Vulnerability of soil aggregates in relation to soil properties

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ABSTRACT

Stability of soil structure represents an indicator of soil quality. The aim of this paper was to assess the effect of soil properties on structure vulnerability in an Orthic Luvisol. The aggregates were most vulnerable to fast wetting (mean K_{v1} = 9.99, i.e. this effect can decrease the aggregate size 9.99 times). Lower destruction was caused by slow wetting and drying (K_{v2} = 3.70) and mechanical forces (K_{v3} = 1.67). Fine silt (particles of 0.002–0.01 mm) was the most important soil characteristic decreasing aggregate vulnerability (r = –0.334, –0.248, and –0.393 for K_{v1}, K_{v2}, and K_{v3}, respectively). Silt (0.01–0.05 mm) increased vulnerability to fast wetting (r = 0.318). Very fine sand (0.05–0.1 mm) increased vulnerability to mechanical impacts (r = 0.307). Organic carbon decreased vulnerability only slightly. Humus quality was rather related to porosity. Higher moisture of samples in time of collection increased aggregate vulnerability. Multiple regression, used for description of the effect of basic soil properties, provided the best model for K_{v1} (R^2 = 27.45%), the poorest for K_{v2} (R^2 = 7.23%).

Keywords: soil structure; aggregate vulnerability; porosity; soil moisture; soil texture; organic matter

Soil structure determines porosity and infiltration, erodibility, carbon turnover, N gas losses and other processes (Six et al. 2000). It also influences plant roots, both directly and indirectly (Angers and Caron 1998). Stability of soil structure therefore represents an important indicator of soil quality. Its state results from the effect of different soil properties, soil management practices and environmental factors (Six et al. 2000). Saturation with exchangeable sodium, content of iron and aluminium oxides and hydroxides, and organic matter play the most important role among soil properties in determination of soil aggregate stability (Le Bissonais and Le Souder 1995, Le Bissonais 1996). Other soil factors include soil texture, clay content and mineralogy, $CaCO_3$ content etc.

Tisdall and Oades (1982) formulated an aggregate hierarchy theory. It explains a gradual breakdown of macroaggregates into microaggregates, preceding complete dissociation into primary particles. Another consequence of this principle is the fact that younger and more labile organic matter is contained in macroaggregates than in microaggregates. In agreement with this, Elliott (1986) found in a temperate grassland soil that organic matter associated with macroaggregates was more labile than organic matter in microaggregates. Six et al. (2000) showed that fast turnover rate of macroaggregates in conventional tillage leads to lower stabilisation of new soil organic matter, compared to soils with no-tillage management. Oades and Waters (1991) showed that this theory applies well on temperate soils, where organic matter forms major structural bonds. On the contrary, the hierarchy was not proved in strongly weathered tropical soils, where iron and aluminium oxides were the dominant stabilizing agents.

Four principal mechanisms causing aggregate destruction can be distinguished (Le Bissonnais and Le Souder 1995, Le Bissonnais 1996):

a) breakdown by air entrapped in the aggregates during sudden and fast wetting,
b) breakdown by differential swelling and shrinkage during slow wetting and drying,
c) mechanical breakdown by raindrop impact,
d) physico-chemical dispersion after diminishing the internal attractive forces between colloidal particles during wetting (influenced by monovalent cations, especially Na^+); this mechanism takes place only under specific conditions.

A set of three tests was proposed to assess the effect of these breakdown mechanisms (Le Bissonnais and Le Souder 1995, Le Bissonnais 1996). Test 1 enables an assessment of aggregate resistance to fast wetting – mechanism a). Test 2 enables an assessment of aggregate resistance to desaggregation caused by slow wetting and drying – mechanisms b) and d). Test 3 enables an assessment of aggregate resistance to mechanical influences on attractive forces between textural elements – mechanism c). These tests were used on soils with high salinity (Saidi et al. 1999) and on anthropogenic soils on reclaimed dumpsites (Valla et al. 2000).

The aim of this paper was to describe relationships between soil properties related to soil structure stability and to assess the effect of basic soil properties on soil structure vulnerability to different breakdown mechanisms on an agricultural field. Relationship of soil properties and structure stability to soil porosity was also assessed.

MATERIAL AND METHODS

Origin of samples

Soil samples were collected on a 54 ha field in Klučov, Central Bohemia, in the spring of 1999. The soil was classified as Orthic Luvisol, with loamy texture. Conventional tillage had been used. In the time of sampling, the field was cropped to winter wheat. A map of the field can be seen in Brodský et al. (2001).

The samples were collected in a regular grid of 80 × 80 m. In total, separate samples were collected from 94 points over the whole field. Disturbed soil samples were collected from the topsoil (0–20 cm). They were air-dried and a part of each sample was sieved through 2 mm sieve for textural and chemical analyses. From the other part of air-dried sample, aggregates of the diameter 2 to 5 mm were separated on sieves for soil structure analyses. In addition, undisturbed soil samples were collected in two replicates from the same sites using soil physical rings with the volume of 100 cm^3.

Basic soil analysis

Textural composition was determined areometrically. Content of clay (< 0.002 mm), fine silt (0.002–0.01 mm), silt (0.01–0.05 mm), very fine sand (0.05–0.1 mm), and sand (0.1–2.0 mm) was determined. Soil pH was measured in suspension with 1M KCl (1:2.5 w/v). Organic carbon (C_{org}) was determined oxidimetrically using $K_2Cr_2O_7$. Humus quality was described by the ratio of absorbances of 0.05 M $Na_4P_2O_7$ extract of soil (1:20 w/v) at wavelengths 400 and 600 nm, respectively (A_{400}/A_{600}).

Soil moisture (θ) was determined gravimetrically on undisturbed samples in physical rings immediately after collection. Bulk density (ρ_b) was determined on undisturbed samples after oven drying at 105°C. Total porosity (P_t) was calculated from particle and bulk densities. Capillary pores (P_c) were estimated from the water content retained in soil after 24-hours drainage of soil saturated with water. Characteristics of porosity and moisture are expressed on volume basis.

Soil structure stability analysis

Tests proposed and described in detail by Le Bissonnais and Le Souder (1995) and Le Bissonnais (1996) were used to assess the influence of breakdown mechanisms. As the indicator of soil structure stability, coefficient of vulnerability (K_v) proposed by Valla et al. (2000) was used. It shows how many times the initial average size of aggregates decreases under the influence of given desaggregation mechanism. Optimum is $K_v = 1$. The value can be calculated from the mean weighted diameter (MWD) of the aggregates at the end of the test ($K_v = 3.5/MWD$). It is based on the mean diameter of aggregates in the sample used for analysis that equals to 3.5 mm (initial aggregates used are of 2–5 mm in diameter).

Statistical treatment

Statistical treatment was performed using Statgraphics Plus for Windows, version 4.0 (Manugistics 1997). Correlation and regression analyses and factor analysis were used to assess the interrelations between soil properties. Stepwise multiple regression was used to describe soil structure vulnerability as a function of basic soil properties.

RESULTS AND DISCUSSION

Data set characterisation

Generally, the field is relatively homogeneous. Most soil characteristics showed relatively low variability (Table 1). Coefficient of variation (*CV*) was in most cases lower than 20%. For clay and silt content, pH, humus quality parameter A_{400}/A_{600}, bulk density ρ_b, total porosity, and coefficient

Table 1. Summary statistics of determined soil properties

Characteristic	Mean	Median	Variance	Min	Max	Skewness	*CV* (%)
Clay (%)	26.30	26.5	3.380	20.0	33.0	–0.520	6.99
Fine silt (%)	14.20	14.4	2.167	9.9	17.2	–0.363	10.36
Silt (%)	43.16	43.5	7.208	26.9	49.2	–2.550	6.22
Very fine sand (%)	9.82	9.8	3.552	5.3	15.3	0.313	19.20
Sand (%)	6.52	6.2	8.772	0.8	28.4	4.408	45.44
pH	7.13	7.24	0.193	5.76	8.30	–1.021	6.16
C_{org} (%)	1.16	1.16	0.015	0.88	1.44	–0.049	10.72
A_{400}/A_{600}	4.05	4.01	0.050	3.77	5.20	2.804	5.54
ρ_b ($Mg.m^{-3}$)	1.42	1.41	0.008	1.23	1.73	1.273	6.44
P_t (%)	46.51	46.90	11.623	35.16	53.65	–1.189	7.33
P_c (%)	21.47	20.36	20.80	15.12	31.73	0.569	21.24
θ (%)	20.41	18.42	28.579	11.63	31.63	0.614	26.19
K_{v1} – test 1	9.99	10.05	2.222	5.44	14.19	0.093	14.92
K_{v2} – test 2	3.70	3.66	0.923	1.30	6.79	0.211	25.97
K_{v3} – test 3	1.67	1.69	0.020	1.21	2.00	–0.270	8.46

Table 2. Correlation coefficients of the relationships of vulnerability coefficients (K_v), total (P_t) and capillary (P_c) porosity, and momentary soil moisture (θ) to basic soil properties

Characteristic	K_{v1}	K_{v2}	K_{v3}	P_t (%)	P_c (%)	θ (%)
Clay (%)	0.043	–0.012	–0.041	0.150	–0.137	–0.143
Fine silt (%)	–0.334***	–0.248*	–0.393***	0.032	–0.274**	–0.309**
Silt (%)	0.318**	0.048	–0.025	0.339***	0.213*	0.176
Very fine sand (%)	0.127	0.107	0.307**	–0.211*	–0.080	–0.010
Sand (log %)	–0.192	0.011	0.056	–0.172	0.205*	0.230*
pH	0.111	0.023	0.218*	0.022	0.133	0.199
C_{org} (%)	–0.193	–0.161	–0.194	0.206*	0.105	0.011
A_{400}/A_{600}	–0.220*	0.013	–0.002	–0.536***	–0.270**	–0.238*

*, **, and *** indicate statistically significant relationships at the 0.05, 0.01, and 0.001 probability levels, respectively

of aggregate vulnerability to mechanical impacts (K_{v3}), the *CV* was even lower than 10%. The highest variability was found for sand content (*CV* = 45.4%). It can be caused by low values and consequently relatively high analytical error, rather than by real variability in the field. Relatively higher variability was found also for soil moisture (*CV* = 26.2%), capillary pores (21.2%), and coefficient of aggregate vulnerability to destruction by slow wetting and drying (K_{v2}, *CV* = 26.0%). Sand content was transformed to common logarithms for further analyses since it was strongly skewed.

Soil of the field under study can be classified according to its texture as silty loam and loam. Its reaction is predominantly in neutral range. Organic carbon content is medium, as well as humus quality. The values of P_t indicate that the soil is compacted or slightly compacted. This is supported by the share of capillary pores, ranging from 30.6 to as much as 79.2% of total porosity.

The soil is most vulnerable to fast wetting (mean K_{v1} = 9.99). The vulnerability is much higher than that reported for Mollisols and even for recent anthropogenic soils on reclaimed dumpsites (Valla et al. 2000). It can be partly attributed to relatively higher moisture of the samples, since the capillary pores were almost completely filled with water in time of sampling. A decrease in aggregate stability with increased water content was observed for example by Caron et al. (1992). Conventional tillage leading to fast turnover rate of macroaggregates and lower stabilisation of new soil organic matter may have also taken an effect on higher aggregate vulnerability (Six et al. 2000). The effect of slow wetting and drying on aggregate destruction was weaker (mean K_{v2} = 3.70). Mechanical forces showed the lowest influence (mean K_{v3} = 1.67), which is in agreement with findings of Valla et al. (2000).

Table 3. Correlation coefficients of the relationships between vulnerability coefficients (K_v) and soil physical characteristics

Characteristic	K_{v1}	K_{v2}	K_{v3}
ρ_b ($Mg.m^{-3}$)	0.005	0.027	–0.177
P_t (%)	–0.004	–0.027	0.176
P_c (%)	0.164	0.121	0.205*
θ (%)	0.220*	0.181	0.259*

* indicates statistically significant relationships at the 0.05 probability level

Interrelations between soil properties

Most correlations found between soil properties were rather weak, even if statistically significant (Tables 2 and 3). The weakness of correlations may be explained by joint effect of more properties that may support or inhibit the influence of each other. This will be studied by means of factor analysis and multiple regression analysis.

The strongest influence on the coefficients of aggregate vulnerability to destruction was found at fine silt content for all three tests (Table 2). The higher was the fine silt content, the more stable were the aggregates. On the contrary, higher silt content increased aggregate vulnerability to destruction by fast wetting. A similar effect on aggregate vulnerability to destruction by mechanical forces was caused by higher content of very fine sand. Sand content did not show any significant correlation with the vulnerability coefficients. The same was surprisingly true for clay content. Clay mineralogy might have affected this.

The effect of organic carbon was rather weak (Table 2). There is a trend of increasing aggregate stability with increasing C_{org}. Reciprocal relationship between vulnerability coefficients and organic carbon content was shown also by Valla et al. (2000). This trend, however, was not significant in our study. Strong relationship between soil structure stability or vulnerability and organic carbon content is usually found in soils low in clay, while this relationship is weak in soils with higher clay content (Whitbread et al. 1998). Since our samples contain a substantial amount of clay, direct relationship between C_{org} and K_v is weaker. In agreement with results of Valla et al. (2000), higher A_{400}/A_{600} ratio decreased coefficient of aggregate vulnerability to fast wetting (r = –0.220). This

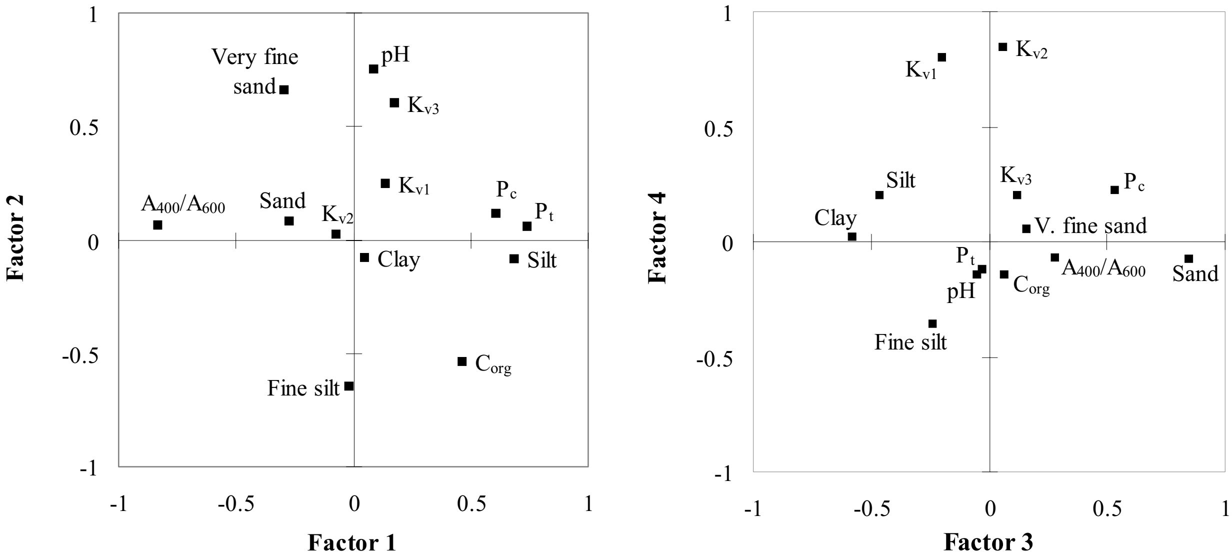

Figure 1. Projection of the weights of four factors rotated using varimax method

means that less developed organic matter increases stability of structural aggregates. It corresponds with data on the importance of labile organic substances in structure stabilisation (Tisdall and Oades 1982). This effect was significantly pronounced in the first test, studying the effect of fast wetting causing aggregate breakdown by the air entrapped inside the aggregates. It may be related to higher hydrophily of labile organic matter facilitating water entrance into the aggregates. Better insight in those phenomena could be provided by detailed characterisation of humus quality and composition. Aggregate vulnerability to mechanical impacts was related also to soil pH ($r = 0.218$).

Soil porosity and momentary moisture were related also to soil texture, especially to silt content: higher silt content increased both total and capillary porosity (Table 2). Higher C_{org} increased total porosity ($r = 0.206$). Soil porosity was reciprocally correlated to the A_{400}/A_{600} ratio. For total porosity, the relationship was fairly close ($r = -0.536$). This might indicate an inverse effect: higher porosity and consequently higher aeration may lead to stronger mineralisation of organic matter rather than to its stabilisation through polymerisation and condensation. The humus quality parameter was reciprocally correlated also to soil moisture ($r = -0.238$). However, this result probably reflects only the relationship between humus quality and total porosity. The same is most probably true for the correlation between P_c and A_{400}/A_{600} ($r = -0.270$)

Relationships between vulnerability coefficients and soil porosity and bulk density were rather weak and in most cases non-significant (Table 3). This implicates that soil porosity is in the soil under study influenced more by other effects than soil structure. Regular soil disturbance by tillage may be one of the most important. Soil moisture, however, showed relationship to vulnerability coefficients. This supports the idea of decreasing aggregate stability due to higher soil water content, as it was mentioned above.

The interrelations between soil properties are apparent from the projection of factor weights resulting from factor analysis (Figure 1). It summarises the findings given in previous paragraphs. Four factors, explaining 62.8% of total variability, were selected and rotated using varimax method. The first factor shows the mutual relationship of total and capillary porosity, silt content and humus quality. Close to the axis of the second factor, at its positive direction, a group of interrelated properties can be seen. It contains pH, K_{v3}, and very fine sand. K_{v1} is also close to this group. Opposite to this group along the axis of the second factor, fine silt content and C_{org} are situated, showing their effect on decreasing aggregate vulnerability to mechanical impacts and fast wetting. The third factor describes the relationship of fine textural fractions versus the coarser ones. A relationship to P_c is also apparent. Vulnerability coefficients from the first two tests (K_{v1} and K_{v2}) lie close to the axis of the fourth factor. These values are only slightly related to measured soil properties. Weak positive relationship is visible only with silt content and P_c, negative with fine silt.

Soil structure vulnerability as a function of basic soil properties

Multiple regression, with vulnerability coefficients as dependent variables and basic soil properties as independent ones, confirmed the results described so far (Table 4). In all cases, fine silt was the most important soil characteristic decreasing vulnerability of soil structure. In basic model of K_{v2} and K_{v3}, it is the only included variable. For these two coefficients, alternative models are also presented, with some other independent variables included. Those additional variables, however, added

Table 4. Models of multiple regression of the aggregate vulnerability coefficients as functions of basic soil properties: regression coefficients of soil characteristics as independent variables, index of determination (R^2) and significance level (P) of the models

Coefficient	Constant	Fine silt (%)	Silt (%)	Very fine sand (%)	C_{org} (%)	R^2 (%)	P
K_{v1}	8.037	–0.334	0.219	–	–2.399	27.45	< 0.001
K_{v2}	5.991	–0.161	–	–	–	6.11	0.016
K_{v2}	6.729	–0.145	–	–	–0.842	7.23	0.033
K_{v3}	0.211	–0.038	–	–	–	15.42	< 0.001
K_{v3}	2.005	–0.031	–	0.011	–	16.92	< 0.001
K_{v3}	2.119	–0.029	–	0.010	–0.105	17.69	< 0.001

only a little to the description of K_v. From the other textural fractions, silt was included in the model of K_{v1} and very fine sand in the alternative models of K_{v3}. Both fractions increase vulnerability of aggregates. For all three coefficients, C_{org} could be included into the models. Higher carbon content stabilizes the aggregates and decreases their vulnerability. Nevertheless, this effect was much weaker than that reported by Tisdall and Oades (1982) and Whitbread et al. (1998), who calculated aggregate stability of soils as a linear regression only of organic carbon content. This is probably due to higher clay content in our samples.

The best regression model was obtained for K_{v1} (R^2 = 27.45%). Aggregate destruction by fast wetting, which is the most important breakdown mechanism, is therefore best controlled by basic soil properties. Aggregate vulnerability to destruction by mechanical forces showed lower dependence on basic soil properties (R^2 = 15.42 to 17.69). The poorest description by the regression models was obtained for K_{v2}, that is for vulnerability of aggregates to slow wetting and drying (R^2 = 6.11 and 7.23). This coefficient also exhibited higher variability (Table 1). Since this mechanism consists in differential swelling and shrinkage of soil constituents and physico-chemical dispersion (Le Bissonnais and Le Souder 1995, Le Bissonnais 1996), it is probably controlled also by clay mineralogy and composition of soil solution, in addition to other factors.

The data used in this study were obtained in the frame of the research plan No. MSM 412100005 of the Ministry of Education, Youth and Sports of the Czech Republic. The statistical part was supported by the grant No. 526/02/1516 of the Grant Agency of the Czech Republic.

REFERENCES

Angers D.E., Caron J. (1998): Plant-induced changes in soil structure: Processes and feedbacks. Biogeochem., *42*: 55–72.

Brodský L., Vaněk V., Száková J., Štípek K. (2001): Spatial heterogeneity of soil properties. Rostl. Výr., *47*: 521–528.

Caron J., Kay B.D., Stone J.A. (1992): Improvement of structural stability of a clay loam with drying. Soil Sci. Soc. Amer. J., *56*: 1583–1590.

Elliott E.T. (1986): Aggregates structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Amer. J., 50: 627–633.

Le Bissonais Y. (1996): Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. Eur. J. Soil Sci., *47*: 425–437.

Le Bissonais Y., Le Souder Ch. (1995): Mesurer la stabilité structurale des sols pour évaluer leur sensibilité à la battance et à l'érosion. Etud. Gest. Sols, *2*: 43–56.

Oades J.M., Waters A.G. (1991): Aggregate hierarchy in soils. Austral. J. Soil Res., *29*: 815–828.

Saidi D., Douaoui A., Le Bissonais Y., Walter C. (1999): Sensibilité de la surface des sols des plaines du Chélif à la dégradation structurale. Etud. Gest. Sols, *6*: 15–25.

Six J., Elliott E.T., Paustian K. (2000): Soil structure and soil organic matter: II. A normalized stability index and the effect of mineralogy. Soil Sci. Soc. Amer. J., *64*: 1042–1049.

Tisdall J.M., Oades J.M. (1982): Organic matter and water-stable aggregates in soils. J. Soil Sci., *33*: 141–163.

Valla M., Kozák J., Ondráček V. (2000): Vulnerability of aggregates separated from selected anthrosols developed on reclaimed dumpsites. Rostl. Výr., *46*: 563–568.

Whitbread A.M., Lefroy R.D.B., Blair G.J. (1998): A survey of the impact of cropping on soil physical and chemical properties in north-western New South Wales. Austral. J. Soil Res., *36*: 669–681.

Received on April 11, 2002

ABSTRAKT

Zranitelnost půdních agregátů ve vztahu k půdním vlastnostem

Stabilita půdní struktury představuje významný ukazatel kvality půdy. Cílem práce bylo posoudit vliv půdních vlastností na zranitelnost půdní struktury v hnědozemi. Nejvyšší zranitelnost agregátů byla zjištěna při prudkém zatopení vodou (průměrná hodnota K_{v1} = 9,99, tj. tento mechanismus může zmenšit velikost agregátů 9,99krát). Menší vliv mělo postupné ovlhčování a vysoušení (K_{v2} = 3,70) a mechanické síly (K_{v3} = 1,67). Jemný prach snižoval nejvýznamněji zranitelnost agregátů (r = –0.334 pro K_{v1}, –0.248 pro K_{v2} a –0.393 pro K_{v3}). Prach zvyšoval zranitelnost prudkým zatopením (r = 0,318), práškovitý písek mechanickými vlivy (r = 0,307). Organický uhlík snižoval zranitelnost agregátů jen slabě. Kvalita humusu vykázala vztah spíše k pórovitosti půdy. Vyšší vlhkost půdy při odběru zvyšovala zranitelnost struktury. Vícenásobná regrese použitá k popisu vlivu základních půdních vlastností poskytla nejlepší model pro K_{v1} (R^2 = 27.45 %), nejhorší pro K_{v2} (R^2 = 7.23 %).

Klíčová slova: půdní struktura; zranitelnost agregátů; pórovitost; půdní vlhkost; zrnitost půdy; organická hmota

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