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Evaluation of soil Force of Resistance to Penetration with the Use of New Design of Penetrometer's Probe Tip

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ABSTRACT

Background/Objectives: This paper considers design of penetrometer's conical tip that works on the principle of compressed air release for the purpose of evaluation of soil porosity. This provides determination of soil state upon influence of all types of agricultural equipment. Methods/Statistical analysis: Four variants of design with different geometric parameters of radiuses of their beddings and cone angles were used. Findings: The conducted analysis revealed the optimal variant for working measurements is the cone tip with 300 cone angles and bedding radius equal to 7 mm. The tip includes four venting orifices, which under pressure of 6 bar provides better penetration to soil of various depth without causing damage to its structure

KEYWORDS

Penetrometer, soil consolidation, resistance force, compressed air release time

ARTICLE HISTORY

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Introduction

Consolidation of soil leads to change of its structure under influence of external factors and has impact on structure with lower porosity thereby increasing its density (Dickerson, 1976; Mcnabb & Froehlich, 1984; Perumpral, 1987; Shein, 2005). There is growing interest towards measurements of soil shrinkage due to numerous factors having impact on its fertility and germination of cultivated plants. The values of soil consolidation measurement depend on climatic conditions, provide estimation of root system distribution within soil and also help to avoid any problems linked to soil fertility and germination of plants (Romig et al., 1995). The process of agricultural soil consolidation has an impact on many of its physical properties. One of the most widespread methods for measurement of soil consolidation is the cone penetration, the results of which are displayed on penetrometer's scale. There are many factors that influence soil consolidation degree - for example, the size of soil particles, density and content of organic substances (Howard & Singer, 1981). They also include structural composition of soil and moisture content, which have the most significant impact on evaluation of resistance force due to the degree of soil shrinkage. Another one factor is the presence of large pores in

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soil - it influences soil in general. Although different types of soils possess wide range of structure types, it was determined the soil possessing more fine-granular structure is exposed to shrinkage to a greater degree and has higher density (Geist & Hazard, 1989; Page-Dumbroese & Harvey, 1997; Swanson, 1950). According to (Williamson & Neilsen, 2000), typical forest soil forms on the basis of solid structures and is being more resistant to the process of soil consolidation, than a soil of rain forests that possesses clay structure. Moreover, as source (Froehlich, 1980) determines, the clay soil possesses more solid and coherent structure - so when it remains dry for a long time, its density has a tendency to change significantly when moisturized. The result of applying agricultural equipment to the moist soil is the increase of its density within the traces left by the equipment. Maximum shrinkage of soil takes place when its moisture level is being close to field moisture capacity. The higher the content of moisture in soil, the less pressure is required to lead to its consolidation. When the level of moisture is low, the consolidation of soil is not performed even in cases when pressure is rather high, which is confirmed in (Howard & Singer, 1981). The soil resistance force is influenced by many factors, including in particular its moisture, density and the whole structure (Froehlich, 1980). There is a number of factors that have impact on the degree of soil shrinkage as a result of agricultural works, for example, the amount of passages performed by used agricultural equipment, type of the equipment, wheel slipping, vehicle speed, vibration, etc. (Baver, Gardner & Gardner, 1972; Geist & Hazard, 1989; Gomez & Powers, 2002; Hatchell & Ralston, 1970; Hesse, 1971; Huang et al., 2004; Jackson, 1969; Johnson & Beschta, 1980; Meek, 1996). However, it is considered that the most significant factor is the amount of passages performed by vehicles. There are also some researches for defining factors having impact on growth of cultivated plant as a result of influence of heavy equipment that led to soil consolidation (Gomez & Powers, 2002; Johnson & Beschta, 1980). The researches revealed the consolidation of soil causes reduction of germinating ability of cultivated crops, for example, of corn. Consolidated soils were measured for penetration to the depth of 45,7 cm. in places that have not been exposed to consolidation, as well as in tracks that has been consolidated by wheels of vehicles. It was found out that in the tracks consolidated the force of resistance to penetration turned out to be higher and possessed quite high level at depth of just 7,6 cm., while in the places that have not been exposed to influence of equipment wheels it became tangible only at depth of 30,4 cm.

The results revealed the higher degree of soil shrinkage, the higher force of resistance to penetration and its density are.

Scientific research goals

This research is aimed at study of factors having impact on grounding of design of probe that works on the principle of compressed air release for defining force of soil resistance to penetration of the probe, as far as use of manual method of evaluation of force of probe introduction to soil will be different depending on strength of this or that person.

Materials and methods

The procedure on measurement of physical and mechanical properties of soil depends on many variables due to big differences in soil types and therefore there is a necessity of defining characteristic of any device used for obtaining of various physical and mechanical characteristics and chemical properties of soil. In the present research new design of probe meant for measurement of force of resistance to penetration works on the principle of compressed air release, as it is shown in figure 1, including influence of the following factors:

1. Form of cone. There are four types of cone forms (fig. 2) being in accordance with specificity presented in (Antibas & Dyachenko, 2014; Meek, 1996):

- cone No.1: top part with cone angle of 300 and 20 mm. bedding;
- cone No.2: top part with cone angle of 300 and 14 mm. bedding;
- cone No.3: top part with cone angle of 600 and 20 mm. bedding;
- cone No.4: top part with cone angle of 600 and 14 mm. bedding.

To define the best variant the measurements of present cones' soil penetration capacity have been carried out.

2. Amount of venting orifices: one, two and four orifices.

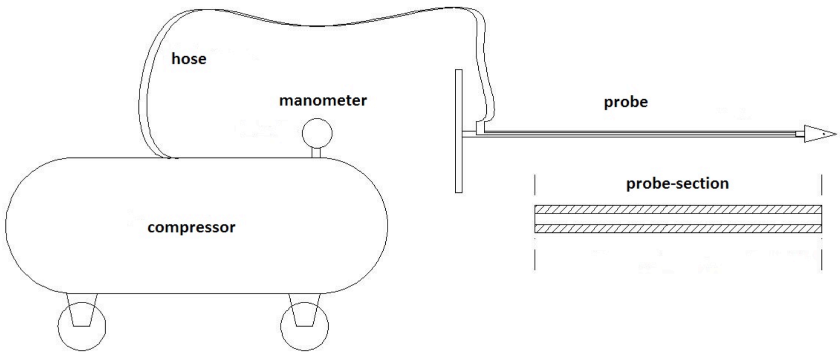

Figure 1. Scheme of facility for measurement of soil force of resistance to penetration.

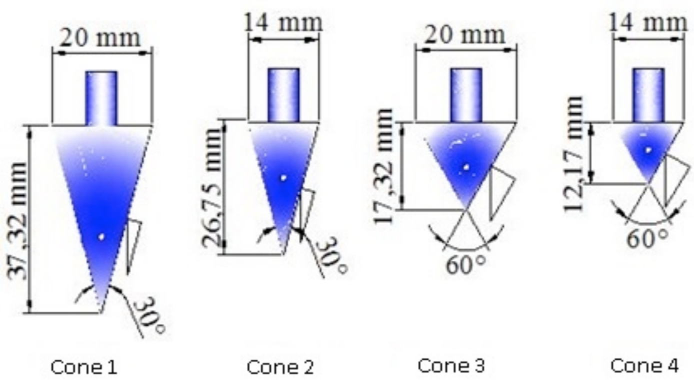

Figure 2. Forms of cones and their specifications used in the research.

3. The alumina density was defined by four values. The soils were placed to metal containers with square section of 25 x 25 cm. and volume of 1 liter. The values of density for the soil block of 15 kg. are the following: 1; 1,2; 1,3 and 1,5 (g/cm3).

4. Air pressure. The pressure of air generated by compressor made 2,4 and 6 bar. Either was estimated the time necessary for air compression in soil pores for every sample. The applied working pressure of compressor - 10 bar, cylinder capacity - 200 l. To evaluate the strength of soil structure all the measurements were conducted with use of alumina (Kaurichev, Panov & Rozov, 1989) possessing structure, the size of soil particles of which makes less than 2 mm.

Depending on the method of separation of main components used in definite order it was determined the content of calcium carbonate (% $CaCO_3$) should be measured by calcimeter (Busscher et al., 1997), while general content of organic substances in calibrated sample after rapid oxidation with potassium bichromate $K_2Cr_2O_7$ and wet oxidation should be in accordance with the method described by Black and Walky (Jackson, 1969).

First we have carried out measurements of acidity (pH) and electrical conductivity of pastelike soil (Smith & Mullins, 2001), while densimeter has been used for evaluation of density. To calculate porosity the following formula was used (Adams & Froehlich, 1981):

$$f = 1 - \frac{\rho_b}{\rho_r} \%,$$

where ρ_b - soil density; ρ_r - particle density.

All the measurements were carried out in specialized laboratory for the aim of defining soil resistance to penetration of penetrometer.

Analysis of results

Mechanical stimulation of soil causes change of its structure, which leads to increase of density that is attended by decrease of moisture content and the process of gaseous interchange with environment. Simultaneously there is an increase of soil force of resistance to penetration. The more moisturized soils on the contrary possess increased resistance to penetration (especially, those types of agricultural soils with more porous structure).

The value of density is influenced by sizes of soil structure, content of organic substances and water in alumina.

At the present time an alternative method for determination of soil shrinkage on a large scale is used. It implies scaled-up evaluation of soil force of resistance to penetration with help of penetrometer with metal probe and conical tip. The resistance is supposed to be similar to the force of soil resistance to penetration of roots, which is evaluated in kPa (Foster et al., 2005).

In this research we have drown a comparison between values of soil resistance to penetration of different probe's tips, which had been performed with use of soil with two levels of density (1,1 и 1,5 g/cm3). In figures 3 and 4 there are different values of resistance to penetration of conical tips with above-listed parameters. The obtained data show that the values of force of soil resistance reduces for cones with different designs and the same bulk density of 1,1 g/cm3 (figure 3) in comparison to the values of soil resistance before penetration of cone to soil with density of 1,5 g/cm3.

The graphs represented in figures 3 and 4 show the cone No.3 possessing 600 angle and 20 mm. bedding is being more resistant to penetration in both cases (i.e. when the values of bulk density make 1,1 g/cm3 and 1,5 g/cm3) reaching the maximum values of forces applied to the cone when penetrating to soil of 110 H with bulk density of 1,5 g/cm3 and 85 H with bulk density of 1,1 g/cm3.

On the contrary, cone No.2 possessing corner of 300 with bedding of 14 mm. experienced the lowest value of soil force of resistance to penetration reaching the maximum value of force applied for penetration of probe's conical tip to the soil of 60 H and bulk density of 1,5 g/cm3, while in case of soil density being equal to 1,1 g/cm3 the present value reduced to 35 H.

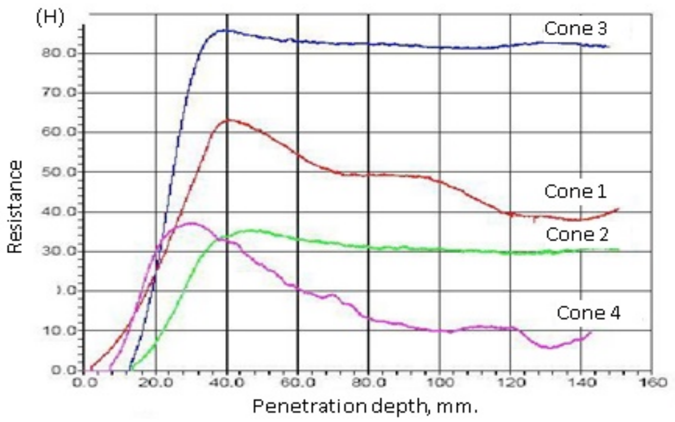

Figure 3. Force of soil resistance to penetration for different types of conical tips along with soil density of 1,1 g/cm^3

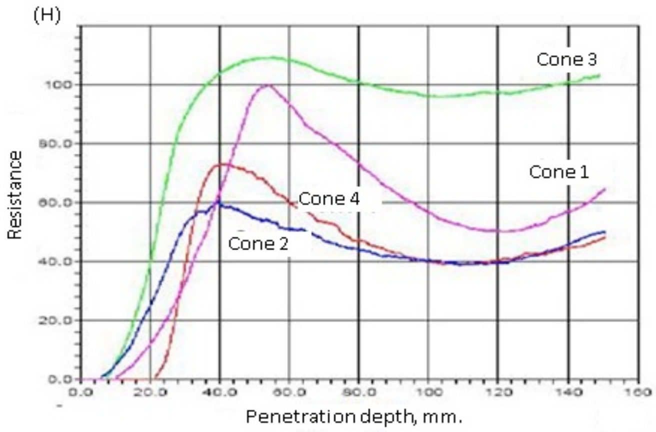

Figure 4. Force of soil resistance to penetration for different types of conical tips along with soil density of 1,5 g/cm^3

In case of soil bulk density equal to 1,1 g/cm3 and use of cone No.4 possessing cone angle of 600 and 14 mm. bedding the force reduced from 36 H to 10 H, while cone No.2 provided the most stable results on resistance force throughout the whole depth of cone's penetration. The data obtained with help of penetrometer are completely coincide parameters that influence force of soil resistance to penetration of cone tip:

- soil density is influenced by the share of free spaces in soil and its general porosity. The parameters for prediction of soil compressibility are used mainly due to the fact they most often show direct changes in sizes of pore spaces;

- the square area of conical tip surface that has direct contact with soil (A); the four researched cones were named "cone 1", "cone 2", "cone 3", "cone 4" (with square areas of 1210, 607, 627 and 309 mm2 correspondingly). The values were calculated with the ratio: $A = \pi r\sqrt{r^2 + h^2}$, where r - radius of cone's bedding, mm; h - height of cone, mm;

- cone's angle: it was revealed the resistance force being perpendicular to the top of cone and angled 600 is approximately 2 times higher, than resistance force upon the cone's surface under the same pressure force (see figure 5). This explains growing resistance of soil in bigger cones' angles in comparison to cmaller ones (see figures 3 and 4).

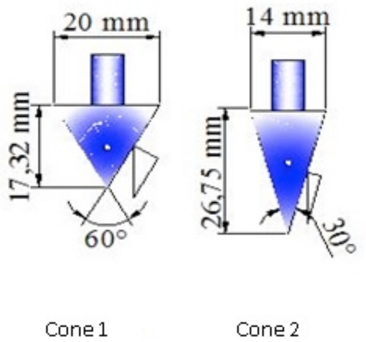

Figure 5. Force of resistance upon side faces of cones

The data on soil resistance to penetration obtained with help of penetrometer found limited application in the agricultural sector, namely, in the area of root system distribution. Roots of plants are influenced by free space in soil structure, while soil resistance to penetration depends on many factors. Pore spaces and general porosity (including disposition and size of soil pores) can be largely expressed by soil density having significant impact on environment in the area of root system distribution. Optimal method of soil treatment will influence the growth of plants, while big sizes of soil pores affect the content of air for oxygen supply and sustaining vital processes.

From this point of view we have grounded that penetrometer can evaluate the volume of pore spaces in soil by means of measurement of time necessary for elimination of compressed air through venting orifices of penetrometer probe's cone tip when using different values of pressure equal to 2-4 and 6 bar.

Different measurements of alumina have been taken. In table 1 there are the most important physical and chemical properties of this type of soil, the share of clay in which made 63%, calcium carbonate 11,5%, organic substance 0,58 %, while its density was equal to 2,68 g/cm3.

Measurements of compressed air release under four values of density were carried out as well. The soil was allocated in four metal containers of 1 liter each. The mass of soil block was determined as 15 kg, while the values of density made 1; 1,2; 1,3 and 1,5 g/cm3.

Figures 6, 7 and 8 show correlation between density values and intensity of compressed air release under working pressure of 2-4 and 6 bar using definite number of venting orifices (1-2-4). Thus, we have revealed the most appropriate design of cone tip, as well as values of working pressure, which provided the highest correlation coefficient. In table 2 there are results on coefficients of determination and correlation taken in the research. The used pressure of 4-6 bar provided the highest coefficients of correlation R: 0,96; 0,96 and 0,98. These data were obtained when using one, two or four orifices in conical tips of probe, at that it was found out that when using working pressure of 6 bar and the tip with four orifices the coefficient of correlation R for compressed air release make the maximum value of 0,98.

Table 1. Physical and chemical properties of soil samples

Soil structure	Size	Dimension
clay	634.7	$g.kg^{-1}$
silt	193.2	$g.kg^{-1}$
fine sand	129.7	$g.kg^{-1}$
solid sand	42.4	$g.kg^{-1}$
structure	clay	-
% moisture content	10.39	-
Specific electrical conductivity, dc/m	0.52	-
pH acidity	7.89	-
general value CaCO3%	11.5	-
% organic substances	0.58	-
density	2.68	g/cm^3

This result is being commensurate with even distribution of compressed air in soil pores surrounding the surface of cone tip and all its aspects in comparison to results taken when using tips with one or two orifices. Subsequently, the exponent equation, which links together the time necessary for elimination of compressed air from soil pores and the values of soil shrinkage expressed through density under pressure of 6 bar when using cone tip with four orifices, is the following:

$$y = 1{,}378e^{2{,}717x},$$

where y - volume porosity; x - time of air release, sec; e - base of natural logarithm.

This equation allows us to define the sizes of space necessary for performance of compressed air pressure under the present conditions with use of materials listed in (Baver, Gardner & Gardner, 1972). So it can be used for calculation of volume porosity. The defined values of porosity with corresponding values of bulk density (1; 1, 2; 1,3 and 1,5 g/cm3) made 62,69; 55,49; 51,49 and 44,03, while the time of compressed air release is in direct ratio to base of natural logarithm for general soil porosity.

Table 2. Value of determination coefficient for different values of correlation coefficient

Amount of orifices	pressure (bar)	R2 correlation coefficient	R determination coefficient	Forms of logarithms
1	P1 (2 - 0)	0.881	0.94	$y = 5.963e^{3.542x}$
	P2 (4 - 2)	0.843	0.92	$y = 2.065e^{3.884x}$
	P3 (6 - 4)	0.927	0.96	$y = 6.780e^{1.902x}$
2	P1 (2 - 0)	0.809	0.90	$y = 5.705e^{3.403x}$
	P2 (4 - 2)	0.822	0.91	$y = 0.730e^{4.495x}$
	P3 (6 - 4)	0.931	0.96	$y = 3.170e^{2.253x}$
4	P1 (2 - 0)	0.840	0.92	$y = 10.56e^{2.757x}$
	P2 (4 - 2)	0.809	0.90	$y = 4.705e^{2.580x}$
	P3 (6 - 4)	0.953	0.98	$y = 1.378e^{2.717x}$

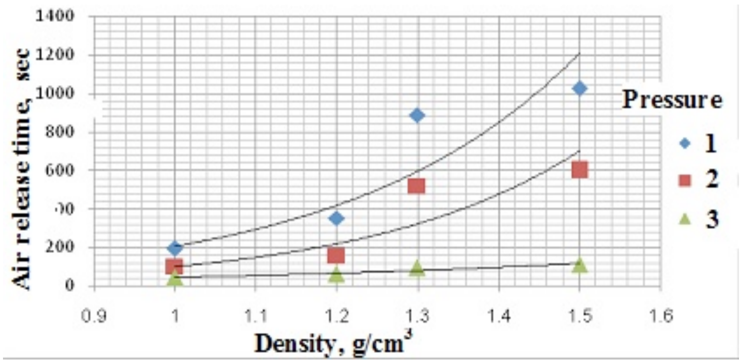

Figure 6. Time of injection of compressed air to soil possessing various density by means of conical tip with one orifice

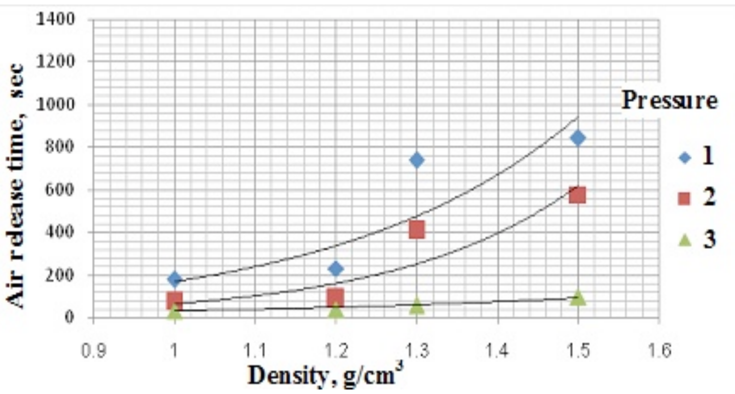

Figure 7. Time of injection of compressed air to soil possessing various density by means of conical tip with two orifices

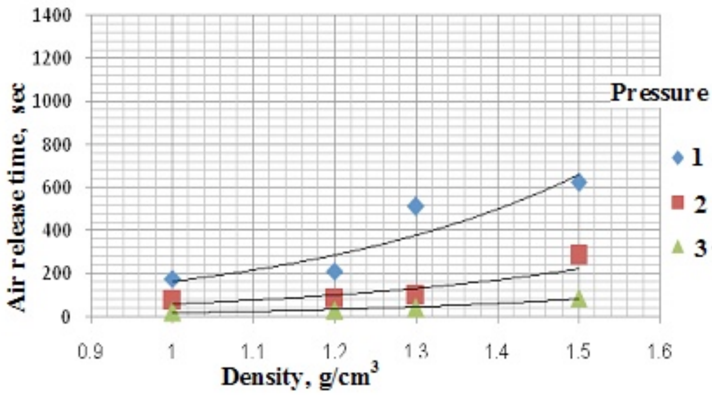

Figure 8. Time of injection of compressed air to soil possessing various density by means of conical tip with four orifices

Conclusions

Taking into account the above-mentioned facts we can state that:

1 – use of cone tip possessing 300 cone angle and bedding of 7 mm. is the most appropriate for measurement of compressibility of heavy soils. It can freely penetrate to various depth without causing damage to soil structure.

2 – use of cone tip with four venting orifices provides better evenness of compressed air diffusion to soil pores in all directions.

3 – use of working air pressure of 6 bar provides the best results in the context of air penetration capacity even to the tiniest pores of heavy soils.

4 – the penetrometer design works on the principle of compressed air minimizing side effects that can be caused by different components of sandy soils, for example, calcium carbonate and different salts causing additional resistance to penetration when standards methods are used.

5 – size of soil pore spaces is the only factor that influences time of compressed air release, consequently, the soil compressibility can be expressed through this factor.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

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