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Correlations between statistical moments of soil aggregate size distributions

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A b s t r a c t. In this paper, following the common practice, the shapes of soil particles size distributions are quantified by higher-order statistical parameters: skewness, flatness, superskewness, superflatness, hyperskewness and hyperflatness factor. Based on the experimental data from six independent experiments, precise non-linear relationships between these higher-order statistical parameters are evidenced and adequate formulas are developed by least-square fitting. These expressions could be useful in modelling and controlling the tillage quality and the resulting size distributions of soil aggregates. In opposite to the classical methods, most commonly based on histograms and mean values of the soil fraction sizes, *etc*., this approach is more sensitive with respect to the soil structure irregularities and it enables additional advanced check of tillage quality.

K e y w o r d s: soil mechanics, decomposition, aggregates, size distribution

INTRODUCTION

Soil is a fundamental natural resource of crucial importance for the whole civilization. Agricultural production directly depends on the soil quality, and as soil degrades so does the crop yield and its quality. Therefore, maintaining soil quality at acceptable level is crucial not only for agricultural sustainability, but also for environmental protection and energy efficiency of the production systems. However, there is a deficiency of methods for measurement and estimation for the purpose of understanding changes in soil quality. Methods to measure relevant parameters related to soil quality are important if scientists are to develop more efficient, reliable and accurate approaches to manage the soil/crop systems (Torbert *et al*., 2008).

Recently, soil mechanics has taken on a new significance as a field worthy of expended research and application. Among others, the soil characterization parameters are of great importance for determining the off-road vehicle performance and the rolling resistance of agricultural soils. Thus, detailed soil information is also required in precision agriculture for terrain trafficability (Massah and Noorolahi, 2008).

Soil structure plays a key part in modelling different properties of the soil, including those which are mechanical, hydraulic, and shrink-swell. Quantitatively, the soil structure is characterized by size and shape distributions of different pore types, size and shape distributions of different solids forming the soil, as well as connectedness and tortuosity of pore walls and channels (Chertkov, 2004).

Soil cultivation assumes a variety of mechanical soil decomposition mechanisms, intended to improve its physical structure and provide suitable conditions for a specified crop production. Therefore, quality control of each specific tillage concept is of crucial importance. It regularly includes the analysis of resulting soil aggregate sizes distribution, ordinarily quite different from the normal Gaussian model.

Tillage has not only a strong effect on the aggregate characteristics (Lipiec *et al*., 2006), but also on the fuel consumption and gases and particles emission. Nowadays, there is growing interest in developing systems of reduced tillage with mulching (conservation tillage) as an alternative technology to traditional tillage to reduce emissions of greenhouse gases whilst producing good conditions for plant growth (Czyż and Dexter, 2008).

Recently, a comparison study of conventional, conservation and zero-tillage system has been performed, using four different tractors (Mileusnić *et al*., 2010). They verified significant reduction of fuel consumption (and, therefore, decreased emission of green house gases also), working time and number of tractors employed in tillage, if conventional system is replaced by the reduced tillage systems. The most energy-consuming part in plant production, concerning the fuel consumption, is tillage (Dyer and Desjardins, 2007).

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Therefore, the applied tillage technique should minimize the energy inputs in crop production, while simultaneously keeping good soil quality and sufficient crop yield (Dyer and Desjardins, 2003; Tabatabaeefar *et al*., 2009, *etc.*).

The term 'soil structure' most commonly assumes a combination of primary mineral building blocks arranged into soil aggregates (soils.usda.gov). The information on the aggregate sizes, shapes and distinctness as the basis for classes, types and grades, respectively, describes the soil structure *ie* the manner in which soil particles are aggregated (Fig. 1). This information is of crucial importance, because the soil structure influences water and air intake, movement and exhaust from the soil bulk volume, thus controlling soil ability to sustain crops life and perform other vital functions.

It is widely recognized nowadays that contemporary agricultural production processes, including the tillage systems, require careful and detailed planning, as well as guidance and control of all relevant biological, technical, technological and other processes. Among others, competitive and sustainable crop production systems assume highly efficient and controlled mechanized soil tillage. One of the main purposes of tillage is to produce a soil structure that represents a compromise between the best possible conditions for plant growth and development on the one hand, and minimal investment of money, labour, energy, *etc*. on the other.

Such demands have initiated the introduction of sophisticated mathematical, statistical, mechanical and other methods in agricultural, biological and mechanical sciences, especially during the last few decades. Among many other possible approaches, an important role in estimating the quality of mechanized tillage belongs to information on the distribution of cultivated soil aggregates sizes (Fredlund *et al*., 2000; Gee and Bauder, 1986; Gee and Or, 2002; Hwang *et al*., 2002; Nemes *et al*., 1999; Petrović *et al*., 2005, *etc*.). Nowadays, statistical approach in resolving these problems is facilitated by a variety of available commercial software packages and statistical literature focused on theoretically founded application of different statistical computer programs (Dunn, 2008; Maletić, 2005; Marques de Sá, 2007).

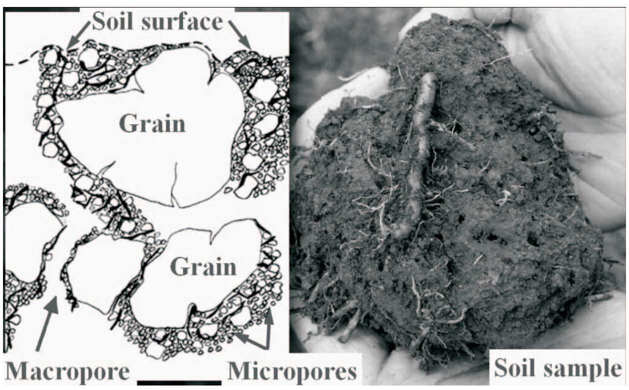

Fig. 1. Basic elements of soil structure (www.soils.usda.gov).

Up to date, the normal-Gaussian function, $N_{\mu,\sigma}$, has been successfully applied in describing the behaviour of relevant parameters in a variety of non-deterministic processes. It is characterized by two parameters, the mean, μ, and standard deviation, σ, and probability density function (*pdf*) defined by:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(x-\mu)^2}{2\sigma^2}} . \qquad (1)$$

However, there exist many situations where the assumption of this function fails. Therefore, other different statistical distribution types have been formulated in the past. Consequently, nowadays the researcher has a possibility to estimate the shape of each real (empirical) distribution of interest and to select the most appropriate analytical function in order to describe it.

A simple method for quantifying the distribution shape is based on the non-dimensional parameters: the skewness S and flatness F factor. For the Gaussian function, S=0 and F=3. Higher difference between the empirical and these theoretical values of S and F results in larger discrepancy of the empirical distribution with reference to the normal. Thus, on the basis of empirical values of S and F, a distribution shape can be preliminarily estimated. Increase of the order of these parameters enhances their sensitivity with respect to distribution shape deviation according to the normal model. Therefore, in some cases the superskewness, SS, superflatness, SF, factors, or even hyperskewness, HS, and hyperflatness, HF, factors are used for this purpose. The present paper is focused on analysis of general statistical interrelations between these factors.

It is known that soil type, field conditions and applied technique crucially influence the resulting soil aggregate size distribution and, therefore, the corresponding S, F, SS, SF, HS and HF factors. Their values are mutually different in different experiments, showing their dependence on the experimental conditions and technique. However, it is evidenced in this paper that S, F, SS, SF, HS and HF factors follow identical non-linear relationships in all tested situations, independent of the soil type, experimental conditions and applied technique.

MATERIALS AND METHODS

The empirical data analyzed in this paper originate from six independent experiments comprising three soil types *ie* Calcic Chernozem, Humic Gleysol and Eutric Cambisol, as well as six concepts of applied mechanization technique. Basic details related to the experimental set-up and conditions are listed in Table 1.

T a b l e 1. Applied technique and soil properties

Tractor	Experiment 1	2	3	4	5	6a (1.31 km h^{-1})	6b (2.41 km h^{-1})
	John Deere 4440[1]	John Deere 4440[1]	Same Titan 190[2]	MTZ-592[3]	John Deere 8520[1]	IMR-65[4]	
Technique	Plough 'Panter'[5] + disc harrow 'OLT Drava'[6]	Plough 'Panter'[5] + disc harrow 'OLT Drava'[6]	Plough Kverneland 'Pakomat S'[7]	'RAU'[7] seed bed cultivator + rototiller 'IMT'[8] 612-73	Germinator 'Franqet' type	'OMMAS Magnum' rotary cultivator with single speed[10]	with two speeds[10]
Date	5.04.2005	8.04.2005	20.04.2005	22.04.2005	25.04.2005	25.06.2005	25.06.2005
Sample size (g)	9350	8700	7750	8350	8600	5450	5750
Sampling depth (cm)	15-20	15-20	15-20	15	15-20	15-20	15
Soil type	Humic Gleysol	Calcic Chernozem	Humic Gleysol	Calcic Chernozem	Humic Gleysol	Eutric Cambisol	Eutric Cambisol
Soil bulk density (g cm^{-3})	1.28	1.15	1.42	1.29	1.30	1.42	1.42
Moisture (%)	16	18	18.5	23.5	20.5	22	22

[1]John Deere: http://www.deere.com and co.yu; [2]Same Titan: http://www.same-tractors.com; [3]Minsk Tractor Works: http://www.belarus-tractor.com; [4]Industry of Engines Rakovica: http://www.imr-rakovica.com; [5]Panter: former http://www.lemind-proleter.co.yu, active http://www.udruipm.rs; [6]OLT Drava: http://www.olt.hr; [7]Kverneland: www.kvernelandgroup.com; [8]Industry of Machines and Tractors, Belgrade: http://www.imt.co.rs; [9]Franqet: http://www.franquet.com; [10]OMMAS: http://www.ommas.com

The first two experiments involved the application of an identical mechanization system in two different soil types: Calcic Chernozem and Humic Gleysol. A JD 4440 tractor was primarily aggregated with a Panter plough and in the second stage with an OLT Drava disc-harrow. The third experiment was performed in the Humic Gleysol using a Kverneland Pakomat plough with ring roller, aggregated with a Same Super Titan tractor, while in the fourth experiment a RAU seed bed cultivator and an IMT 612.730 rototiller were aggregated with an MTZ 592 tractor, in the Calcic Chernozem. These results are supplemented by data acqui- red in a Humic Gleysol, cultivated by a JD 8520 tractor and a Franqet germinator. Technical characteristics of the tractors and aggregated machines are presented in Tables 2 and 3, respectively.

The last (sixth) experiment was performed in Eutric Cambisol of a peach orchard, using the OMMAS Magnum rotary cultivator, aggregated with an IMR-65 tractor. Two different operational velocities were applied: 1.31 km h^{-1} in the experiment 6a and 2.41 km h^{-1} in the experiment 6b.

Therefore, analyzed experimental data generally cover a fairly wide range of different real situations and represent a relevant database for a study related to research of the size distributions of soil aggregates after mechanized tillage.

In all experiments, conducted in Belgrade outer region, hygroscopic soil humidity at the tillage layer depth was estimated by the Katchinsky method. The bulk soil density was measured in Kopecky cylinders, while the Savinov method was applied to analyze the aggregate size distributions.

Each soil sample comprized five replicates which were sieved through the standard set of six sieves (i = 1, 2,..., 6) having specified mesh sizes, L_i, (5, 9.5, 16, 19, 25, 50 mm). In the paper the average of these five replicates is analyzed for each sample.

This way, a representative measure, named mean equivalent diameter, D_{e_i}, is defined for each of seven soil aggregate fractions, by simple formulas:

$$D_{e_1} = \frac{0+D_{e_{\max_1}}}{2} = \frac{L_1}{2} = 2.5 \ (i = 1), \qquad (2)$$

$$D_{e_i} = \frac{D_{e_{\min_i}} + D_{e_{\max_i}}}{2} = \frac{L_{i-1}+L_i}{2} = 2.5, (i = 2, 3, \dots, 6), \qquad (3)$$

$$D_{e_7} = \frac{D_{e_{\min_6}} + 100}{2} = \frac{L_6 + 100}{2} = 75, (i = 7). \qquad (4)$$

T a b l e 2. Technical parameters of the tractors

Parameters	John Deere 4440	Same Titan 190	MTZ-592	John Deere 8520	IMR-65
Engine power (kW)	114	139	45	217	47
Engine rotation rate at max. power (min^{-1})	2200	2209	1800	2000	2300
Max. torque M_{max} (Nm)	–	649	267	1320	185
Rotation rate at max. torque n_{Mmax} (min^{-1})	–	1406	1000	1400	1200
Speciffic fuel consumption q ($g\ k^{-1}\ Wh^{-1}$)	265	247	263	235	282
Mass (kg): - without ballast - with ballast	 5545 6820	 6510 11000	 2670 3800	 9700 14000	 2360 3600
Specific power supply at nominal mass ($kW\ t^{-1}$)	20.55	21.35	16.85	22.37	20.33
Specific mass ($kg\ kW^{-1}$): - without ballast - with ballast	 48.64 59.82	 46.83 79.13	 59.33 84.44	 55.85 85.71	 49.16 75.00
Wheels: - front - rear	 16.9R30 20.8R42	 480/70-30 580/70-38	 11.2 R20 15.5 R38	 620/70R30 710/70R42	 6.00R16 14.9/13R28
Tyres contact area (m^2) (ASAE 2003) - front - rear	 2x0.194 2x0.256	 2x0.194 2x0.241	 2x0.081 2x0.212	 2x0.228 2x0.295	 2x0.035 2x0.156
Average soil contact pressure ($10\ N\ cm^{-2}$)	0.60-0.74	0.73-1.24	0.45-0.64	0.91-1.31	0.61-0.92

T a b l e 3. Technical parameters of the aggregated machines

Parameters	Plough 'Panter'	Disc harrow 'OLT Drava'	Plough Kverneland 'Pakomat S'	Rototiler IMT 612.730	Germinator 'Franqet'	Rotary cultivator 'OMMAS Magnum'
No. of working organs	3	36	3/4	25		16
Operational width of the plough organs (cm)	35	–	35-46	–	–	–
Working width (cm)	105	450	142-183	125	650	80
Tillage depth (cm)	40	10-15	40	20	15	15
Clearence (cm)	81	–	75	–	–	–
Aggregating	mounted	pulled	mounted	mounted	pulled	mounted
Mass (kg)	900	3200		295	6500	524
Working organs distance (cm)	90	25	78	–	42	20

Directly speaking, to provide data for D_{e_1} and D_{e_7} calculation (the smallest and the largest fractions, respectively), two virtual sieves (Nos 0 and 7) were introduced. Their mesh sizes were adopted arbitrarily as $L_0 = 0$ and $L_7 = 100$ (mm) (Table 4).

After sieving, the mass participation m_i, of each $i^{\text{-th}}$ of seven soil fractions was measured and the total acquired mass of the whole sample was evaluated by the sum:

$$m_\Sigma = \sum_{i=1}^{n=7} m_i \;. \tag{5}$$

Sequentially, adequate relative mass-based empirical frequencies p_{m_i}, of each $i^{\text{-th}}$ of seven soil aggregate fractions were then calculated using Eq. (6), enabling the formulation of statistical tables and preparing the histograms:

$$p_{m\,i} \; \frac{m_i}{m_\Sigma} 100\,(\%),\; (i = 1, 2, \ldots, 7) \tag{6}$$

Basic statistical parameters were calculated for each soil sample. Primarily, the arithmetic mean, which represents an expected value of the whole data set, was estimated:

$$\overline{D}_e = \sum_{i=1}^{n=7} p_{m_i} D_{e_i} \,. \tag{7}$$

Standard deviation, or the so-called root-mean-square, was also calculated, this time as a measure of data dispersion around the mean, using the formula:

$$\sigma_m = \sqrt{\sum_{i=1}^{n=7} p_{m\,i} (D_{e\,i} - \overline{D_e})^2} \,. \tag{8}$$

If a distribution of a statistical property is assumed to be normal, the standard deviation σ and the mean value $\bar{x}$ have special meanings, the interval:

$(\bar{x} - \sigma; \bar{x} + \sigma)$ covers 68.26% of data;

$(\bar{x} - 2\sigma, \bar{x} + 2\sigma)$ comprises 95.44% of data, and

$(\bar{x} - 3\sigma, \bar{x} + 3\sigma)$ comprises 99.73% of data.

Unfortunately, most of the real distributions evidently deviate from the normal. Therefore, this information is only a crude approximation in most of the real situations.

However, standard deviation represents the absolute measure of data dispersion, expressed in measuring units equal to the units of measured stochastic variable. It is not quite appropriate for comparison of the stochastic variables which originate from distributions possessing different levels of average values. Therefore, following the common statistical practice, an additional relative measure of dispersion (variability), the coefficient of variance, is also calculated. It is defined as the ratio between the standard deviation and the mean value, expressed in percentage:

$$C_{Vm} = \frac{\sigma}{\overline{D}_e} (\%). \tag{9}$$

This statistical measure is independent of the measuring units and the level of the mean value, enabling the comparison of variability of different realizations of the same or different statistical variable types. It preserves the relative level of distribution variability and therefore it is comparable. In addition, C_V enables the tracing and comparison of some stochastic property: for $C_V < 30$ (%) a distribution is obviously designated as homogeneous. Otherwise, it is called inhomogeneous.

Typical parameters of a distribution shape are also evaluated. The skewness factor Eq. (10), which represents a measure of a distribution symmetry, and the flatness factor Eq. (11) that characterizes the distinction between narrow and flat distributions, are calculated and used to estimate the deviation of an empirical distribution shape from the normal:

$$S_m \; \frac{\sum_{i=1}^{n=7} \left[p_{m\,i} (D_{e\,i} - \overline{D_e})^3 \right]}{\sigma^3} \,, \tag{10}$$

T a b l e 4. Source data describing the cultivated soil aggregate sizes mass distributions

Interval No.	Fraction size limits (mm) Minimum	Fraction size limits (mm) Maximum	Interval width (mm)	Equivalent diameter (mm)	Mass participation (g) Experiment 6a $v_1 = 1.31$ km h^{-1}	Mass participation (g) Experiment 6b $v_2 = 2.41$ km h^{-1}
i	$D_{e\min}=L_{i-1}$	$D_{e\max}=L_i$	ΔD_e	D_e	m_1	m_2
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	0	5	5.0	75.00	3500	2300
2	5	9.5	4.5	38.00	800	800
3	9.5	16	6.5	22.00	500	950
4	16	19	3	17.50	250	0
5	19	25	6	12.75	200	500
6	25	50	25	7.25	200	1200
7	50	100	50	2.50	0	0

$$F_m \frac{\sum_{i=1}^{n=7}\left[p_{m\,i}(D_{e_i}-\overline{D_e})^4\right]}{\sigma^4}. \tag{11}$$

Higher order moments that are more sensitive with respect to discrepancies of a distribution from the Gaussian are also calculated (superskewness and superflatness, hyperskewness and hyperflatness factors):

$$SS_m = \frac{\sum_{i=1}^{n=7}\left[p_{m\,i}\left(D_{e_i}-\overline{D_e}\right)^5\right]}{\sigma^5}, \tag{12}$$

$$SF_m = \frac{\sum_{i=1}^{n=7}\left[p_{m\,i}\left(D_{e_i}-\overline{D_e}\right)^6\right]}{\sigma^6}, \tag{13}$$

$$HS_m = \frac{\sum_{i=1}^{n=7}\left[p_{m\,i}\left(D_{e_i}-\overline{D_e}\right)^7\right]}{\sigma^7}, \tag{14}$$

$$HF_m = \frac{\sum_{i=1}^{n=7}\left[p_{m\,i}\left(D_{e_i}-\overline{D_e}\right)^8\right]}{\sigma^8}. \tag{15}$$

Finally, relationships between these factors are verified and presented in this study.

RESULTS AND DISCUSSION

Single-pass tillage, based on the disc-harrow OLT Drava, provides satisfying results if applied in the Calcic Chernozem (experiment No. 2). The dominant mass part of the fractions of 1-9.5 mm in diameters, of 45%, and small mass participation of fractions larger than 50 mm (9.2%) directly prove this finding.

The particle size distribution differs in the conditions related to the Humic Gleysol (experiment No. 1). Mass participation of the fractions of 1-9.5 mm in diameters is 18.5-27%, with dominant fractions characterized by diameter larger than 50 mm and fractions of diameter in the range of 26-50 mm (26-33 and 19-24%, respectively). These results show that, in this case, additional tillage is needed to provide necessary conditions for seeding – the mass participation of the fractions having sizes between 1 and 9.5 mm should be over 50% (Hillel, 2003; Kovačević *et al*., 2010). Consequentially, the additional tillage operations increase the energy inputs of a crop production.

The application of the Pakomat S plough with ring roller, which performs both the tillage and the seed-bed preparation, in the Humic Gleysol (experiment No. 3) gave quite different results. Mass participation of the fractions of 1-9.5 mm was in the range of 33-51%, while the mass part of the fractions of 26-50 mm and over 50 mm was 13-18 and 7-28%, respectively. This large fractions range shows that Pakomat S gives good results on medium hard soils, under ideal hygroscopic humidity of about 17%. The additional tillage is not necessary under these conditions.

Rototiller applied in the Calcic Chernozem (experiment No. 4) provides the largest mass participation of fractions smaller than 5 mm in dia – 69%. Soil aggregates over 50 mm in diameter do not exist, because the construction of the machine and its technological scheme do not allow the existence of such large particles.

Experiment No. 5 is based on Humic Gleysol, cultivated by JD 8520 tractor and Franqet germinator. The smallest aggregates, below 5 mm in diameter, were dominant in this case. Their mass participation exceeded 50%, while the participation of the largest aggregates, over 50 mm in diameter, did not reach 5%.

In the sixth experiment, realized in a peach orchard on the Eutric Cambisol, the IMR-65 tractor and OMMAS Magnum rotary cultivator were applied at two different operational velocities of 1.31 and 2.41 km h^{-1}, respectively. As it can be seen in Table 4, which illustrates typical primary experimental results (raw data), this difference in velocity resulted in significantly different structures of the cultivated soil.

The first column contains sequential numbers of the fraction intervals, while the interval limits and width are presented in the second, third and the fourth column. Mass participations are given in columns 6 and 7 for representative (equivalent) diameter (column 5) of each soil aggregate fraction. As it was expected, the mass participation of smaller fractions is larger at smaller operational velocity, while the participation of larger aggregates is increased at higher velocity of 2.41 km h^{-1}, and *vice versa*. The largest fractions, over 50 mm in diameter, are not evidenced. This is a logical consequence of the cultivator design and operational regime.

Graphic illustration of the same experiment (No. 6) is given in Fig. 2. Empirical probability density function (*pdf*) is presented for each of the seven intervals (of aggregate equivalent diameter sizes) as the ratio between the relative mass-based frequency, p_{mi}, defined by expression (6), and interval width, ΔD_{e_i}:

$$\Delta D_{e\,i} = L_i - L_{i-1} = D_{e\,\max_i} - D_{e\,\min_i}, \tag{16}$$

ie by expression:

$$(pdf_m)_i = \frac{p_{m\,i}}{\Delta D_{e_i}} = \frac{p_{m\,i}}{D_{e\max_i} - D_{e\min_i}}. \tag{17}$$

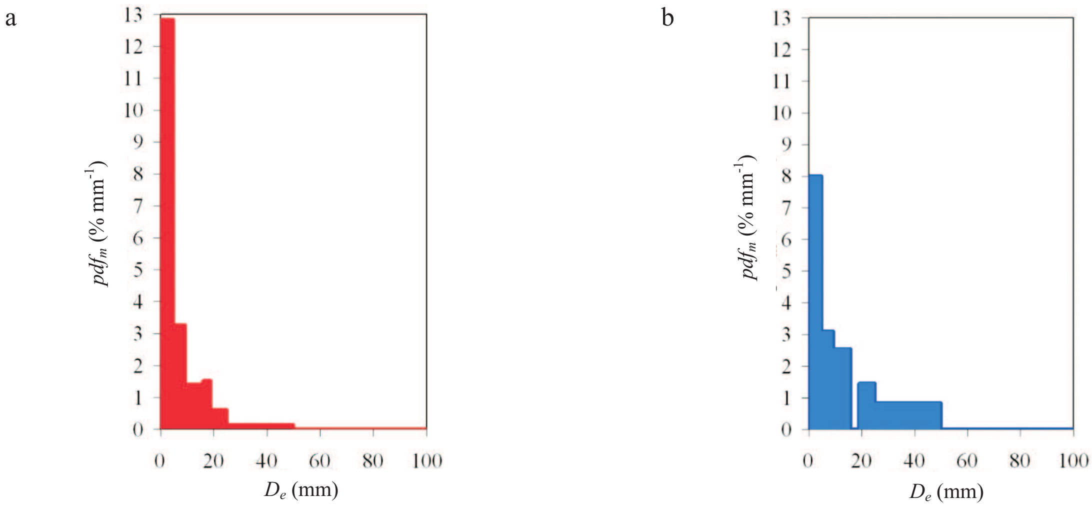

Fig. 2. Functions pdf_m of aggregate size distributions of an Eutric Cambisol cultivated by OMMAS rotary cultivator (experiment 6, a – v = 1.31 km h^{-1} and b – v = 2.41 km h^{-1}).

By definition, the area under pdf_m curve (shaded areas in Fig. 2) has to be equal to 100%:

$$\int_0^{100}\left(pdf_m\right) dD_e = \sum_{i=1}^{7}(pdf_m)\Delta D_{e\,i} = 100\%. \qquad (18)$$

This rule is known as 'normalization condition', and was used for preliminary testing of the calculation results of empirical frequency tables.

Presentation of a distribution by *pdfs* has a simple, but important, advantage. The *pdf* is normalized by the interval width. Therefore, it represents a balanced function in situations where the interval width is non-uniform. Such a kind of presentation is applied in the charts given in Fig. 3. The area between the abscissa and the *pdf* function curve, defined by integral in the Eq. (19), is a % mass participation of aggregates having equivalent diameters between a and b (mm).

$$p_{m\,i}\left(a < D_e < b\right) = \int_a^b \left(pdf_m\right) dD_e. \qquad (19)$$

Statistical descriptive parameters, which characterize fraction size distributions of soil samples acquired during six independent experiments, are listed in Table 5. Depending

T a b l e 5. Basic statistical descriptive parameters of different soil structures

Experiment	Serie	$\overline{D_e}$ (mm)	$\sigma_m(D_e)$ (mm)	$Cv_m(D_e)$ (%)	$S_m(D_e)$	$F_m(D_e)$	$SS_m(D_e)$	$SF_m(D_e)$	$HS_m(D_e)$	$HF_m(D_e)$
1	1	36.9	28.6	77.47	0.32	1.50	0.83	2.41	1.73	4.02
	2	34.8	26.5	76.18	0.53	1.79	1.67	3.66	4.29	7.93
2	1	16.9	18.0	106.06	1.91	6.24	19.21	61.76	198.79	642.35
	2	19.3	21.6	112.13	1.51	4.28	10.43	27.05	69.35	178.76
3	1	14.6	12.7	87.37	1.01	2.50	4.03	7.91	14.12	26.42
	2	11.0	14.0	127.31	1.24	2.77	5.10	10.00	19.27	37.36
4	1	32.4	28.9	89.08	0.53	1.65	1.61	3.17	3.87	6.49
	2	17.9	19.3	107.27	1.85	5.75	16.34	48.40	142.91	423.35
5	1	9.7	14.5	149.79	2.83	11.62	49.31	216.53	963.12	4309.14
	2	10.8	15.9	147.70	2.71	10.50	40.82	162.46	651.27	2619.63
	3	10.7	15.7	147.07	2.70	10.51	41.29	166.54	677.43	2766.46
6a		6.8	8.0	117.44	2.43	8.97	33.17	126.42	485.99	1876.80
6b		14.0	13.6	97.51	0.91	2.25	3.42	6.48	11.07	19.87

on the soil type and tillage system applied, soil statistics vary very much. For example, the mean equivalent diameter lies in the range between 6.8 and 36.9 mm, while the range of standard deviation is from 8.0 to 28.9 mm. The distribution variability characterization factor, coefficient of variation, lies within the limits of 76.18 and 149.79%.

With the increase of the order of analyzed statistical parameter, differences between their values increase also. For example, the hyperskewness factor varies between 1.73 and 963.12, while the range of hyperflatness factor is between 4.02 and 4309.14. Listed values, as well as the pdf charts in (Fig. 3), confirm the strong discrepancies of soil aggregate distributions from the normal Gaussian in most cases. To illustrate this observation, it can be mentioned that skewness factors reach the value of 2.83, while it should be 0 for the symmetrical function, like the normal is. Furthermore, the flatness factors reaches the value of 11.62, while its value is 3 for the normal function.

It is well known that higher-order moments are more sensitive to changes of distribution function in comparison to the lower-order parameters. Therefore, the higher-order parameters can be also used as additional complementary criteria, with respect to average value and standard deviation, in controlling the specified production process of interest - the process of soil cultivation in this case. Besides that, skewness and flatness factors also have an important role in estimating the distribution shape.

The differences between the presented parameters confirm a fairly wide variety of experimental conditions and analyzed soil structures. However, although large variations of listed parameters exist, it is normal to expect that some general rules should exist in each physical phenomenon, which tillage generally is.

Figure 3 presents non-dimensional statistical higher order moments of the soil aggregate size (D_e) distributions, plotted one against the other. This way, the existence of relationships between these parameters is analyzed and finally verified. The figures include moments from the third and up to the eighth order. Following common practice, they are designated in the paper as skewness, flatness, superskewness, superflatness, hyperskewness and hyperflatness factors. Mathematical definitions of these factors are given by Eqs (10)-(15). The value of an exponent that exists in an expression defining a specified moment (factor), defines its order. For example, exponent 3 exists in definition Eq. (10) of the skewness factor. Therefore, skewness is denoted as a non-dimensional moment of the third order, *etc*.

As it can be seen in Fig. 3, clear relationships in the form of the second order parabola exist between the higher-order statistical parameters: $F(S)$, $SF(SS)$, $SS(S)$, $SF(F)$, $HS(S)$, $HF(F)$, $HS(SS)$, $HF(SF)$, $HF(HS)$ and $HF(SS)$. In all of the tested cases, determination coefficients R^2 of fitted second-order parabolic curves are extremely high. Their values are 0.995 or even higher, thus confirming the strong statistical dependence between these parameters and verifying the evidenced relationships.

Measured values of higher-order statistical parame- ters are different in acquired soil samples originating from various experiments based on different soil varieties and different tillage systems applied. However, although the achieved results are at the very beginning stage, it is evident that all experimental data points tightly follow the general trend curves of identical type (second-order parabola). This means that the tillage process is statistical only partially. Some kind of quasi-determination, which cannot be described analytically at present, still exists. The main problem is that poor knowledge of the extremely complex soil structure, tillage mechanical decomposition mechanisms, *etc.*, decrease the range of applicability of mathematical and mechanical analysis in solving the problems in this area. In contrast to initial success, the final result (if such a term exists in this multidisciplinary area) is quite unpredictable because of the extreme complexity of the problem itself.

CONCLUSIONS

1. This paper presents an initial analytically oriented trial in one among a variety of possible orientations of mathematical modeling the aggregates structure in soils exposed to different systems of mechanized tillage.

2. Statistical estimations of the distribution shapes, based on the non-dimensional higher-order statistical parameters such as skewness, flatness, superskewness, superflatness, hyperskewness and hyperflatness factors are applied.

3. Statistically, measured values of skewness and flatness factors, presented in this paper, verify that cultivated soil structure is non-Gaussian by nature.

4. The original parabolic interrelations, between the higher-order parameters of the soil fraction size distributions (after mechanized tillage) are evidenced.

5. These interrelations are preserved in three different soil types (Humic Gleysol, Calcic Chernozem and Eutric Cambisol) cultivated by various tillage approaches and techniques.

6. The evidenced relationships between different statistical parameters enable calculation of higher-order parameters based on the values of lower-order parameters. The experimental and calculation procedure is simpler in this case: the mass of collected soil sample, required for accurate evaluation of a lower-order statistical moment, is much smaller in comparison to the mass required for evaluation of the higher-order moment. The reason for this lies in the fact that higher-order parameters are much more sensitive to the small changes of a data distribution, and therefore demands larger samples for accurate evaluation in comparison to the less sensitive lower-order moments.

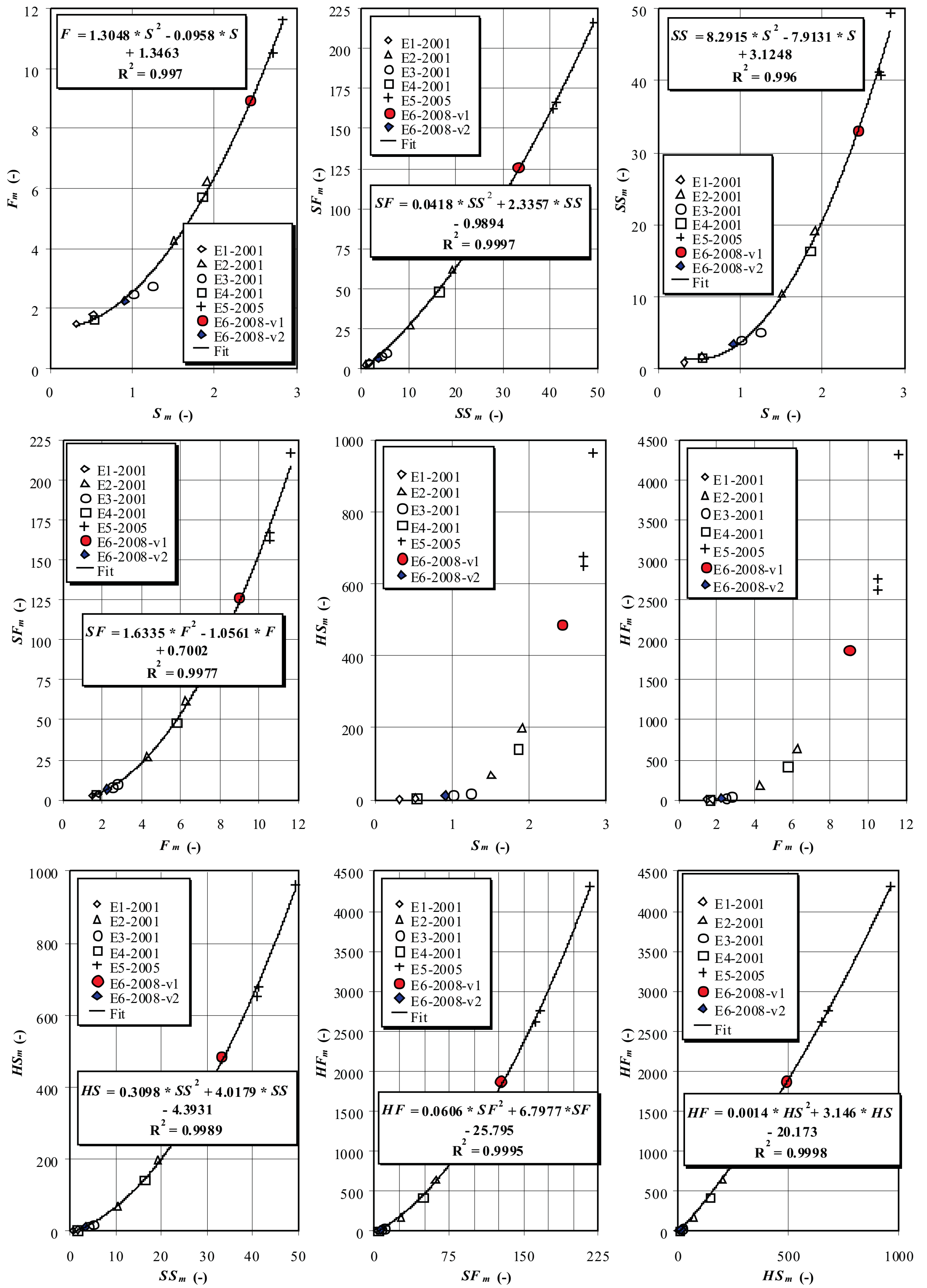

Fig. 3. Relationships between different higher-order statistical moments of a soil aggregates size distributions: $F(S)$, $SF(SS)$, $SS(S)$, $SF(F)$, $HS(S)$, $HF(F)$, $HS(SS)$, $HF(SF)$ and $HF(HS)$.

7. Recognizing the relationships of such kind has an additional advantage. The tillage process and the measurement procedure can be additionally tested – the experimental data points that significantly deviates from the general $F=F(S)$, $SF=SF(SS)$ and other curves describing relationships between higher-order moments could represent a problem marker of: incorrect soil structure, incorrectly acquired or processed experimental data, *etc*.

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