

Influence of Terrain Attributes and Soil Properties on Soil Aggregate Stability

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Abstract: The study on the relationship between the soil aggregates stability assessed using water stable aggregate (WSA) index and the selected terrain and soil properties was performed on a morphologically diverse study site in Chernozem soil region of Southern Moravia. Soil analyses and detailed digital elevation model processing were the main methods adopted in the study. The soil structure stability is negatively influenced by the soil material removal from the steep parts of the back-slope and re-deposition of the mineral loess material at the base of the slope. The highest aggregates stability was identified in the upper flat parts of the study plot, undisturbed by erosion processes, and at the concave parts of the back-slope with intensive accumulation of organic matter. Statistical analysis showed a significant dependence of aggregates stability on organic carbon content and plan curvature index.

Keywords: loess; soil erosion; soil structure; topography; water stable aggregates

Soil aggregate stability represents an important characteristic of the soil structure, which is closely connected with the soil water regime, soil erodibility, and soil nutrient availability. An enhanced aggregate stability decreases the losses of soil, carbon, nitrogen, and phosphorus (KASPER *et al.* 2009), and increases the amount of macro-aggregates and the total and effective porosity (SHAVER *et al.* 2007). The aggregate (structure) stability influences water flow and contaminants transport in soils KODEŠOVÁ *et al.* (2009b). The soil aggregation is affected by different mechanisms in particular soil types. Flocculated clay particles or their complexes with humus (organo-mineral complexes) and soil organic matter act as the main cementing agents in the soil aggregates development (SIX *et al.* 2002). The level of aggregation and stability of aggregates increase along with the increasing organic matter content, surface area of clay minerals, and cation exchange capacity (BRONICK & LAL 2005).

The reciprocal relationship between organic matter and soil aggregation was shown in numerous studies. Organic carbon acts as an important binding agent and reversely, the soil aggregation influences organic matter accumulation by providing physical protection to soil organic carbon by its incorporation into aggregates (WU *et al.* 1990; FOX & LE BISSONNAIS 1998; SIX *et al.* 2004). Close linear relationships between organic carbon content and water-stable aggregate variables (mean weight diameter or wet-sieve index) for various soils were found by ANGERS (1992) and CARTER (1992).

The soil management and human disturbances also significantly influence the soil structure stability. The soil processing at improper soil moisture, crossing of heavy machinery, irrigation, and use of fertilisers can lead to soil structure degradation (PAGLIAI *et al.* 2004). Non-tillage practices evidently improve the soil aggregation, opposite to the tillage management practices (OLCHIN *et*

al. 2008). The soil aggregates stability decreases in soils under annual crops (ANGERS *et al.* 1999), continuous tillage, and arable crop production (EYNARD *et al.* 2006).

The soil aggregate stability may be assessed using various methods, which reflect also different aggregate breakdown mechanisms. A comparison of various methods was presented by ROHOŠKOVÁ and VALLA (2004) and KODEŠOVÁ *et al.* (2009a).

Topography is the key factor forming the soil cover in climatically and geologically homogenous areas. It has a significant influence on a great range of soil physical and chemical properties (GERRARD 1981). A loess region with Chernozem as a dominant soil unit is an example of such an area. Quantitative topographic data are widely applied in studies on how topography influences the soil properties. The slope, curvature, and topographic index (TWI) are the most frequent variables (PENNOCK 2003). The properties investigated are various: the soil depth (ODEH *et al.* 1995; PENÍŽEK & BORŮVKA 2006), particle size distribution (ODEH *et al.* 1995; ZÁDOROVÁ *et al.* 2009), organic carbon content (MCKENZIE & RYAN 1999), hydromorphic features (MUMMERY *et al.* 1999), soil units delineation (ZÁDOROVÁ *et al.* 2008, 2011) or, less frequently, the soil structure variability (CANTÓN *et al.* 2009).

Numerous studies describe the relationships between the aggregate stability indexes and soil erosion (LE BISSENAIS 1996; CANTÓN *et al.* 2009). Aggregate stability is a critical component of soil erodibility since it controls the soil dispersion and surface seal development. Aggregate stability and soil erodibility are inversely related.

The spatial heterogeneity of aggregate stability is closely related to the terrain attributes (such as the slope, curvature, aspect) through their impact on various soil properties (RHOTON & DUIKER 2008). Most of the studies emphasise the relation between organic carbon, soil erosion, and, the role of the soil aggregation in organic carbon protection in depression areas (SIX *et al.* 2004; BERHE *et al.* 2007; YADAV & MALANSON 2007). Nevertheless, the studies on the soil aggregate stability spatial distribution and its relationship with topography are rather rare and focused more on the assessment of soil aggregate stability in different parts of the slope system (RHOTON *et al.* 2006; TANG *et al.* 2010) than on their direct relationship with topographic derivatives (CANTÓN *et al.* 2009).

The study presented here was performed to assess the soil aggregate stability with respect to

other soil physical and chemical properties and terrain attributes on a cultivated study site intensely changed by soil erosion and soil mass redistribution. The study serves as a preliminary work for a complex research on the spatial heterogeneity of soil structure stability and its relationship with the selected variables.

MATERIAL AND METHODS

Study site

The study was situated in a loess region in Southern Moravia in the Czech Republic, i.e. in the Haraska river watershed. The wider area is underlain by upper Eocene molasse facies and Oligocene sandstones covered by a Pleistocene loess layer (CHLUPÁČ *et al.* 2002). Haplic Chernozem is the original dominant soil unit in the wider area. An extremely diversified soil cover resulted from erosion. A detailed research was

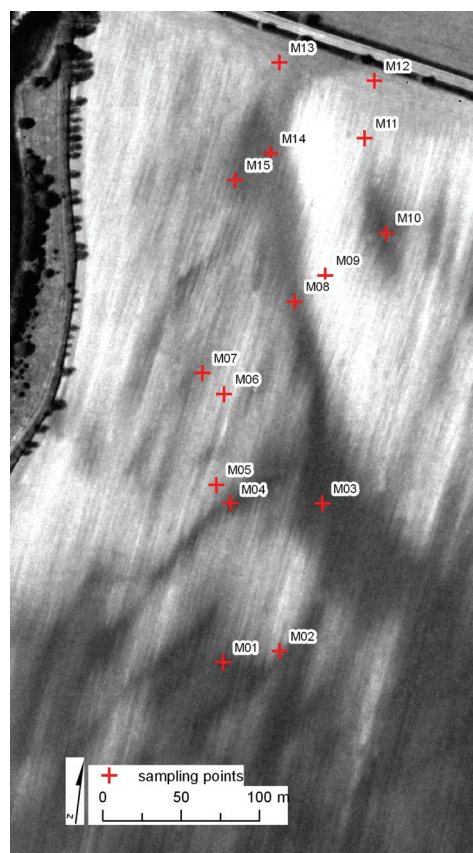


Figure 1. Study plot with sampling points; gray scale shades indicate different colour (caused mostly by organic matter content) within the area

carried out on one study plot (strip part of an agricultural parcel, area of 6 ha) in Brumovice cadastre (Figure 1). The site is characterised by a flat upper part (slope 0–0.5°) covered mostly by Haplic Chernozem. The middle part, formed by a substantive tributary valley, is steeper (up to 15°) with eroded phases of Chernozem and Regosol in the most exposed parts. The base slope and the tributary valley soil cover is represented mostly by colluvial Chernozem and Colluvial soil. Mean slope of the plot is 12.7°. The side valley represents a major line of concentrated runoff emptying into a colluvial fan. Winter barley was planted at the study plot when the soil samples were taken from the surface horizon in November 2009.

Methods

The samples for analysis were taken from 15 points in the representative terrain and soil cover positions (Figure 1).

Particle size distribution, organic carbon content, texture, $\text{pH}_{\text{H}_2\text{O}}$, pH_{KCl} , CaCO_3 content and particle density were measured using the standard

laboratory techniques. The particle size distribution (fractions of clay, silt and sand) was obtained by the hydrometer method (GEE & OR 2002). The total soil carbon content was measured using the dichromate redox titration method (SKJEMSTAD & BALDOCK 2008). The wet oxidation ($\text{K}_2\text{Cr}_2\text{O}_7$) was followed by the potentiometric titration with ferrous ammonium sulfate. The soil pH was measured using a 1:5 (w/v) ratio of soil and water ($\text{pH}_{\text{H}_2\text{O}}$) and 1 M KCl (pH_{KCl}) solution (ISO 10390 1994) using an inoLab Level 1 pH-meter. CaCO_3 content was measured using the volumetric calcimeter method described by LOOPPERT and SUAREZ (1996). The carbonates reacted with HCl (in a sealed system) to form CO_2 . The pressure increase was measured, which is, under the constant temperature, linearly related to the soil sample carbonate quantity. The pycnometer method (FLINT & FLINT 2002) was used to measure the particle density.

The aggregate stability was studied using the procedure presented by NIMMO and PERKINS (2002). Four grams of air-dry soil aggregates of the size of 2–5 mm were sieved for 3 min in distilled water (sieve 0.25 mm). The aggregates remaining on the sieve were next sieved in sodium hexamet-

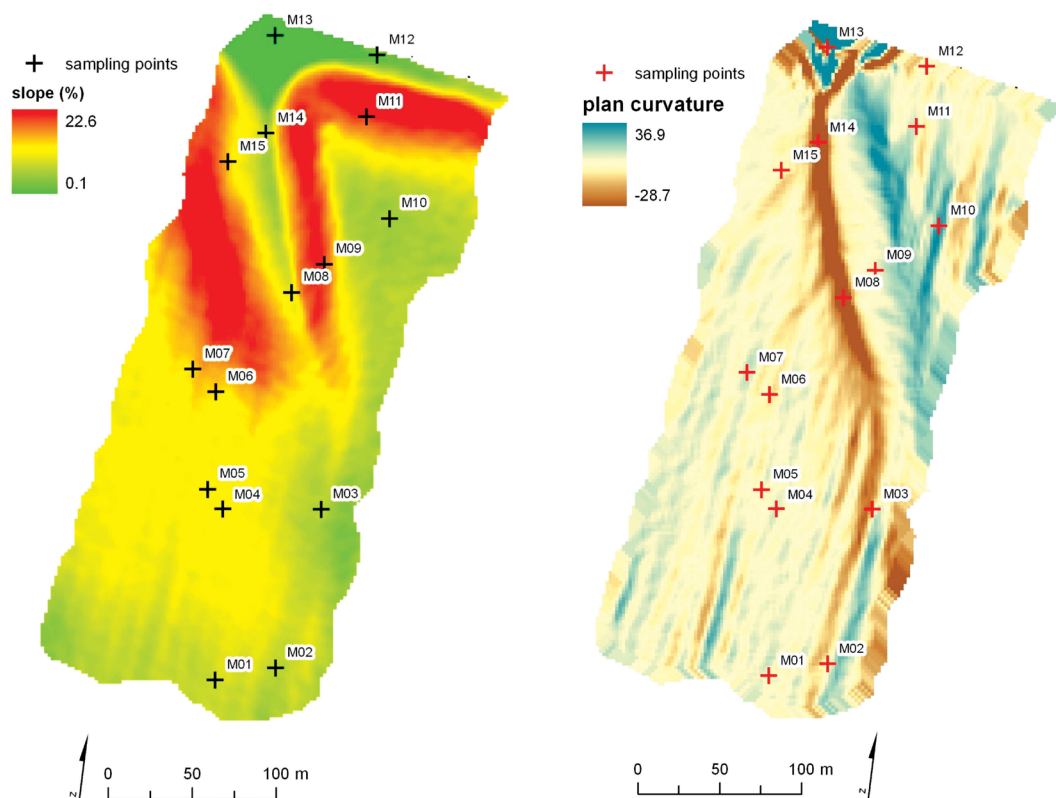


Figure 2. Selected terrain attributes (slope – left and plan curvature – right) with the sampling points

aphosphate until only sand particles remained on the sieve. The index of water stable aggregates, $WSA (-)$, was then determined as:

$$WSA = \frac{WDS}{WDS + WDW} \quad (1)$$

where:

WDS – weight of aggregates dispersed in the dispersing solution (M)

WDW – weight of aggregates dispersed in distilled water (M)

The topographic derivatives were obtained from the digital elevation model (DEM) derived from the ground laser scanning procedure (ZÁDOROVÁ *et al.* 2011). The topographic derivatives were calculated using integrated algorithms implemented in ILWIS 3.3 (Figure 2) from the DEM: slope, plan (planC) (Figure 2), profile (profC) and mean curvature (meanC), topographic wetness index (TWI), sediment transport index (STI) and stream power index (SPI).

The multiple linear regressions were used to evaluate the relationships between the WSA index and the measured physical and chemical soil properties and terrain attributes. The simple correlation between the variables was assessed using Pearson correlation coefficient.

RESULTS AND DISCUSSION

The resulting WSA indexes, the soil properties measured and terrain attributes in each sample,

are shown in Table 1. The soil aggregate stability increased with the increasing WSA index. The highest WSA was determined in undisturbed Chernozem in the flat upper part of the plot. The base of the slope covered by Colluvial soil shows a lower aggregate stability, even though the organic carbon content is relatively high due to the soil mass accumulation. The lower WSA index can be caused by partial accumulation of loess material in the low-laying parts of the slope and its mixing with organic matter. Another factor decreasing the structure stability can be the frequent traversing of heavy machinery in this part of the study plot. On the contrary, the concave parts of the back-slope (the tributary valley) showed a high aggregate stability, given by the accumulation of pure organic matter. A decrease of aggregates stability is evident in the exposed parts of the slope, mainly due to the intensive soil organic carbon removal and subsoil exposing. TANG *et al.* (2010) demonstrated a significant difference of the WSA index between the shoulder and toe slope positions, the WSA at the toe slope being significantly higher than that at the shoulder slope. The result was explained by the fact that the small-sized water stable aggregates displaced at the shoulder slope, transported by surface flow, and redeposited at the toe slope accelerated the development of WSA at the toe slope location. PIERSON and MULLA (1990) found the highest aggregate stability and organic carbon content in the foot-slope and toe-slope positions, and the lowest one at the summit.

Statistical analysis (Table 2, Figure 3) showed the dependency of the WSA index on organic carbon content. This result fully corresponds

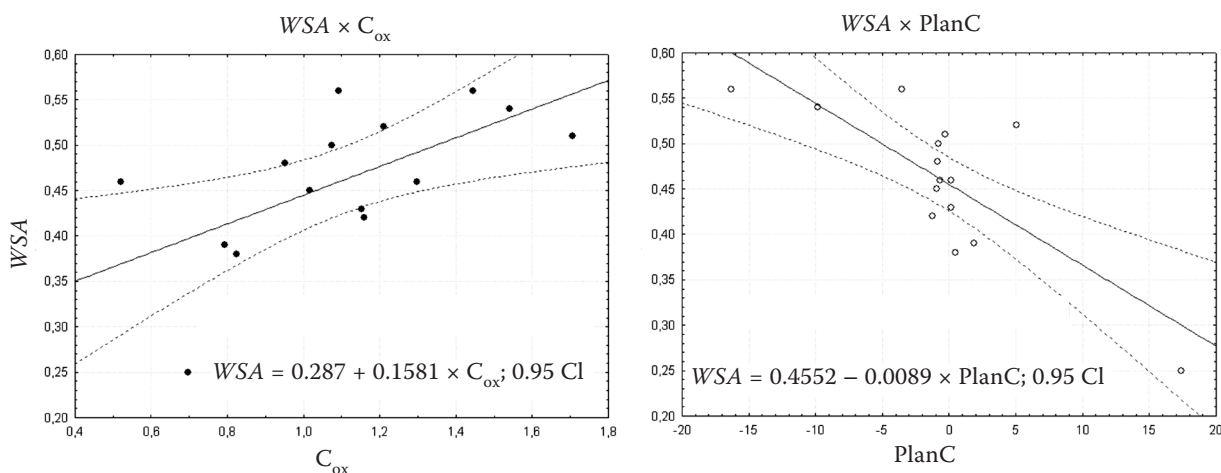


Figure 3. Regression analysis: relationship between WSA index and organic carbon content (left), relationship between WSA index and plan curvature (right)

Table 1. Water stable aggregates (WSA) index, measured soil properties and terrain attributes in each sample

Sample	WSA (-)	Soil unit	C _{ox} (%)	PD (g/cm ³)	(-)			(-)				(-)				
					pH _{H₂O}	pH _{KCl}		CaCO ₃	Clay	Slope	MeanC	PlanC	ProfC	TWI	STI	
M01	0.51	CE	1.71	2.55	7.55	6.76		0.44	18.50	10.50	0.02	-0.26	-0.02		4.87	0.90
M02	0.50	RG	1.07	2.62	7.78	7.01		1.78	18.62	9.90	-0.04	-0.79	-0.02		5.92	1.55
M03	0.56	CO	1.45	2.55	7.81	6.56		0.82	17.07	9.30	-0.15	-3.54	0.00		7.03	2.63
M04	0.46	CE	1.30	2.58	7.66	6.77		0.95	18.22	12.90	0.03	0.16	0.03		6.36	3.32
M05	0.46	RG	0.52	2.64	7.68	7.08		2.36		13.00	-0.06	-0.69	-0.07		6.76	4.34
M06	0.48	RG	0.95	2.67	7.76	7.04		2.92	17.81	14.10	-0.03	-0.84	-0.09		6.51	4.15
M07	0.43	CE de	1.15	2.61	7.74	6.81		1.35	17.66	13.80	0.04	0.17	0.02		6.02	3.05
M08	0.54	CO	1.54	2.61	7.78	6.87		1.21	17.09	12.50	-0.62	-9.82	-0.22		9.45	20.75
M09	0.38	RG	0.82	2.62	7.87	7.16		2.92	15.68	19.70	0.20	0.50	0.29		4.83	2.94
M10	0.52	CE	1.21	2.57	7.87	6.82		1.37	14.55	8.60	0.21	5.06	-0.01		5.25	0.79
M11	0.39	RG	0.79	2.65	7.99	6.97		2.69	14.79	20.10	0.34	1.88	0.31		5.25	3.91
M12	0.42	CO	1.16	2.61	7.83	6.95		1.90	15.59	6.50	-0.31	-1.26	-0.55		7.10	1.37
M13	0.25	CO	0.70	2.63	7.94	7.01		1.46	14.44	1.90	0.34	17.39	0.31		5.47	0.05
M14	0.56	CO	1.09	2.61	7.82	6.87		1.10	14.08	10.60	-0.98	-16.33	-0.33		9.67	16.78
M15	0.45	CO	1.02	2.63	7.85	6.99		2.27	17.38	14.10	-0.20	-0.90	-0.28		5.16	1.92

CE – Chernozem, CE de – degraded Chernozem, RG – Regosol, CO – Colluvial soil; C_{ox} – oxidizable organic carbon; PD – particle density; meanC – mean curvature; planC – plan curvature; profC – profile curvature; TWI – topographic wetness index; STI – sediment transport index

Table 2. Correlation analysis between water stable aggregates (WSA) index and selected soil and terrain attributes (Pearson correlation coefficient)

	C_{ox}	$CaCO_3$	pH_{H_2O}	pH_{KCl}	WSA	Clay	PD	Slope	MeanC	PlanC	ProfC	TWI	STI
C_{ox}		-0.751**	-0.758**	-0.744**	0.718**	0.503	-0.766**	-0.161	-0.379	-0.443	-0.399	0.309	0.262
$CaCO_3$	-0.751**		0.560*	0.817**	-0.417	-0.180	0.823**	0.547*	0.299	0.162	0.187	-0.307	-0.168
pH_{H_2O}	-0.758**	0.560*		0.440	-0.470	-0.754**	0.509	0.060	0.205	0.289	0.266	-0.068	-0.023
pH_{KCl}	-0.744**	0.817**	0.440		-0.563*	-0.220	0.801**	0.276	0.198	0.236	0.155	-0.252	-0.069
WSA	0.718**	-0.417	-0.470	-0.563*		0.318	-0.465	0.075	-0.620*	-0.779**	-0.512	0.513	0.459
Clay	0.503	-0.180	-0.754**	-0.220	0.318		-0.173	0.152	0.029	-0.127	-0.108	-0.138	-0.150
PD	-0.766**	0.823**	0.509	0.801**	-0.465	-0.173		0.323	0.072	0.106	0.080	-0.005	0.101
Slope	-0.161	0.547*	0.060	0.276	0.075	0.152	0.323		0.118	-0.312	0.272	-0.174	0.146
MeanC	-0.379	0.299	0.205	0.198	-0.620*	0.029	0.072	0.118		0.866**	0.775**	-0.888**	-0.788**
PlanC	-0.443	0.162	0.289	0.236	-0.779**	-0.127	0.106	-0.312	0.866**		0.603*	-0.743**	-0.746**
ProfC	-0.399	0.187	0.266	0.155	-0.512	-0.108	0.080	0.272	0.775**	0.603		-0.579*	-0.356
TWI	0.309	-0.307	-0.068	-0.252	0.513	-0.138	-0.005	-0.174	-0.888**	-0.743**	-0.579*		0.874**
STI	0.262	-0.168	-0.023	-0.069	0.459	-0.150	0.101	0.146	-0.788**	-0.746**	-0.356	0.874**	

*, ** $P < 0.05, 0.01$; C_{ox} – oxidizable organic carbon; PD – particle density; meanC – mean curvature; planC – plan curvature; profC – profile curvature; TWI – topographic wetness index; STI – sediment transport index)

with numerous studies on aggregate stability (e.g., ROBERSON *et al.* 1991; LE BISSONNAIS *et al.* 2007; KODEŠOVÁ *et al.* 2009a). The relationship between WSA and other analytic properties was proved only in the case of negative correlation with pH_{KCl} . The increase of pH together with increasing carbonates content in the steep parts of the slope evidence of subsoil loess horizon exposition. A lower aggregation of the subsoil then leads to a lower WSA index. The role of the soil reaction in the soil aggregation was showed by BOIX-FAYOS *et al.* (2001) and BRONICK and LAL (2005). The soil texture did not show any significant relationship with the soil aggregate stability, although the role of the clay content in the aggregation was proven by many authors (e.g. KAY 1998). This fact can be explained by a relatively low spatial heterogeneity of the texture given by a high and non-variable silt content in the whole profile. A similar result was obtained by CANTÓN *et al.* (2009).

The role of the terrain attributes concerning WSA index was apparent in the case of curvature. Correlation analysis showed a significant relationship between the mean and plan curvature and WSA index. Regression analysis proved a strong dependency of the aggregate stability on the plan curvature (Figure 3) meaning that decreasing (concave) plan curvature implies the increase of aggregates stability. The relationship does not consist in the organic carbon content distribution, when no correlation between organic matter and curvature was determined (Table 2). ZÁDOROVÁ *et al.* (2011) identified the plan curvature as the main variable influencing the general soil mass redistribution in the study plot where it showed a significant relationship between the soil unit distribution and soil depth. Correlation with the slope is very low. This fact corresponds with the low control of slope in general soil-mass redistribution at the plot (ZÁDOROVÁ *et al.* 2011). CANTÓN *et al.* (2009) did not find any correlation between the terrain attributes and aggregates stability.

Multiple linear regression showed again that the WSA index was affected mainly by the organic carbon content and plan curvature:

$$\text{WSA} = 0.3498 + 0.0967 \times C_{\text{ox}} (\%) - 0.00722 \times \text{planC} \quad (2)$$

Equation explained 85.5% of the variability in the WSA index. The standard deviation of the residuals was 0.046.

CONCLUSIONS

Soil degradation by erosion and deposition is a significant factor changing the soil cover of the studied area. The study site showed a high variability of the soil units due to an accelerated soil erosion. Heterogeneity of the soil aggregate stability can be related to the strong material redistribution on the slope influencing particularly organic carbon content in the plough layer. The soil structure is negatively influenced by a massive soil material removal from the steep parts of the back-slope and, at the same time, by the deposition of the mineral loess material at the base of the slope. Terrain attributes, as one of the main factors actuating the surface runoff, showed a strong relationship with the structure stability through plan curvature index. The slope, on the contrary, has a very low influence on the spatial distribution of the soil aggregates stability.

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