Models to estimate the mechanical resistance to penetration in Argentine agricultural soils

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Abstract

The mechanical resistance to penetration in agricultural soils varies with the water content of the soil.

Therefore the variation of soil humidity may mask the differences between treatments which were in the process of being evaluated. One way to avoid this problem is to make a correction in the humidity content of the soil. The aim of this study is to determine the ranges of variation in mechanical resistance due to the humidity and the depth for typical Argiudolls soils. The experimental data was obtained from four tests. The relation between the humidity, depth and mechanical resistance to the soil penetration was studied using several mathematical models.

The data were fit by equations with coefficients of determination ranging from 0.14 to 0.44.

Boundary conditions were assigned to adjust the equations. These conditions are referred at wet hard soil, dry and soft. In soils in Centro de la Provincia de Buenos Aires, Argentina, it is possible to explain part of the variability in the resistance to penetration of the soil by the humidity variability, apparent density, soil condition and depth.

The best model adjusted to the experimental data includes as independent variables: the condition of tillage, the depth and the apparent density.

Keywords: model, agriculture soil, mechanical resistance.

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1 Introduction

As a consequence of soil degradation, a decrease in agricultural productivity is produced as well as damage to basic resources and ecosystems, which in turn leads to a loss of biodiversity due to changes in habitat both at a species and genetic level [1]. One of the main factors which cause physical deterioration of the earth is soil compaction [2]. Soil compaction is the collapse of soil structure and porosity due to load application. Besides causing a decrease in agricultural yield, this also leads to higher energy requirements in tillage and cultural labour, re-seeding, the need for higher doses of agrochemicals and more tractor and machinery passes, higher fertilizer use and inefficiency of machinery [3].

The resistance to soil penetration, along with apparent density are the two main parameters for determining the state of compaction in agricultural soil. Only when these two parameters have equal tendencies can we talk about soil compaction [4].

To measure the ground resistance to penetration, a cone penetrometer is used. This instrument has been standardised by the American Association of Agricultural Engineering under regulation ASAE S 313 [5] and, in Argentina under regulation IRAM 8063 [6]. The cone penetrometer has a cone and dipstick, both connected to a load cell and data storage unit [7]. Regulations stipulate two cone measurements, both of 30°: a large one of 20.27 mm in diameter and a smaller one of 12.83 mm in diameter. A penetration velocity of 30.5 mm s^{-1} has also been standardised. The force needed for penetration, related to the cone base surface, provides resistance to soil penetration data, in pressure units. The results of the profile evaluation are expressed in terms of cone index, which is the average taken from sufficient measurements to guarantee reliability of data [7].

Another soil parameter linked to the state of compaction is the apparent density, whose evaluation can be carried out by taking soil samples with a cylinder of known volume, drying said samples in a stove and later weighing them. The main problem with this method is the difficulty of taking a large number of samples without modifying them and the subsequent laboratory work this entails.

Currently, an indirect measurement of apparent density can be utilised by the attenuation of gamma rays, using a nuclear instrument. This will also usually give measurements of humidity present in the profile. Later, said instrument performs calculations to show and record data, directly such as the apparent density when dried [7]. However, this technique can prove difficult to implement owing to the high cost of the instrument and existing difficulties with manipulation of the nuclear instrumental equipment. Humidity is among the natural factors which have most influence on the resistance to penetration of agricultural soil, the link between the two being the main problem for obtaining comparable measurements of both. When humidity content is high, the earth sticks to the cone walls, slightly changing its geometry and, therefore, modifying the measurement registered by the instrument, likewise distorting the interpretation of penetrometry data [8].

In agricultural experimentation, the resistance to soil penetration is often used to compare treatments that differ in their humidity content (different tillage, different times of year, different soil stratums). In these circumstances, this technique presents difficulties in clarifying if the value obtained is a product of compaction itself, or is caused by humidity content which may mask the effects of soil management in resistance to penetration.

Finding a clear mathematical link between the humidity and resistance to penetration will enable comparisons to be made in relation to uniform humidity, eliminating the ‘noise’ caused by differences in humidity. Different equations have been proposed for standardising resistance to penetration data as regards a common humidity, allowing a reduction in confounding effects, [9, 10]. However, it has been affirmed that, to do this, a good adjustment between resistance to penetration and humidity is necessary.

Lapen *et al.* [11] found that this adjustment is good for direct seeding soils but not for laboured soil. Yasin *et al.* [12], argue that the best connection between the cone index and humidity and apparent density is linear, while with the depth it is cubic, although they had to use an adjustment equation for each tillage treatment. The use of specific adjustments for each treatment involves the risk that the adjustment forms part of the specific effect in the tillage, which is what is being evaluated.

Paredes *et al.* [13], find significant regressions with R^2 between 27 and 61%. However, if this was really done with three humidity levels, only a limited index of data for one soil was included, up to 20 cm and without tillage treatments.

The objective of this study is to obtain general equations to enable resistance to penetration estimates, with a cone penetrometer, for agricultural soil in the central region of Buenos Aires, Argentina. Mathematical models which relate mechanical resistance to penetration, soil water content, apparent density, depth and soil condition are adjusted and compared.

2 Materials and methods

The study was undertaken with data from four tests, located in the vicinity of Cuidad de Azul (36°46’ latitude and 59°51’ longitude), Argentina, on three soils classified as typical Argiudoll, between the years 2004 and 2014. The tests included a control treatment, without decompacting, in direct seeding and, another two decompaction treatments. Information for each test is summarised in table 1.

2.1 Statistical analysis

Measurements were taken of gravimetric humidity (W), apparent density (AD) and cone index (CI). The measurements were taken at different stratum depths inside the soil profile (E). The form of measurement of the variables was the following:

- Cone index (CI): was determined using a cone penetrometer, constructed under regulation ASAE S 313, with digital information storage, which took samples every 25 mm. Each cone index value is the average of between 5 and 10 measurements.
- Apparent density (AD): was determined using the cylinder method and drying the soil in a stove until uniform weight was achieved.

Table 1: Characteristics of the tests.

Test	Group	Surface (m^2)	Treatment	Depth (cm)	n	Measuring/Time (month)
1	3	240	Control	0	267	3/11
			Paratill	35		
			Chisel	35		
2	3	240	Control	0	132	2/7
			Paratill	35		
			Chisel	38		
3	4	12,000	Control	0	816	4/36
			Paratill	30		
			Straight	35		
4	4	7,500	Control	0	240	2/12
			Paratill	30		
			Superficial	20		

- Gravimetric humidity (W): was determined in gravimetric form along with apparent density, drying the soil in a stove until uniform weight was achieved.
- Depth (E): in tests 1 and 2 depths of : 0–100, 100–200, 200–300, 300–400 and, 400–500 millimetres were used; in tests 3 and 4 depths of 0–100, 100–200, 200–300 y, 300–450 millimetres were used.
- Condition (C): results were classified, being grouped according to whether they had had decompaction treatment: with and without treatment.

The variation of the variables was studied: humidity (W), cone index (CI) and apparent density (AD) through different depths (E), in the combined results from the 4 tests. For this, variance analysis was performed, taking into account the depth factor (E). The averages were compared using the Duncan test of 5%. Moreover, taking CI as a dependent variable and X = W, X = AD and X = E as independent variables, the adjustment of the following models was studied:

1) Linear: $IC = b_0 + b_1 X$,
2) Logarithmic: $IC = b_0 + b_1 \ln X$,
3) Inverse: $IC = b_0 + b_1 / X$,
4) Quadratic: $IC = b_0 + b_1 X + b_2 X^2$,
5) Cubic: $IC = b_0 + b_1 X + b_2 X^2 + b_3 X^3$,
6) Power: $IC = b_0 X^{b1}$,
7) ExpNoLn: $IC= b_0 b_1^X$,
8) Growth: $IC = e^{(b_0 + b_1 / X)}$,
9) ExpLn: $IC= b_0 e^{b_1 X}$

With the objective of finding equations to estimate cone index values with adequate precision, multiple linear regressions were adjusted, taking condition, depth and apparent density as independent variables. Variables were selected with the Stepwise method.

3 Results

The study of the variation in variables humidity (W), cone index (CI) and apparent density (AD) through different depths shows the existence of a statistically significant effect between depths for the variables studied.

Thus, taking W variable as an example, there are only differences between levels if the letters are different, as can be seen in the table. For example, level 100 is no different from level 400, likewise 450 from 500, but a difference can be seen from level 200 (not having any common letters). By comparing the averages of these variables the results shown in table 2 and fig. 1 are obtained.

Table 2: Comparison of the mean, Duncan test, humidity (W), cone index (CI) and apparent density (AD) through different depths (E).

Depth	Mean (DA)	Stand. Dev.	Mean (W)	Stand. Dev.	Mean (IC)	Stand. Dev.
100	1.13 (a)	0.09	24.11 (ab)	4.45	947.63 (a)	674.64
200	1.23 (b)	0.08	25.22 (cd)	2.75	1847.47 (b)	1018.87
300	1.26 (c)	0.08	25.89 (d)	2.82	1910.43 (b)	1166.88
400	1.30 (d)	0.08	23.52 (a)	3.37	3334.08 (d)	1396.84
450	1.37 (e)	0.09	24.92 (bc)	1.88	1691.67 (b)	431.18
500	1.37 (e)	0.06	24.47 (bc)	2.48	2901.08 (c)	1263.86

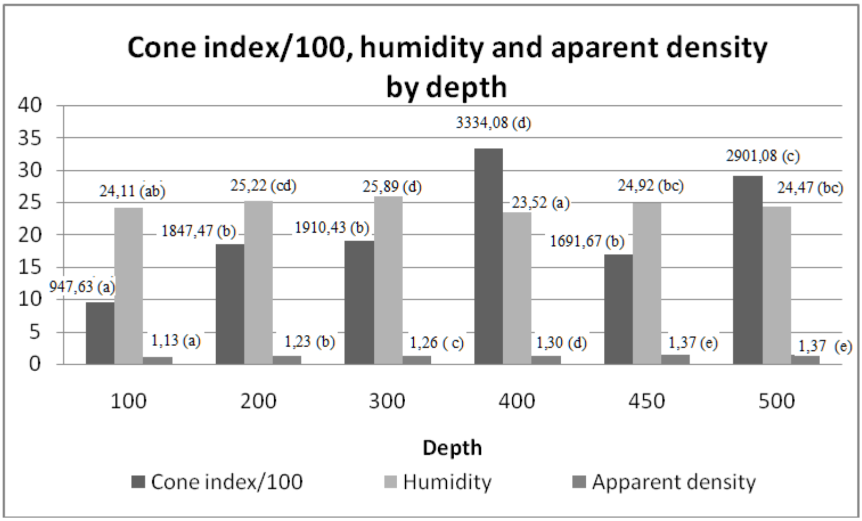

Figure 1: Average values of cone index, Duncan test, humidity and apparent density, at different depths.

The differences in humidity at different depths make the comparison of CI values at different depths difficult, in accordance with De Simone *et al.* [8].

In table 3 results obtained by adjusting the models with dependent variable Cone index (CI) and independent variable Humidity (W) are presented. In this table it can be observed that the models which presented greater R^2 are the linear, the quadratic and the cubic. In each one, it can be observed that, as is expected, the greater the water content, the lower the CI. None of the models analysed can be recommended for making CI estimations from soil humidity, due to the fact that very low R^2 values are obtained, explaining only 14.3% of the variability.

Table 3: Regressions: dependent variable (CI) and independent variable (X=W).

		Estimation of the parameters			
Model	R^2	b_0	b_1	b_2	b_3
1) *Linear:* $IC = b_0 + b_1 X$	0.141	4804.655	-124.672		
2) *Logarithmic:* $IC = b_0 + b_1 \ln X$	0.135	10652.671	-2793.158		
3) *Inverse:* $IC = b_0 + b_1 / X$	0.123	-698.981	58501.13		
4) *Quadratic:* $IC = b_0 + b_1 X + b_2 X^2$	0.142	3734.431	-32.134	-1.956	
5) *Cubic:* $IC = b_0 + b_1 X + b_2 X^2 + b_3 X^3$	0.143	3773.585	0.000	-4.832	0.06
6) *ExpNoLn:* $IC = b_0 b_1^X$	0.076	5802.955	0.944		
7) *Power:* $IC = b_0 X^{b1}$	0.071	82231.575	-1.273		
8) *Growth:* $IC = e^{(b_0 + b_1 / X)}$	0.064	6.148	26.535		
9) *ExpLn:* $IC = b_0 e^{b_1 X}$	0.076	5802.955	-0.057		

In table 4, results obtained for the case of adjusted regressions with dependent variable cone index (CI) and independent variable apparent density (AD) are displayed. In table 4 it can be observed that the models with greater R^2 are those of increase S and potential; however, none of the models analysed can be recommended for CI estimations as the R^2 values are very low, under 12%.

In table 5, results obtained for the case of adjusted regressions corresponding to dependent variable CI and independent variable E can be seen. From the observation of this table it can be deduced that the depth, adopting a model of increase S, would explain almost 30% of the cone index variation

This result concurs with that obtained from carrying out, for variable (CI), variance analysis with one factor: depth. As a result, although statistically significant, the predictive capacity of these variables, when they are taken in an isolated form, proves limited. In these variables, it should also be noted, that the depth of measurement has more influence over the cone index than the humidity or apparent density. In table 6, the models of equations obtained by the adjustment of multiple linear regressions, the adjustments and the estimates of their parameters, are shown.

Table 4: Regressions, dependent variable (CI) and independent variable (X=DA).

		Estimation of the parameters			
Model	R^2	b_0	b_1	b_2	b_3
1) *Linear:* $IC = b_0 + b_1 X$	0.024	-109.744	1450.283		
2) *Logarithmic:* $IC = b_0 + b_1 \ln X$	0.027	1292.947	1876.984		
3) *Inverse:* $IC = b_0 + b_1 / X$	0.030	3621.227	-2375.535		
4) *Quadratic:* $IC = b_0 + b_1 X + b_2 X^2$	0.042	-11610.164	20155.659	-7539.622	
5) *Cubic:* $IC = b_0 + b_1 X + b_2 X^2 + b_3 X^3$	0.042	-7912.088	10966.908	.000	-2043.538
6) *ExpNoLn:* $IC = b_0 b_1^X$	0.107	128.260	6.781		
7) *Power:* $IC = b_0 X^{b1}$	0.113	827.102	2.418		
8) *Growth:* $IC = e^{(b_0 + b_1 / X)}$	0.119	9.661	-2.990		
9) *ExpLn:* $IC = b_0 e^{b_1 X}$	0.107	128.260	1.914		

Table 5: Regressions, dependent variable (CI) and independent variable (X=E).

		Estimation of the parameters			
Model	R^2	b_0	b_1	b_2	b_3
1) *Linear:* $IC = b_0 + b_1 X$	0.112	961.948	2.814		
2) *Logarithmic:* $IC = b_0 + b_1 \ln X$	0.143	-2306.635	738.064		
3) *Inverse:* $IC = b_0 + b_1 / X$	0.161	2448.238	-145697.533		
4) *Quadratic:* $IC = b_0 + b_1 X + b_2 X^2$	0.158	-19.376	11.823	-0.016	
5) *Cubic:* $IC = b_0 + b_1 X + b_2 X^2 + b_3 X^3$	0.166	-1092.860	27.881	-0.082	7.96E-005
6) *ExpNoLn:* $IC = b_0 b_1^X$	0.206	743.536	1.002		
7) *Power:* $IC = b_0 X^{b1}$	0.263	46.120	0.628		
8) *Growth:* $IC = e^{(b_0 + b_1 / X)}$	0.297	7.877	-124.243		
9) *ExpLn:* $IC = b_0 e^{b_1 X}$	0.206	743.536	0.002		

Table 6: Models, adjustments and parameters.

Dependent Variable: Cone index				
R^2	Model	Variables	Coefficients	
			B	Tip. Error
0.141	1	Constant	3357.946	110.556
		$Humidity^2$	-2.628	0.170
0.262	2	Constant	2650.882	112.306
		$Humidity^2$	-2.712	0.157
		Depth	2.924	0.190
0.342	3	Constant	1544.033	134.590
		$Humidity^2$	-3.048	0.151
		Depth	15.024	0.924
		$Depth^2$	-0.022	0.002
0.370	4	Constant	987.287	148.959
		$Humidity^2$	-3.049	0.147
		Depth	15.061	0.904
		$Depth^2$	-0.022	0.002
		Condition	361.269	45.099
0.401	5	Constant	1576.351	159.979
		$Humidity^2$	-3.140	0.144
		Depth	16.544	0.898
		$Depth^2$	-0.022	0.002
		Condition	401.117	44.195
		Apparent $density^3$	-493.581	56.269
0.422	6	Constant	3367.831	292.324
		$Humidity^2$	-13.866	1.482
		Depth	17.281	0.888
		$Depth^2$	-0.023	0.002
		Condition	415.859	43.472
		Apparent $density^3$	-440.195	55.774
		$Humidity^3$	0.292	0.040
0.439	7	Constant	2032.165	349.313
		$Humidity^2$	-15.043	1.470
		Depth	41.299	3.663
		$Depth^2$	-0.121	0.015
		Condition	417.693	42.818
		Apparent $density^3$	-477.878	55.216
		$Humidity^3$	0.324	0.040
		$Depth^3$	0.0001	0.0001

Taking as independent variables: condition, depth, apparent density, and these elevated variables squared and cubed; an adjustment of multiple linear regressions explains 43.9% of the variability in the best cases. The tendencies are similar to those studied by Paredes *et al.* [13], and although the correlation values obtained have been less than those found by different authors in the bibliography [9–13], the sample universe was much broader. The use of a general correction factor which enables the standardisation of the cone index values to a uniform humidity, so as to be able to make comparisons between treatments and/or depths with different water content, therefore appears to be possible in this region.

4 Conclusions

In soil from the central region of the province of Buenos Aires, Argentina, it is possible to explain part of the variability in resistance to penetration by the variability of humidity, apparent density, condition of the soil and the depth at which it is measured.

In this work, defined models for mathematical equations which permit, with a cone penetrometer, estimations of the resistance to penetration in agricultural soil in the central region of the province of Buenos Aires, Argentina, have been generated. The models which relate the mechanical resistance to the penetration, hydrological content of soil, apparent density, depth and condition of soil, have been compared.

Moreover, in the region analysed, in accordance with the results obtained, the use of a general correction factor which enables a standardisation of cone index values to a uniform humidity content is possible, therefore making possible the comparison between treatments and/or depths with different water content.

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