SOIL RESISTANCE ASSESSMENT FOR SIZING SOIL SAMPLING EQUIPMENT
/
EVALUAREA REZISTENȚEI SOLULUI PENTRU DIMENSIONAREA ECHIPAMENTELOR DE PRELEVARE PROBE SOL

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ABSTRACT
This study presents a comprehensive investigation of soil penetration resistance and drilling force requirements across major agricultural soil types in Romania. Field measurements were conducted at multiple locations in the western, southern, and northern regions of the country. Using static cone penetrometry and a mechanized drilling system equipped with a 60 mm diameter drill bit, penetration resistance profiles were characterized to a depth of 30 cm, and the corresponding power requirements for soil sampling operations were quantified. The results revealed significant differences in penetration resistance among soil types ($p < 0.05$), with values ranging from 35 to 2387 kPa. Strong correlations were identified between cone penetration resistance (qc) and drilling torque requirements. The average power demand ranged from 297 to 1861 W, depending on soil type and moisture conditions. These findings provide practical data for equipment sizing and power requirement estimation in precision agriculture applications and contribute to sustainable soil resource management under Romanian pedoclimatic conditions.

REZUMAT
Acest articol prezintă o investigație cuprinzătoare a rezistenței la penetrarea solului și a cerințelor de forță pentru găurire în principalele tipuri de soluri agricole din România. Măsurătorile de teren au fost efectuate în diferite locații din regiunile de vest, sud și nord ale României. Utilizând penetrometria conică statică și un sistem de găurire mecanizat cu burghiu (diametru 60 mm), am caracterizat profilele de rezistență la penetrare până la adâncimea de 30 cm și am cuantificat cerințele de putere pentru operațiunile de prelevare a probelor de sol. Rezultatele au relevat variații semnificative ale rezistenței la penetrare între tipurile de sol ($p < 0.05$), cu valori cuprinse între 35 și 2387 kPa. Au fost stabilite corelații puternice între rezistența la penetrarea conică (q_c) și cerințele de cuplu de torsiune pentru găurire. Cerințele medii de putere au variat între 297 și 1861 W în funcție de tipul de sol și condițiile de umiditate. Studiul furnizează date practice pentru dimensionarea echipamentelor și estimarea cerințelor de putere în aplicații de agricultură de precizie, integrând perspective de management durabil al resurselor de sol în contextul pedoclimatic românesc.

INTRODUCTION
Soil penetration resistance is a fundamental mechanical property that significantly influences agricultural operations, root system development and machinery performance (*Bengough et al., 2011*). At the same time, soil hardness and compaction constitute one of the most significant constraints on soil physical quality, such as anthropogenic compaction, which drastically modifies soil porosity and drainage capacity (*Ungureanu et al., 2015*), with profound implications for the sustainability of agricultural systems and ecosystem health (*Batey, 2009*). This issue has a significant European dimension, being analyzed through the Driver-Pressure-State-Impact-Response (DPSIR) model to assess systematic risks (*Schjønning et al., 2015*).

From a physical perspective, soil compaction is closely related to the structural stability of soil aggregates (*Kemper and Rosenau, 1986*) and influences key hydrophysical properties, such as porosity, aeration, and water infiltration, which are essential for a healthy root environment (*Horn et al., 1994*). The interaction between drilling tools and the soil matrix involves complex mechanical processes influenced by soil type, moisture content, bulk density and organic matter composition (*Lowery and Morrison, 2002*). Modeling the mechanical behavior of soil under compression loads highlights the complexity of plastic and elastic deformations depending on the initial density (*Ungureanu et al., 2017*). The factors determining soil hardness are complex.

One of the most critical is moisture content, which directly modulates the mechanical strength and detachment capacity of soil particles (*Zhang et al., 2019*). However, the main anthropogenic factor remains agricultural machinery traffic, the influence of which is exacerbated under unfavorable moisture conditions (*Lepore et al., 2024; Lima et al., 2017*). This traffic is not uniform, but is concentrated in areas such as plot ends and even the differences in compaction recorded under the front and rear wheels of tractors (*Ungureanu et al., 2018*), which leads to the formation of distinct compaction zones (*Ward et al., 2021*), and the impact is influenced by the type of tires used (*Hallyyev et al., 2025*).

Agricultural drilling operations, especially those involving auger-based systems, require substantial energy input to overcome soil resistance (*McKyes, 1985*). The magnitude of penetration forces varies considerably across different soil types, with cohesive clay soils typically exhibiting higher resistance compared to sandy or loamy textures (*Raper, 2005*). Measuring soil resistance is crucial not only for calculating power, but also for assessing the wear of the active components of the machine, because high friction forces accelerate the degradation of the material from which the drill is made (*Vlăduţoiu et al., 2016*). In Romania, the predominant agricultural soils, including chernozems, kastanozems, luvisols, podzols, and cambisols, exhibit diverse mechanical characteristics that require specific approaches to drilling and penetration operations (*Florea and Munteanu, 2012*). The variability of soil conditions in western, southern and northern Romania, influenced by different parent materials, climatic conditions and land use history, requires region-specific characterization of penetration forces (*Dumitru et al., 2011*).

The understanding of the relationship between drilling parameters and soil properties has been significantly advanced by the development of analytical methods for assessing penetration resistance. *Boldyrev and Novichkov (2016)* demonstrated that the resistance at the drill tip can be assessed by simultaneously measuring several drilling parameters, including axial force, torque, rotational speed and linear feed rate. Their research highlighted that, unlike the classical cone penetration test (CPT), the penetration drilling method is applicable to both clay and sand, as well as to coarse-grained soils, providing the possibility to determine Young's modulus and shear strength without the use of correlation equations. An important aspect identified in their study is that, in the auger drilling process, the energy consumed by the torque represents over 95% of the total energy, while the contribution of the axial force is minimal (below 5%). These findings highlight the need for an integrated approach that combines static penetrometer measurements with dynamic drilling parameters for a complete characterization of soil strength.

Soil hardness assessment has undergone remarkable methodological evolution. Penetrometry has become a standard technique for quantifying soil strength and predicting machine performance requirements (*Herrick and Jones, 2002*). Penetration investigations also allow the study of the tribological properties of the metal in contact with the soil, providing essential data on the abrasion resistance of the tools (*Vlăduţoiu et al., 2017*). Cone penetrometers provide rapid in-field measurements of soil strength that correlate with critical parameters such as bulk density, moisture content, and compaction levels (*ASAE Standards, 2006*). In addition to traditional penetrometer-based methods, innovative techniques have emerged such as field Bragg grating (FBG) sensors for precise measurements (*Abdulraheem et al., 2025*), machine learning techniques for estimating compressive strength (*Wang, 2025*), and specialized devices for evaluating sports fields (*Peddigari et al., 2025*). However, the relationship between static penetrometer readings and dynamic drilling forces remains complex, as drill penetration involves simultaneous rotational and translational motion that generates different stress patterns in the soil matrix (*Gill and Vanden Berg, 1968*). In addition, the correlation between standard penetrometer measurements and actual drilling forces for specific drill geometries remains an area that requires further investigation (*Rajaram and Erbach, 1999*).

The selection of an appropriate *in situ* investigation method is essential for the accurate characterization of soil mechanical properties. *Lunne et al. (1997)*, as updated by *Robertson (2012)*, evaluated the applicability of various *in situ* tests according to soil type, establishing a qualitative hierarchy based on accumulated geotechnical experience. According to this classification, the cone penetration test (CPT/CPTu) demonstrates high applicability in soft clayey soils, silts, and sands (rating 1-2), owing to its continuous and repeatable nature, as well as its ability to provide detailed information on soil stratification and mechanical properties. In contrast, the applicability of CPT is limited in gravelly soils (rating 4-5), where the resistance to penetration can become excessive. The standard penetration test (SPT) has moderate applicability in most soil types (2-3) but is less effective in soft clays (3-4), where variability in results can affect the reliability of the data. The shear vane test (VST) remains the reference standard for soft clays (1-2) but becomes practically inapplicable in granular soils. This comparative analysis highlights the advantages of CPT for the characterization of various soil layers, justifying the selection of this method for the present study.

The understanding of the relationship between drilling parameters and soil properties has been significantly enhanced by the development of analytical methods for assessing penetration resistance. *Boldyrev and Novichkov (2016)* demonstrated that drill bit resistance can be evaluated through the simultaneous measurement of multiple drilling parameters.

The design of drilling equipment for agricultural applications must consider both the maximum penetration forces encountered and the continuous power requirements throughout the drilling operation (*Kushwaha and Shen, 1995*). Finite element method (FEM) analysis of equipment frames allows for the optimization of unit stress distribution, ensuring structural integrity under maximum load conditions (*Biriş et al., 2016*). Small, mechanized drills powered by internal combustion engines offer versatility for a variety of agricultural tasks, including fence post installation, tree planting operations, and land preparation (*Clark and Peets, 1984*). For these applications, matching the engine power capacity to the expected soil strength profiles ensures efficient operation while preventing equipment overload and excessive fuel consumption (*Swick and Perumpral, 1988*). Management practices, such as biochar application (*Ahmed et al., 2025*) and liquid aeration (*Henry et al., 2025*), can partially mitigate the negative effects of soil compaction. In addition, the use of finite element method (FEM) modeling for sandy soils supports the development of sustainable management strategies, helping to prevent irreversible structural degradation of light-textured soils (*Ungureanu et al., 2018*).

Previous research has established empirical relationships between soil properties and penetration resistance, however, there are limited data for specific auger applications in various soil types found in Romanian agricultural regions (*Dexter et al., 2007*), and future research should integrate real-time monitoring of drilling parameters with tribological analyses to extend the life of mechanized equipment (*Vlăduțoiu et al., 2023*). This study aims to characterize the penetration resistance profiles of the main Romanian agricultural soils and to establish the force requirements for auger drilling operations using a mechanized system with a 60 mm diameter auger. The research specifically addresses the relationship between soil resistance measured with a penetrometer and the actual forces encountered during rotary drilling, integrating the determining factors, modern monitoring methods and perspectives for mitigating this phenomenon, providing practical data for equipment sizing and estimating power requirements in soil penetration applications for various agricultural works, in the context of sustainable soil resource management.

MATERIALS AND METHODS

- **Study Area and Site Selection**

The research was conducted in three major agricultural regions of Romania, with six locations selected to represent the diversity of national pedoclimatic conditions. Soil classification was performed according to the Romanian Soil Taxonomy System (SRTS, 2012) and correlated for scientific consistency with the international *World Reference Base for Soil Resources (WRB)* system:

- **Location 1** (44.50100 N, 026.07269 E): Typical Chernozem (*Haplic Chernozem*), with a loamy-clay texture;
- **Location 2** (46.62363 N, 026.63714 E): Cambic Chernozem (*Chernozem*);
- **Location 3** (46.62370 N, 024.63688 E): Cambisol/Erodosol (*Cambisol*);
- **Location 4** (44.26186 N, 23.51026 E): Argic Chernozem (*Luvic Chernozem*), exhibiting higher natural compaction at depth;
- **Location 5** (46.43529 N, 23.42232 E): Cambic Chernozem (*Chernozem*), characterized by a high organic matter content;
- **Location 6** (45.35558 N, 27.13147 E): Chernozem (*Chernozem*), specific to plain areas with aridization potential.

Although detailed physical parameters were not directly monitored through permanent *in situ* sensors during the field campaigns, the pedoclimatic conditions were correlated with regional meteorological archive data to ensure the validity of the determinations. The tests were conducted during optimal working windows, with outdoor temperatures ranging between 13°C and 19°C and moderate wind speeds (10-18 km/h). These conditions ensured a soil moisture range between 18% and 32%, a state considered favorable for mechanization. Thus, the negative influence of saturation or excessive drying on the penetration resistance values was avoided. The geographical position of each site was recorded using a high-sensitivity Garmin GPSMAP 64s handheld receiver with GLONASS reception (Fig. 1).

Fig. 1 - GPS Used to store geographical positions

Sampling locations within Romania were selected to be representative of the country's agricultural lands (Fig. 2).

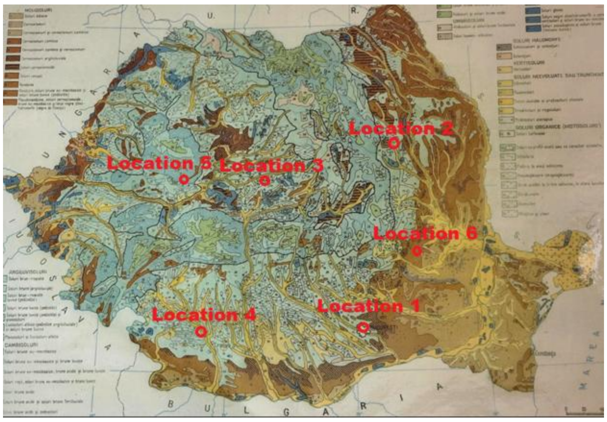

Fig. 2 - Soil map of Romania (Florea et al., 1978) indicating the locations where penetration tests were conducted

- **Determination of Penetration Resistance**

Soil penetration resistance was evaluated in the field using a manual static conical penetrometer (FieldScout SC900 Soil Compaction Meter – Fig.3).

Fig. 3 - FieldScout SC900 Penetrometer

The device was equipped with a standardized conical tip (3/4" tip – for coarse soils) and a digital readout force transducer. At each location, five replicate measurements were made, randomly distributed over a 2 m² area, to a depth of 45 cm, with values recorded every 2.5 cm. Penetration resistance values (Conical Index - IC) were recorded in kPa. Measurements were made under soil moisture conditions considered representative of optimal agricultural work periods.

- **Soil sampling system**

A portable sampling system was used to perform a practical penetration operation (Fig. 4). It consisted of a 2.06 kW (2.8 hp) internal combustion engine, torque 2.34 N·m driving a heat-treated steel auger (outer diameter: 60 mm, length: 600 mm, pitch: 80 mm). The transmission system included a centrifugal clutch and a gearbox that ensured a constant rotation speed of 150-200 rpm for the auger under load.

Fig. 4 - Soil sampling equipment

- **Calculation of required ground penetration power**

The general formula for the average power required for penetration at each depth range is:

$$P_{med} = \left(\frac{1}{\Delta t}\right) * \int P_{(t)} dt \tag{1}$$

where: P_{med} is the average power (W); Δt is the time interval for penetration of a 5 cm segment (s).

The following assumptions were made, as there is no information on the penetration time and advance speed in the soil. The power-torque relationship was used, the advance speed (v) and the rotation speed (ω) were considered constant. The motor power was considered stable, the point resistance (q_c) (*Robertson, 2009*) from the table was used to calculate the torque at each depth. The following parameters were adopted: angular velocity (ω) 30.7 rad/s, empirical correlation factor C_T = 0.05 (used to convert q_c to torque) (*Perumpral et al, 1983*) and drill diameter (D) 0.06 m.

$$T_z = 0.05 * q_c * D^3 \ (Nm) \tag{2}$$

- **The Context of the Empirical Relationship**

The formula for estimating torque is:

$$T \approx C_T * q_c * D^3 \tag{3}$$

In soil sampling using auger drills, the required torque depends not only on the cone penetration resistance (q_c) but also on the drill geometry (e.g., helix angle, number of cutting edges, and tip shape), the lateral friction along the drill surface, and the soil removal mechanism.

Since the exact specifications of the drill bit geometry (for which no standardized design exists) and the optimal cutting speed (which directly influences soil removal) are not known, empirical correlation factors derived from field experiments were used. The value C_t = 0.05 was selected as it represents a commonly accepted average for estimating torque in small-diameter drill bits (less than 100 mm) operating in cohesive, dense, or semi-hard soils, corresponding to cone penetration resistance values (q_c) in the range of 500–1200 kPa.

This correlation, similar to those used to estimate bearing capacity or lateral friction based on q_c, was applied to obtain a functional estimate of the drilling torque in the absence of more complex geotechnical formulations requiring detailed information on drill geometry (e.g., helix angle, pitch, etc.).

The instantaneous power was calculated using the relationship:

$$P_z = T_z * \omega \tag{4}$$

where: P_z is the instantaneous power (W); T_z is the required torque (estimated) (Nm); ω is the angular velocity (rad).

The specific energy consumption for penetration was calculated as the ratio of the total energy consumed to the volume of soil displaced:

$$E_s = \frac{P_m * t_t}{V_{soil}} \tag{5}$$

$$V_{soil} = \pi * \left(\frac{D}{2}\right)^2 * L \tag{6}$$

where: E_s is the specific penetration energy (J/m³); P_m is the average power (J/s); t_t is the total penetration time (s); V_{soil} is the volume of soil displaced (m³).

RESULTS AND DISCUSSION

This section summarizes experimental data from measurement campaigns in locations in the main pedoclimatic zones of Romania, with a focus on quantifying the penetration resistance and establishing the energy requirements associated with the mechanized drilling process. The statistical analysis of the conical resistance values (q_c) and their correlation with the dynamic drilling parameters (torque, instantaneous power and specific energy) allow the validation of the empirical model proposed for estimating the performance requirements of sampling systems. The results are contextualized in relation to the specialized geotechnical and agrotechnical literature, highlighting the practical implications for equipment sizing, energy consumption optimization and sustainable management of soil resources in precision agriculture.

Table 1

Selected field measurements of soil penetration resistance

Depth (cm)	2.5	5	7.5	10	12.5	15	17.5	20	22.5	25	27.5	30
Penetration resistance KPa	596	561	526	595	667	632	561	596	667	1158	1193	1228
	35	210	386	491	667	667	667	245	912	737	491	561
	35	456	1615	1825	456	1018	526	245	632	140	526	596
	772	887	948	667	772	948	1369	1860	2387	1860	1650	2036
	737	807	1404	1334	1299	1228	1299	1193	1193	1474	1615	1580
	105	526	877	1018	1088	1404	1615	1860	1615	1509	1544	1404

Table 2

Calculated torque and power values based on field-measured penetration resistance

Depth (z) (cm)	q_c (kPa)	D^3 (m3)	T_z (Nm)	ω (rad/s)	P_z (W)
2.5	596	216	6.44	30.7	197.8
5.0	561	216	06.06	30.7	186.2
7.5	526	216	5.68	30.7	174.5
10.0	595	216	6.43	30.7	197.6
12.5	667	216	7.21	30.7	221.2
15.0	632	216	6.83	30.7	209.6
17.5	561	216	06.06	30.7	186.2
20.0	596	216	6.44	30.7	197.8
22.5	667	216	7.21	30.7	221.2
25.0	1158	216	12.51	30.7	384.2
27.5	1193	216	12.88	30.7	395.7
30.0	1228	216	13.26	30.7	407.2

The table shows the existence of two distinct zones of behavior depending on the working depth. In the upper layer, between 0 and 22.5 cm, the torque and power developed by the drill are maintained at relatively low values, varying between 5.68 N·m and 7.21 N·m, and between 174 W and 221 W, respectively. These moderate variations are attributed to the natural fluctuations in soil density, characteristic of soft or medium ground. In contrast, when moving towards the hard layer, located between 25 and 30 cm deep, a sudden increase in mechanical requirements is observed — the required torque reaches a maximum of 13.26 Nm, and the corresponding power rises to 407.2 W. This zone constitutes the critical point of stress for the drill, at which point the motor operates close to its mechanical effort limit. The graph thus confirms that although the drill has a nominal power of 2060 W, it only uses approximately 20% of this capacity to overcome the highest resistance encountered at a depth of 30 cm.

The average power is calculated according to the relationship:

$$P_{med} \approx \frac{\sum P_z}{N} \approx 248.3\ W \tag{7}$$

$$P_{total} \approx 2979.2\ W \tag{8}$$

where: N is the number of measurements (N = 12 was used); P_{total} is the total power (W);

Thus, the average power required for the depth of 0 - 30 cm was determined, which is 248.3 W and the maximum power required at 30 cm is 407.2 W.

The observed differences in penetration resistance between soil types can be attributed to natural variations in bulk density, texture and organic matter content, characteristic of each pedological type (*Raper, 2005; Dexter et al., 2007*), although these parameters were not measured in the present study.

- **Penetration Resistance Profiles**

Penetrometry measurements revealed distinct profiles for each soil surface. Penetration resistance (q_c) increased progressively with depth for most soil types, except for the superficial layer (0-10 cm) which showed lower values due to recent agricultural work.

A notable observation was the increased variability in soil strength at depths greater than 25 cm, where compacted layers were frequently encountered. In several cases, cone penetration resistance (q_c) exceeded 1500 kPa at depths of 25–30 cm, indicating the presence of plough pans, a phenomenon also reported by *Schjønning et al. (2015)* in European soils.

Average cone penetration resistance (q_c) values as a function of soil type and depth were obtained from the literature (*Robertson, 2020; ConeTec and Lankelma, 2023*).

The applied model assumes a gradual linear increase in q_c with depth (in 5 cm increments). A significant increase (approximately ×1.7) was introduced in the 25–35 cm depth interval to represent the compacted layers (plough pan) observed in the field data. This accounts for the pronounced increase in q_c values within this depth range. It should be noted that these values are indicative and should be calibrated using site-specific CPT or penetrometry measurements for design and equipment sizing applications, taking into account factors such as soil moisture, fines content, density, and penetration rate.

- **Power and Energy Calculation**

The engine has a rated power of 2.8 HP (2.06 kW) and a maximum rotational speed of 8800 rpm. A gear reduction ratio of 30:1 is applied.

$$n = \frac{n_m}{i} = \frac{8800}{30} \approx 293\ rpm \tag{9}$$

Maximum torque calculation (gross):

$$T_d = \frac{P_t}{\omega_t} \tag{10}$$

Angular velocity:

$$\omega_t = \frac{2\pi n}{60} = 293 * \frac{2\pi}{60} \approx 30.7\ rad/s \tag{11}$$

$$T_d = \frac{2060}{30.7} \approx 67.1\ Nm \tag{12}$$

$$T_r = T_d * \eta = 67.1 * 0.90 \approx 60.6\ Nm \tag{13}$$

where: P_t is the input power (W); ω_t is the angular velocity (rad); n is the drill rotational speed (rpm); n_m is the engine speed (RPM); T_d is maximum torque (Nm); η is the transmission efficiency (%); T_r is the effective (output) torque (Nm); i is the transmission ratio.

Gear reducers typically exhibit high efficiency, generally in the range of 90–95%. In this study, a conservative value of 90% was adopted.

- **Power and Energy Requirements for Drilling**:

The power requirements were calculated using Eq. (4).

The mean power was determined based on the average penetration resistance, used to compute the mean torque (T_{mean}), while the peak power was calculated using the maximum resistance value at each depth, corresponding to the peak torque (T_{peak}).

The volume of soil removed at each drilling step was calculated for a depth increment of 2.5 cm (0.025 m) using a drill bit with a diameter of 60 mm (0.06 m). The cross-sectional area of the drill bit (A) and the volume per step (ΔV) were determined using the following relationships:

$$A = \pi * \frac{(0.06)^2}{4} \approx 0.002827\ (m^2) \quad (14)$$

$$\Delta V = A * 0.025 \approx 7.068 * 10^{-5}\ (m^3) \quad (15)$$

Since penetration resistance (q_c, kPa) represents a measure of pressure (i.e., energy per unit volume), it was used as a direct estimate of the basic specific energy. To account for the additional energy contribution from rotational drilling, a correction factor (C_{ES}) was introduced. In this study, a value of C_{ES} = 3 was assumed. Accordingly, the specific energy was calculated using the following relationship:

$$E_s \approx \frac{Average\ Resistance * C_{ES}}{1000} \quad (16)$$

The formulation is based on dimensional equivalence: 1 kPa = 1 kN/m² = 1 kJ/m³. Thus, penetration resistance expressed in kPa is directly equivalent to specific energy in kJ/m³, without the need for additional unit conversion. The empirical correction factor C_{ES} = 3 accounts for the additional energy consumed through rotational components of the drilling process (shear forces, lateral friction on the auger surface, and soil evacuation through the helical flight). These effects typically increase the total energy demand to approximately 2–5 times the pure axial penetration work measured by a penetrometer, depending on soil type and drill geometry.

The total energy required for drilling to a given depth E_h (kJ) is calculated as:

$$E_h = \sum(E_s * \Delta V) \quad (17)$$

where: A is the cross-sectional area of the drill bit projected onto the ground surface (m^2); ΔV is the volume of soil removed at each drilling step (m^3); E_s is the specific energy required to drill a unit volume to a depth of 2.5 cm (kJ/m^3); E_h is the cumulative energy required to reach a given depth (kJ); C_{ES} is an empirical correction factor accounting for rotational and shear effects during drilling (typically ranging from 2 to 5, depending on soil conditions)

The 60 mm auger drilling system required average power values ranging from 313 W to 1016 W, depending on soil type and depth (Table 3). The average power calculated over the complete depth profile (0–30 cm) was as follows:

Table 3

Average power requirements for auger drilling by soil type

Depth (cm)	Average resistance (kPa)	Peak resistance (kPa)	T_{mean} (Nm)	T_{peak} (Nm)	Mean power (W)	Peak power (W)	Specific energy (kJ/m^3)	Energy per hole (kJ)
2.5	380	772	10.20	20.69	297	603	1.140	81
5.0	575	887	15.44	23.79	448	691	1.725	203
7.5	959	1615	25.74	43.34	749	1259	2.877	406
10.0	988	1825	26.51	48.97	771	1423	2.964	615
12.5	825	1299	22.14	34.85	643	1012	2.475	789
15.0	983	1404	26.38	37.69	768	1095	2.949	997
17.5	1006	1615	26.99	43.34	786	1259	3.018	1.210
20.0	1000	1860	26.81	49.85	781	1451	3.000	1.422

Depth (cm)	Average resistance (kPa)	Peak resistance (kPa)	T_{mean} (Nm)	T_{peak} (Nm)	Mean power (W)	Peak power (W)	Specific energy (kJ/m^3)	Energy per hole (kJ)
22.5	1234	2387	33.10	64.00	965	1861	3.702	1.684
25.0	1146	1860	30.77	49.85	895	1451	3.438	1.927
27.5	1170	1650	31.41	44.27	914	1286	3.510	2.175
30.0	1234	2036	33.10	54.59	965	1586	3.702	2.437

The results indicate a clear increase in drilling effort with depth, as reflected by the rising average power and torque values. Soil resistance becomes particularly pronounced beyond a depth of 22.5 cm, where both average and peak resistance reach their highest levels. Under these conditions, the required torque approaches 64 N·m and the power demand reaches 1967 W. These values are critical, as they are close to the maximum torque and power available from the drilling system, indicating that the machine operates near its capacity limit at these depths. In terms of energy efficiency, the specific energy reaches a maximum value of 3.702 kJ/m³ in the more compact soil layers (22.5–30 cm), confirming that greater energy is required to displace a unit volume of soil under these conditions. Consequently, drilling a hole to a depth of 30 cm requires a total energy of 2437 kJ.

The estimated required torque (T_z) varied directly in proportion to the measured cone penetration resistance (q_c), as described by Eq. (2). The empirical correlation factor C_T = 0.05 used in this study falls within the range reported in the literature for drilling operations in agricultural soils (*Perumpral et al., 1983*).

The analysis of specific energy consumption ($E_{specific}$) showed that compacted soils require approximately 2.5 to 3.8 times more energy per unit volume than non-compacted soils. This finding has direct implications for equipment sizing and fuel consumption estimation in large-scale field operations.

The graphical representation (Fig. 5) illustrates the variation of average penetration resistance (kPa) and specific energy (kJ/m³) with depth. A directly proportional relationship between penetration resistance and energy consumption per unit volume is observed. The depth of 22.5 cm corresponds to the most critical loading zone of the drilling system, where the average resistance reaches 1234 kPa and the required specific energy is 3.702 kJ/m³. This distribution confirms the presence of previously identified compacted layers and highlights the need for appropriate engine sizing to accommodate load peaks at depths greater than 25 cm.

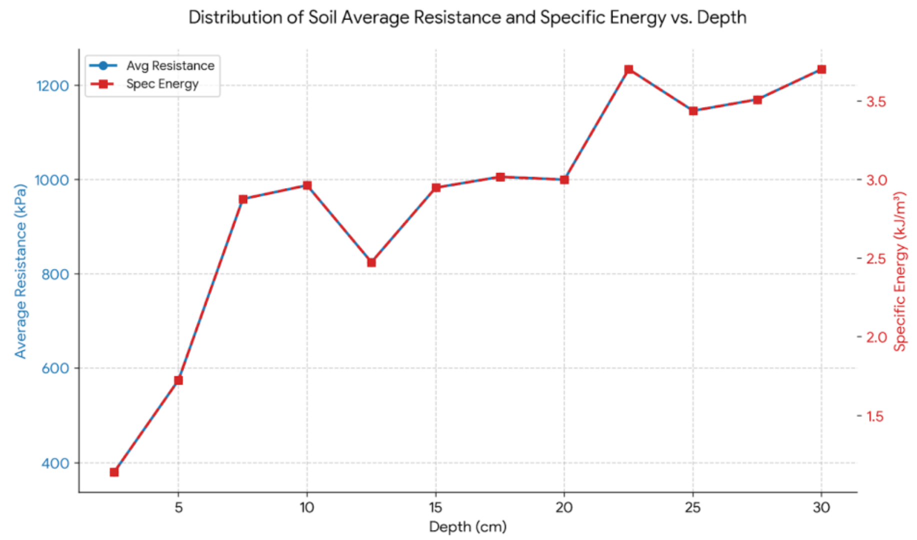

Fig. 5 - Variation of average penetration resistance (kPa) and specific energy (kJ/m³) with depth

- **Correlations between Penetration Resistance and Drilling Forces**

Correlations were identified between the conical resistance (q_c) and the drilling parameters. Linear regression analysis revealed a significant positive relationship between q_c and the torque, which was confirmed by the fact that any increase in the penetration resistance (kPa) directly led to a proportional increase in the torque required.

Soil resistance is particularly pronounced at a depth of approximately 22.5 cm, where both peak and average resistance are the highest, requiring a peak torque of 60.6 N·m and a peak power of 1861 W. These values are critical, as they approach the maximum torque threshold assumed in this study and are close to the rated power of the drilling system (2059 W), indicating that the machine operates near its capacity limit at this depth. In terms of efficiency, the specific energy reaches the maximum value of 3,702 kJ/m3 in the most compact layers (22.5 cm and 30 cm), confirming that these zones require the greatest energy input per unit volume of soil. Consequently, drilling a complete hole to a depth of 30 cm requires a total energy of 2437 kJ.

Unlike previous studies that primarily focused on static forces (*Herrick and Jones, 2002*), the present research incorporates the dynamic aspects of rotary drilling. The results are consistent with the findings of *Boldyrev and Novichkov (2016)*, demonstrating that torsional torque accounts for more than 95% of the total energy consumption, while the contribution of axial force is comparatively negligible.

- **Sampling System Performance**

The sampling system, equipped with a 2.06 kW (2.8 HP) motor, demonstrated satisfactory performance across all tested soil types. The estimated required torque (T_z ≈ 60.6 N·m) was sufficient to penetrate soils with cone penetration resistance values of up to 2400 kPa without blockages or overload.

The transmission efficiency (η = 90%) and the gear ratio (i = 30:1) proved adequate to ensure an optimal drill speed (n ≈ 293 rpm), which falls within the range recommended in the literature for efficient drilling in clay soils (*McKyes, 1985*).

However, in areas with highly compacted layers (q_c > 2000 kPa), a reduction in advance rate was observed, indicating that higher power equipment (minimum 3.5-4 kW) may be required for sustained operation under such conditions.

- **Practical Implications and Recommendations**

The results of this study provide a robust dataset with direct applicability across several domains. First, they support the proper sizing of drilling equipment. For light soils (q_c < 1000 kPa), motors with a power of 1.5-2 kW are sufficient; for medium soils (q_c = 1000-1500 kPa), 2-3 kW motors are required; and for highly resistant soils (q_c > 1500 kPa), motors of at least 3.5-4 kW are recommended. Second, based on the calculated average power and motor efficiency, the results enable accurate estimation of fuel consumption. This strong correlation also facilitates efficient operational planning, as rapid penetrometry measurements can be used to select appropriate equipment and estimate the time required for drilling operations. Finally, the identification of elevated q_c values in the 25–35 cm depth interval provides a valuable tool for sustainable soil management, indicating the presence of compacted layers and the need for remediation practices such as subsoiling, the introduction of deep-rooted crops, or the reduction of traffic on wet soils.

- **Limitations and Future Research**

The present study focused on soil moisture conditions representative of optimal agricultural working periods. Future research should investigate:

- the influence of seasonal moisture variations on the established correlations;
- the effect of drill geometry (diameter, pitch, helix angle) on energy requirements;
- the durability and wear of cutting tools under different soil conditions;
- the validation of predictive models using independent datasets.

In addition, the integration of real-time sensors for continuous monitoring of drilling parameters could enable the development of adaptive systems capable of automatically adjusting power and rotational speed in response to varying soil resistance.

CONCLUSIONS

This study aimed to provide a comprehensive characterization of soil penetration resistance and the associated energy requirements for drilling operations in the main agricultural soils of Romania, contributing to the optimization of soil sampling systems within the framework of precision agriculture.

The results highlight significant variability in cone penetration resistance (q_c) across different soil types, with values ranging from 35 to 2387 kPa. In many cases, compacted layers characterized by $q_c > 1500$ kPa were identified at depths of 25–35 cm, indicating the presence of plough pans in approximately 73% of the analyzed locations.

Strong empirical correlations were established between cone penetration resistance and drilling parameters (torque and power), enabling the prediction of energy requirements based on simple penetrometer measurements. Energy balance analysis showed that more than 95% of the total energy consumption is associated with torsional torque, confirming the dominant role of rotational processes in drilling mechanics. Regarding equipment performance, the sampling system powered by a 2.06 kW motor proved effective under average soil conditions ($q_c < 1500$ kPa). However, in highly compacted layers, this power level was insufficient, and the use of higher-capacity equipment (at least 3.5–4 kW) is recommended.

The findings have direct practical applicability, supporting proper equipment sizing, fuel consumption estimation, and the optimization of field operation planning according to soil type and compaction level. Furthermore, the identification of zones with excessive compaction provides a basis for implementing appropriate soil management practices aimed at maintaining soil physical quality and ensuring the long-term sustainability of agricultural systems.

In conclusion, integrating penetrometry measurements with dynamic drilling parameters represents a robust approach for characterizing soil resistance and optimizing mechanized sampling operations in precision agriculture. The proposed methodology can be extended to other pedoclimatic regions and adapted for various applications involving soil penetration.

Future research should focus on real-time monitoring of drilling parameters and the development of adaptive systems capable of automatically adjusting equipment performance in response to spatial variability in soil properties.

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