig. 3. Conical (a) and cylindrical (b, c) penetrometer tips

Using each penetrometer tip, at least 50 soil penetration resistance measurements were taken across a 5-hectare field plot to the maximum depth (h parameter) determined during the theoretical studies described above. Measurements were taken diagonally across the field at 1-meter increments, with triplicate measurements at each.

Before conducting field research, soil moisture and bulk density were measured in the study field. A device developed by us at Tavria State Agrotechnological University (TSATU, Ukraine) (Fig. 4) was used to measure soil moisture. The data obtained with this device are based on the relationship between soil moisture and its permittivity. Thirty measurements of this parameter were taken.



Fig. 4. Device for measuring soil moisture

Soil bulk density was determined using a special device developed at TSATU (Ukraine) (Fig. 5).



Fig. 5. Device for measuring soil bulk density

The measurement algorithm used by this device is as follows. The soil collected in the cutting cylinder was placed on an MS 2020 electronic scale (Scale, China) with a measurement accuracy of ± 0.01 g. The scale's LCD displayed the soil density in $\text{g}\cdot\text{cm}^{-3}$. This result is explained as follows. The scales used were set to measure in ounces, not grams. One ounce equals 28.3 g. At the same time, the cutting cylinder volume (V) of the density meter used is 28.3 cm^3 . Based on this, the scale, while displaying the soil mass in ounces (U), automatically displays the soil density (ρ) in $\text{g}\cdot\text{cm}^{-3}$. Analytically, this looks like this:

$$\rho = \frac{U}{V} = \frac{U \cdot 28,3 \text{ g}}{28,3 \text{ cm}^3} = U \left[\frac{\text{g}}{\text{cm}^3} \right].$$

The number of soil density measurements made by this densitometer was at least 30. The measured data were used to calculate the mean values of soil moisture and density.

Results and Discussion

Results of theoretical research

During the calculation of the analytical dependence (1), the coefficient value of volumetric soil compression (k parameter) was varied in the range of $3\text{--}7 \text{ MN}\cdot\text{m}^{-3}$. **The authors of this article determined the range of values for this coefficient during their long-term research into soil penetration resistance across virtually the entire territory of Ukraine. Furthermore, the data in this range are consistent with the data presented in [10].**

The values of the parameters σ_0 and f were constant and equal to 0.45 MPa and 0.40, respectively.

The dynamics of dependence (1) in the form $\sigma = f(h)$ is shown in Fig. 6.

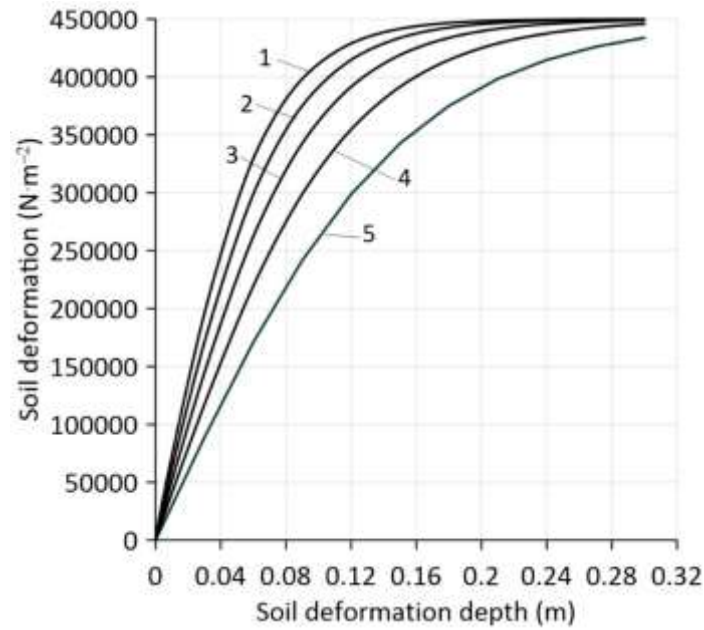


Fig. 6. Dependence of soil strength on depth for different values of the volumetric compression coefficient:
 1 – $k = 7 \text{ MN} \cdot \text{m}^{-3}$; 2 – $k = 6 \text{ MN} \cdot \text{m}^{-3}$; 3 – $k = 5 \text{ MN} \cdot \text{m}^{-3}$; 4 – $k = 4 \text{ MN} \cdot \text{m}^{-3}$; 5 – $k = 3 \text{ MN} \cdot \text{m}^{-3}$

Its analysis reveals the following. Each resulting curve consists of two zones. The first is characterized by a relatively intense growth of the function as the argument value increases. In the second zone, conversely, an increase in the argument value causes a relatively weak increase in the function value. It should be noted that in the first zone, the curvature of the $\sigma = f(h)$ dependence is so slight that it can be considered quasi-linear.

An analysis of Fig. 6 shows that the higher the value of k parameter, the greater and more intense the increase in σ parameter with increasing h . This is true in the first zone. In the second zone, greater values of the soil volumetric compression coefficient (k parameter) also correspond to greater values of soil deformation (σ parameter). However, the intensity of this process gradually decreases. And this decrease is more pronounced the higher the value of k parameter.

The problem with such two-zone curves is determining the coordinates of the point that divides the zones. Conventional practice is to use a visual method, which provides a rather approximate solution to this problem. With this in mind, we have developed a graphical-analytical method for determining the coordinates of the point dividing the dependencies into two zones, similar to those shown in Fig. 6 [28]. To do this, as shown in Fig. 7, the extreme points of the curve in question (OA) should be connected by a straight line. This line should then be moved parallel to itself until it becomes tangent to the two-zone curve. The resulting point C divides the curve into two zones: zone OC and zone CA.

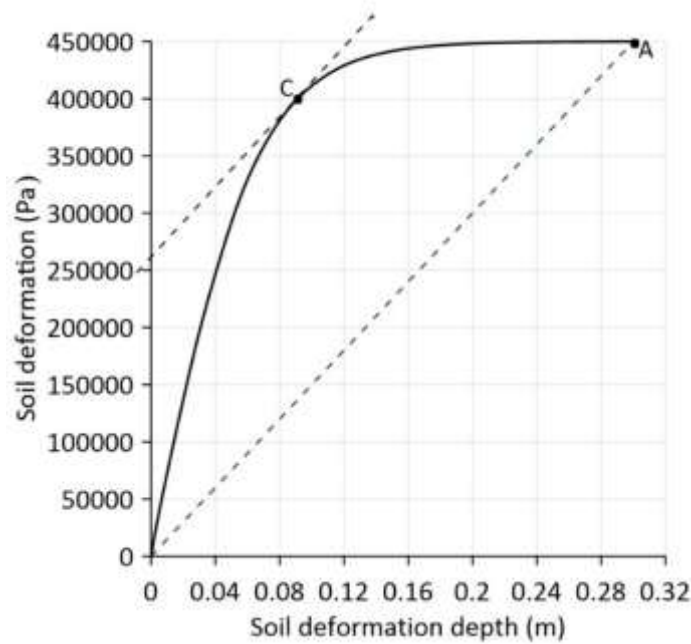


Fig. 7. Methodology for determining the dividing point of two-zone curves

The curve shown in Fig. 7 reflects relationship (1) for a soil volumetric compression coefficient of $3 \text{ MN} \cdot \text{m}^{-3}$. As we can see, in the range of $h = 0-0.09 \text{ m}$, the OC relationship is quite close to linear. Within this range of h , accurate soil penetration resistance values can be obtained. With the k parameter equal to $7 \text{ MN} \cdot \text{m}^{-3}$ (curve 5, Fig. 6), the abscissa of point C falls on the value $h = 0.15 \text{ m}$. It should be noted that in all soil-climatic zones of Ukraine, values of the volumetric soil compression coefficient below 3 and above $7 \text{ MN} \cdot \text{m}^{-3}$ are practically not found. A similar state of affairs is observed in the European agronomic space [29].

Based on Fig. 6, it can be concluded that to obtain accurate soil penetration resistance values using a cylindrical-tipped penetrometer, the penetration depth should not exceed 0.15 m . This range ($0-0.15 \text{ m}$) of the h parameter is adopted for use in further research. As is already clear, this range is due to differences in soil deformation characteristics between penetrometers with conical and cylindrical tips. An example of these characteristics, as follows from the analysis of dependencies (6) and (7), is the patterns in the dynamics of the forces applied to the penetrometer with conical and cylindrical tips of equal radii (Fig. 8).

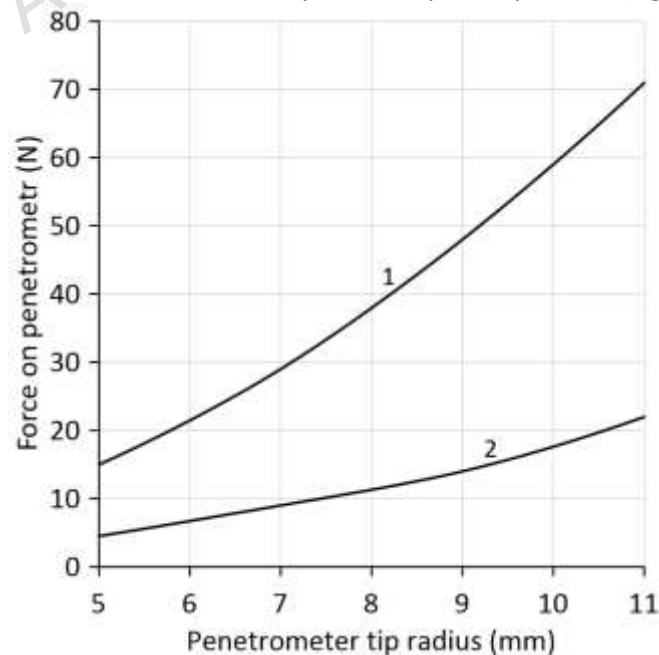


Fig. 8. The effect of the cylindrical (1) and conical (2) penetrometer tips' radius on the force applied to it when penetrated to a depth of 0.05 m

The first pattern is quite obvious and logical: the larger the penetrometer tip radius, the greater the force applied to it. However, even with soil deformation to a depth of 0.05 m, the force applied to a penetrometer with a cylindrical tip (curve 1) is greater than that applied to a conical tip (curve 2). Furthermore, the smaller the penetrometer tip radius, the less the difference (ΔP) between the forces P_k and P_c . Thus, if the radius of the compared tips is 5 mm, then $\Delta P = 10$ N. If this parameter is 10 mm, then ΔP is almost 39 N, that is, 3.90 times greater. In other words, doubling the penetrometer tip radius requires a P_c force four times greater than P_k .

Another pattern is worth noting. It is found that a penetrometer with a cylindrical tip increases the force applied to it more rapidly than a penetrometer with a conical deformer. Looking at the specific results, it's easy to see that the rate of increase in curve 1 (Fig. 8) with increasing penetrometer tip radius is greater than that of curve 2. This suggests, a priori, that a penetrometer with a conical deformer is less sensitive to the radius of the latter. However, further experimental studies are needed to confirm this assumption definitively.

When immersing the cylindrical and conical deformers to a depth of 0.10 m (Fig. 9), we have a qualitatively similar situation to that shown in Fig. 8. The quantitative assessment is as follows. With a tip radius of 5 mm, the ΔP parameter value is equal to 16 N. Increasing the deformer radius to 10 mm leads to an increase in ΔP to 62 N, that is, by 3.88 times. And, finally, when immersing the cylindrical and conical penetrometers to a depth of 0.15 m, an increase in the tip radii from 5 to 10 mm is characterized by the rise in the ΔP parameter value from 18 to 71 N, that is, by 3.94 times (Fig. 10).

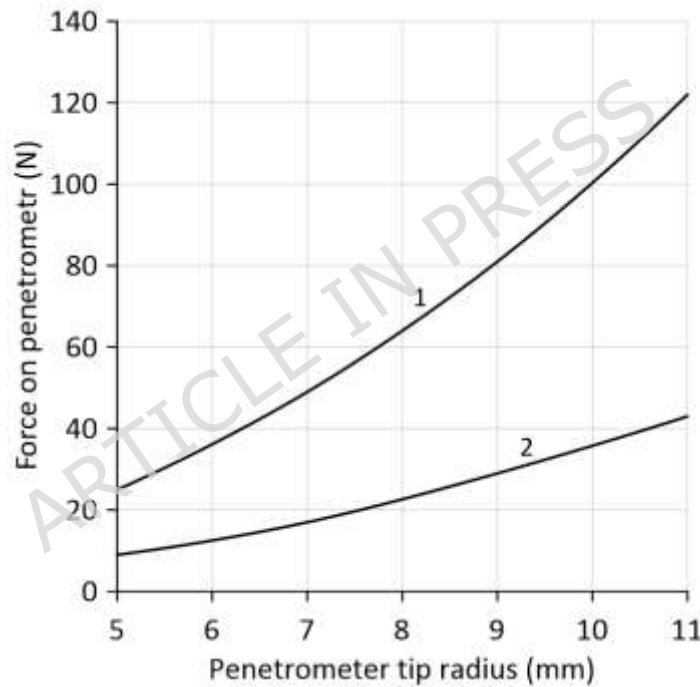


Fig. 9. The effect of the cylindrical (1) and conical (2) penetrometer tips' radius on the force applied to it when penetrated to a depth of 0.10 m

As we can see, across the entire penetration depth range for both conical and cylindrical tips (0-0.15 m), doubling their radius results in a nearly fourfold increase in the difference in applied force. Moreover, as noted above, this difference favors the penetrometer with a conical tip.

If the analytical equation (8) is represented as a functional relationship $P_c = f(P_k)$, it turns out that, when graphically interpreted, it takes the form of a straight line (Fig. 11). Knowledge of this relationship is very useful in practice. A researcher, given specific values for the f , α , k , σ_o and h parameters, can use equation (8) to obtain data for determining the relationship between the radii of the cylindrical and conical penetrometer tips. In this case, the accuracy of the measured soil penetration resistance data will not depend on the selected penetrometer type.

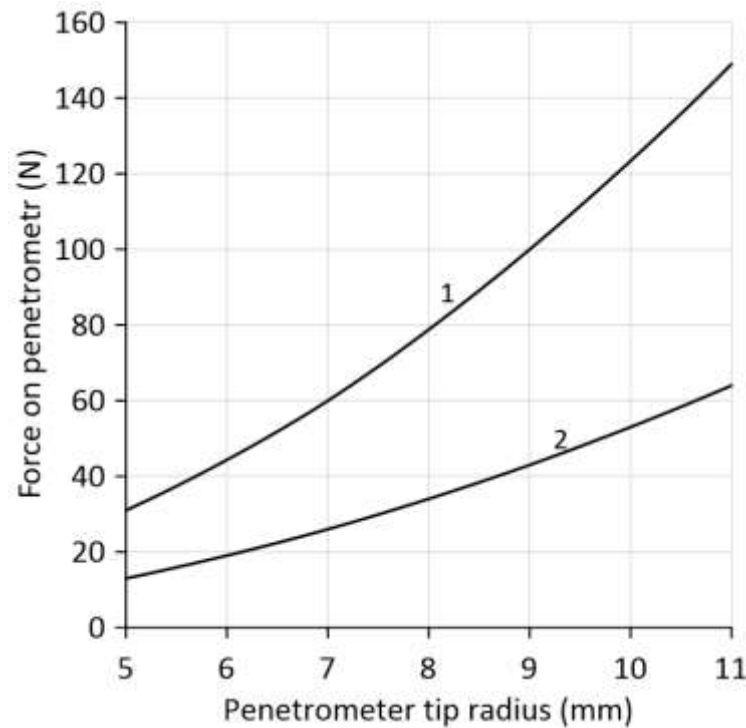


Fig. 10. The effect of the cylindrical (1) and conical (2) penetrometer tips' radius on the force applied to it when penetrated to a depth of 0.15 m

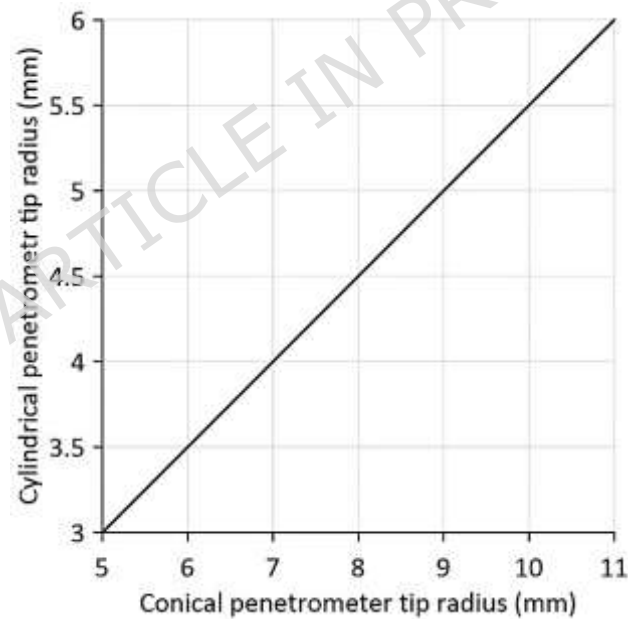


Fig. 11. Dependence of the radius of a cylindrical tip on the radius of a conical tip

Results of experimental studies

Laboratory and field measurements using a penetrometer were conducted at a field site in the Zaporizhzhia region (Ukraine). The soil conditions were as follows: dark chestnut, medium loamy soil with a mean humus content of 3.1% in the 0-15 cm layer. This layer contained 20.3 mg of total nitrogen, 39.1 mg of phosphorus, and 285.0 mg of potassium per kg of soil. During the experiments, the **mean** soil moisture in the 0-15 cm layer was 17.8%, and the **mean** bulk density was 1.29 g·cm⁻³.

Analysis of the obtained data (Fig. 12) shows that penetrometer readings are approximately the same with conical and cylindrical tips of 12.7 mm diameter when inserted to a depth of 5 cm (see Fig. 3). The resulting

difference in soil penetration resistance values, at the statistical significance level 0.05, is random and insignificant. The significant overlap in the confidence intervals of the measured parameter clearly confirms this.

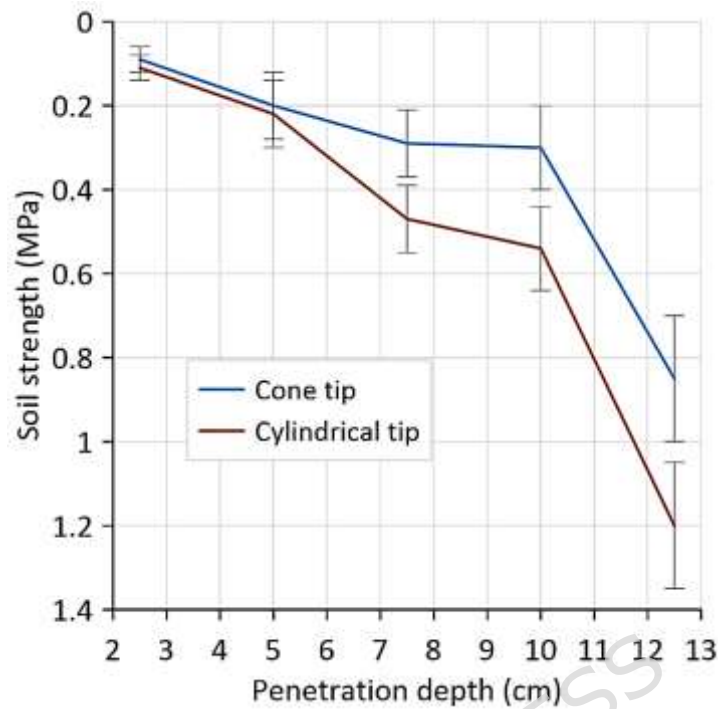


Fig. 12. Soil penetration resistance dynamics in the 0-12.5 cm layer measured using a penetrometer with conical and cylindrical tips of the same diameter

However, at a deformation penetration depth of 5.0-12.5 cm, there is no overlap in the confidence intervals of the compared average soil penetration resistance values. This means that when a conical and cylindrical deformer is inserted to the same depth in the range of 5.0-12.5 cm, the penetrometer readings differ significantly and are not random. For a penetrometer with a cylindrical tip, they are greater than for the same instrument with a conical tip. Therefore, we can conclude that using conical and cylindrical deformers with the same base radius will yield data that are not comparable. This is true when they are obtained under the same soil conditions.

Using relationship (8), it was found that, with a conical tip of 12.7 mm base diameter (d parameter), comparable data can be obtained with a cylindrical tip of 8.0 mm base diameter. Experimental studies fully confirmed the validity of this result. In the soil penetration resistance measurement range of 2.5-15.0 cm, the one-sided confidence intervals for the mean values of this parameter overlap significantly (Fig. 13).

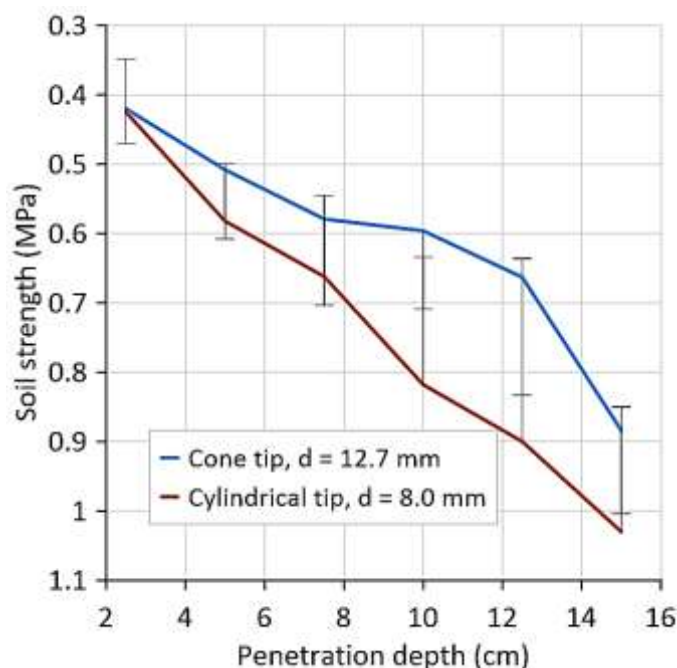


Fig. 13. Soil penetration resistance dynamics in the 0-15 cm layer measured with a penetrometer with conical and cylindrical tips of different diameters

This result gives the right to assert that the analytical dependence (8) is suitable for determining such a ratio of the penetrometer's conical (R_k) and cylindrical (R_c) tips radii, which will ensure comparability of the obtained results on soil penetration resistance.

Conclusions

Research has shown that to obtain accurate soil penetration resistance data, the penetration depth of the penetrometer's cylindrical tip should not exceed 15 cm.

A comparison of penetrometers with conical and cylindrical tips of equal radii showed that the forces required to penetrate them to the same depth into the soil differed. The former required less force than the latter. Moreover, the larger the penetrometer tip radius, the greater the difference between these forces.

It has been experimentally established that, when using penetrometers with conical and cylindrical tips of equal diameter, it is impossible to obtain comparable penetration resistance data for the same soil type at depths exceeding 0.05 m.

An analytical equation has been developed that, given soil characteristics such as ultimate bearing capacity, volumetric compression coefficient, and steel friction coefficient, establishes a relationship between the radii of cylindrical and conical penetrometer tips, yielding comparable and accurate data on soil penetration resistance. The penetrometer with a conical tip is the decisive factor in this regard, as its parameters, unlike those of the cylindrical tip, are standardized.

Author Contributions:

Conceptualization, V.N, T.H., and G.G.; methodology, V.N, S.G., and V.K.; software, V.N., I.H.; validation, I.H., S.G.; formal analysis, S.D., and V.K; resources, T.H., W.T.; data curation, S.D., and G.G.; visualization, S.D., W.T.; project administration, V.N.; funding acquisition, S.G.; supervision, T.H. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement:

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Conflicts of Interest:

The authors declare that they have no conflict of interest.

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