Chapter 7

The Impact of Clay Minerals on Soil Hydrological Processes

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Additional information is available at the end of the chapter

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1. Introduction

In literature clay and clay-loamy soils are sometimes called heavy soils. The origin of this term lies in agriculture – they are difficult to cultivate and thus increasingly energy demanding. One of the basic characteristics of heavy soils is their capacity to change their volume, which is induced by swelling and shrinking processes. These processes occur in three dimensions. In horizontal plane they are represented by formation of cracks and in vertical plane by vertical movement of soil surface. With the formation of cracks, soil environment becomes a two-domain structure, cracks being one domain and soil matrix being the other one. Shrinkage cracks are distributed through the unsaturated zone of a soil profile. In general, unsaturated zone is a three-phase system pertaining to litosphere and limited by land surface upwards and water table downwards. Simultaneously, it is a sub-system of a wider system formed by atmosphere - plant cover - soil – groundwater. All these sub-systems are interconnected by interaction (hydrological) processes and together they constitute soil water regime. Hydrological processes as a part of soil water regime are called water regime elements. Water regime elements can cause temporal and spacial changes in soil water storage, which are denoted soil moisture regime.

Soil volumetric changes and related formation, duration and termination processes of two-domain soil structure have a great impact on the dynamics of soil hydrological processes. Volumetric changes depend on the content of clay minerals in soil and their response to contact with water. Clay minerals content in soils is relatively stable and it is characteristic of every soil type. Soil moisture level varies with the changes in hydrometeorological conditions, depth of active root zone and the intensity of anthropogenic activity in the area. Soil water regime and related issues have been well monitored and examined in rigid soils, i.e. soils which do not shrink. Water transport in unsaturated rigid soil have been described by Richards` equation [1]. It is based on the theory of laminar flow in small pores. Many mathematical models have been developed to be used for numerical solution of this problem.

In this regard, heavy soils are similar to rigid soils, but only until reaching the point of first crack formation. The presence of shrinkage cracks considerably alters hydrodynamic properties of rigid soils and consequently the methods used for the description of rigid soils water regime cannot be used with cracking soils. At the time of shrinkage crack formation, heavy soils profile contains two distinct elements: cracks (also called macropores) and soil matrix (containing, inter alia, micropores). Each of these elements is characterised by very different conditions for water transport and retention. In the study of a two-domain soil structure, unlike in the study of rigid soils, it is necessary to consider the phenomena caused by soil volumetric changes, such as definition of crack network geometry, soil surface vertical movement, shrinkage characteristics, water flow to cracks, water flow within cracks and water flow from cracks to soil matrix.

The aim of this chapter is to quantify the impact of clay minerals on soil hydrological processes. The presented results were gained from the field measurements on Eastern-Slovak Lowland and from numerical simulation of heavy soils water regime.

2. Clay minerals in soil

2.1. Properties of clay minerals

Crystals of clay minerals are formed by sheets (formed by silicon tetrahedrals and aluminium octahedrals) of varying number, from 1 (montmorillonite) theoretically up to infinite. The individual sheets are extremely thin (5 – 10 Å) and their specific surface is very large (15 $m^2.g^{-1}$ – kaolinite, 80 $m^2.g^{-1}$ – illite; 800 $m^2.g^{-1}$ – montmorillonite). Sheets specific surface is very closely linked to the volumetric changes [2]. The larger specific surface is, the better is the capacity of soil to expand. The surface of clay sheets carries negative charge and thus it is able to bond molecules of water. As a result, the crystals of some clay minerals can bond water within their sturcture and expand. They can re-gain their original volume by drying. The ability of clay minerals to bond water in their structure and expand is different:

- kaolinite clays – relativelly inactive (in this group only halloysite has a very restricted ability to bond water);
- illites – low to medium – expanding clays
- Montmorillonite clays – extremely expanding clays. In their original form (under laboratory conditions) they can expand by 1 400 up to 2 000 % (Na-montmorillonite), [3].

In nature, clay minerals do not occur in pure form but they combine into mixed structures composed of various clay and other minerals. In literature, the word “clay” is used for both clay soil and clay minerals. “Clay”, however, denotes a material that contains clay minerals smaller than 0.002 mm, as well as material whose structure contains predominantly clay minerals [4]. That means the material can be formed not only by clay minerals but also by other minerals smaller than 0.002 mm, such as silica, carbonates or metal oxides. With regard to the classification of clay minerals by their grains, clay minerals pertain to the category I. of Kopecký division (< 0.01). This is further divided into two sub-categories: I. colloidal clays (< 0,001 mm) and II. physical clays (0.001 – 0.002 mm) and very fine silt (0.002 – 0.01 mm). Thus when measuring clay minerals content in soil, clay percentage can be considered the same as the percentage of particles smaller than 0.002 mm (colloidal clay and physical clay). The limit value of 0.002 mm, which divides clay particles from fine silt, is the value used most worldwide [5]

2.2. Characteristics of the observed area

Research into the quantification of clay minerals impact on soil hydrological processes was carried out in the Eastern-Slovak Lowland fig. 1. ESL forms part of a neogene basin, which was created by irregular tectonic subsidence of crust within Carpathian arc during Neogene and Post-tertiary. Because of the subsidence, accumulation processes dominated in the area and a flat lowland surface was formed, mainly composed of fluvial sediments, loess and windblown sands.

Figure 1. Localization of the observed area

From the climatic point of view, ESL lies on the boundary between oceanic and continental climate. The area is characterised by a high changeability of metheorological elements in time. Precipitations formation is heavily influenced by circulation factors. Long-term avg sum of precipitations per year is 600 – 900 mm. Annual sum of potential evapotranspiration is 619 – 687 mm with the maximum value of 115 – 125 mm in July and minimum values in January. Bearing in mind real moisture conditions of the upper soil layer, the actual evaporanspiration is lower than the potential. It reaches 450 – 480 mm.

Soil conditions on ESL correspond to the hydro-geological development in the area fig.2. There is 209 518 ha of farmland. Only 3.2% of the farmland is composed of light soils. Up to 20.6% of the total farmland in the ESL is formed by very heavy soils which contain more than 75% of clay particles < 0,01 mm. The average depth of unsaturated zone is up to 1m. It can be found on 23.36% of the area whereas the unsaturated zone reaches 2m depth on 45% of the area and 3m depth on 68% of the area.

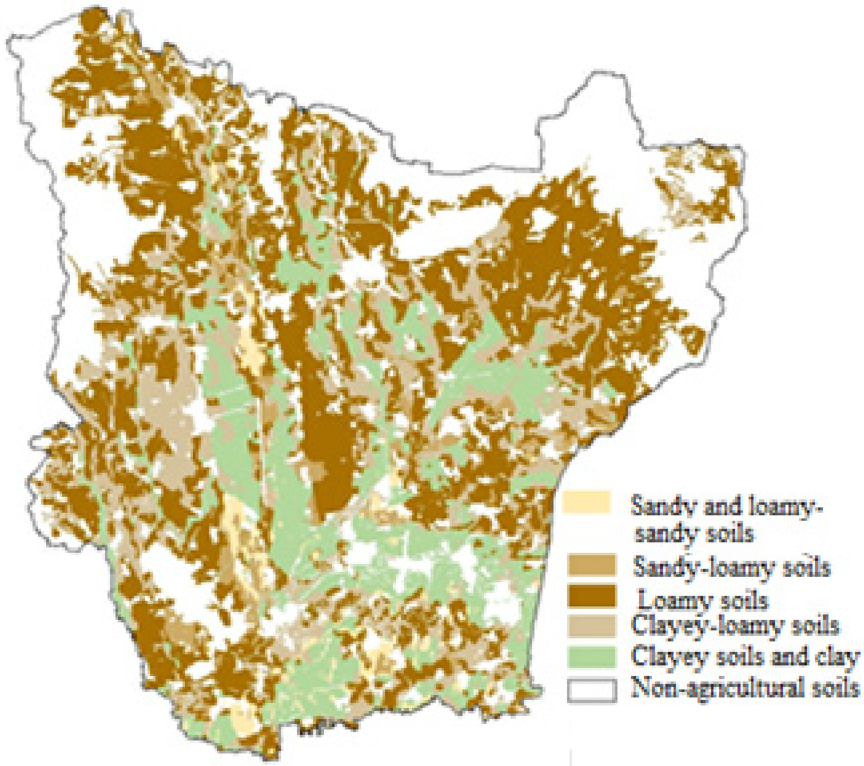

Figure 2. Planar distribution of soil types on East Slovakian lowland

2.3. Clay minerals in the soils of Eastern-Slovak lowland

The overall study of mineralogical soil structure in Slovakia was performed in 1970s. The results were published in Čurlík`s work [6]. In spite of time distance between the year of publication and the present time, the work and the data published within are still topical and applicable. Due to demanding character of determining soil clay minerals in laboratory and unlike in other analysed areas, where pedological reasearch was performed, selected methotodology was based on determining the mixed layer clay structures in the individual soil types. This methodology presumes that pure forms of clay minerals are extremely rare in nature. More often than not they form combinations of diferent types. The study showed that predominant clay mineral in ESL is montmorillonite, others are kaolinite, chlorite, mica clay and mixed structures. The following table 1 illustrates the results of the research and presents the data from Svätuša probe (48^0 25´ 14,00˝, 28^0 55´02,70˝, 95m). This area is typical of ESL. The analysed soil profile was divided into six horizons from the surface to the depth of 1.50m. The data in the tab.1 concern clay and silt fraction which are typical of ESL.

2.4. Specific features of heavy soils water regime

2.4.1. Vertical and horizontal hydraulic conductivity of cracks

In our latitudes, heavy soil are severly dried in the summer half-year (April - September). As a result, cracks are formed and soil has a two-domain structure - domain of micropores and domain of macropores fig. 3. The first domain is formed by micropores in soil matrix.

Water movement here can be described by Richards` equation. Rate of water movement in this domain is relatively low. In case of macropores (cracks), Richards` equation cannot be used. Provided that large amount of water gets into cracks in a short time and the cracks are not properly closed, rainwater movement in cracks is analogous to the water movement in an open ditch. Rate of water movement is higher by orders in comparison with the water movement through micropores. Crack networkwork is a system of preferred water flow paths both in horizontal (horizontal crack conductivity) and vertical (vertical crack conductivity) direction. Cracks geometry changes in time and therefore hydraulic parameters of the preferred paths change too. In cracks, open water level can occur only if the cracks are open. The presence of water in cracks rapidly increases soil moisture and thus boosts the crack closure. Consequently, water movement in cracks is restricted by soil response time to moisture changes. Water shall move within cracks only if the cracks are filled with large amount of water in a very short time (e.g. torrential rains). Under normal conditions, cracks usually close before open water level could be formed.

Fraction / Sample	Microstructure				
	Oriented preparations			Non-oriented preparations	
	1 µm	1 – 2 µm	2 – 5 µm	5 – 10 µm	10 – 50 µm
P – 88 0,0 – 0,20 m mass. %	montmorillonitee clay mica kaolinitee, quartz 69,4	quartz, chloritee clay mica spar, kaolinitee 11,6	quartz, mica feldspars,mixed structure 6,2	quartz, feldspars chloritee, mica 6,4	quartz,feldspars mica, chloritee 3,8
P – 89 0,21 – 0,40 m mass. %	montmorillonitee clay mica kaolinitee, quartz 75,9	quartz, chloritee clay mica feldspars, kaolinitee 9,6	quartz, mica feldspars, mixed structure 4,7	quartz, feldspars chlorite, mica 2,2	quartz, feldspars mica, chlorite 4,8
P - 90 0,41 – 0,55 m mass. %	montmorillonite clay mica kaolinite, quartz 73,8	quartz, chlorite clay mica feldspars, kaolinite 7,8	quartz, chlorite mica, feldspars 6,8	quartz, mica feldspars, chlorite 2,0	quartz, feldspars mica, chlorite 8,2
P – 91 0,56 – 0,70 m mass. %	montmorillonite clay mica kaolinite, quartz chlorite 78,4	quartz, chlorite clay mica feldspars, kaolinite montmorillonite 8,8	quartz, chlorite mica, feldspars 2,0	quartz, mica feldspars, chlorite 2,4	quartz, feldspars mica, chlorite 7,2
P – 92 0,71 – 1,00 m mass. %	montmorillonite clay mica kaolinite, quartz chlorite 68,1	quartz, chlorite clay mica feldspars, kaolinite montmorillonite 4,6	quartz, chlorite mica, feldspars 8,0	quartz, mica feldspars, chlorite 11,3	quartz, feldspars mica, chlorite calcite 6,0
P – 93 1,01 – 1,50 m mass. %	montmorillonite clay mica quartz, chlorite 46,7	quartz, chlorite clay mica feldspars, kaolinite montmorillonite 7,6	quartz, chlorite mica, feldspars gypsum 13,1	quartz, mica feldspars, chlorite calcite 15,0	quartz, feldspars mica, chlorite calcite 15,2

Table 1. Clay and silt characteristics on Svätuš locality. Mineralogical phase analysis of soils is difficult.

Figure 3. Double-domain soil structure and detail of a crack, photo Gomboš, locality Milhostov

With regard to the intensity of rainfall and rate of water interception, the following situations can occur fig.4. The symbols have the following meanings: I_c – intensity of crack infiltration [$m.s^{-1}$], I_{c1} –infiltration ratio from rainfall exceeding maximum infiltration intensity of soil matrix surface [$m.s^{-1}$], I_{c2} – crack infiltration of rainwater fallen directly to cracks [$m.s^{-1}$] , I_{in} – interception intensity [$m.s^{-1}$], I_m – soil matrix infiltration intensity of [$m.s^{-1}$], I_{po} – surface runoff intensity [$m.s^{-1}$], P_{in} – rainfall intensity [$m.s^{-1}$], S_c – inner crack surface on a unit of soil surface area [$m^2.m^{-2}$], S_m –soil matrix surface on a unit of area [$m^2.m^{-2}$], S_{pr} – cracks sectional area on a unit of soil surface area [$m^2.m^{-2}$].

1. $P_{in} – I_{in} \leq I_{m,max}$, $I_{c1} = 0$, $I_{c2} = S_{pr} . P_{in}$, $I_c = I_{c2}$, $I_m – S_m . (P_{in} - I_{in})$

   In the first and simplest case the intensity of rainfall is lower than or equal to the rate of water infiltration to soil matrix ($I_{m,max}$). The ratio of rainwater absorption by soil matrix surface and the area of crack sectional surface is the same as the ratio of their surfaces (fig.4a).

2. $P_{in} - I_{in} > I_{m,max} \wedge I_{po} = 0$, $I_{c1} = S_m . (P_{in} – I_{in} I_{m,max})$, $I_{c2} = S_{pr} . P_{in}$, $I_c = I_{c1} + I_{c2}$, $I_m = S_m . I_{m, max}$

   In the second case the intensity of rainfall is higher than water infiltration in soil matrix. Rainwater that is not absorbed by the surface of soil matrix (I_{c1}) drains to the nearest crack and thus increases water content absorbed by cracks (fig.4b).

3. $P_{in} - I_{in} > I_{m,max} \wedge I_{po} > 0$, $I_c = S_c . I_{m,max}$, $I_m = S_m . I_{m, max}$, $I_{ho} = (P_{in} - I_{in}) . (S_{pr} + S_m) -I_c - I_m$

   In the third case the intensity of rainfall exceeds the maximum rate of water infiltration in soil matrix while crack capacity to absorb another water flow has been exhausted and cracks are now wholly filled with water (fig.4c). There is surface run-off.

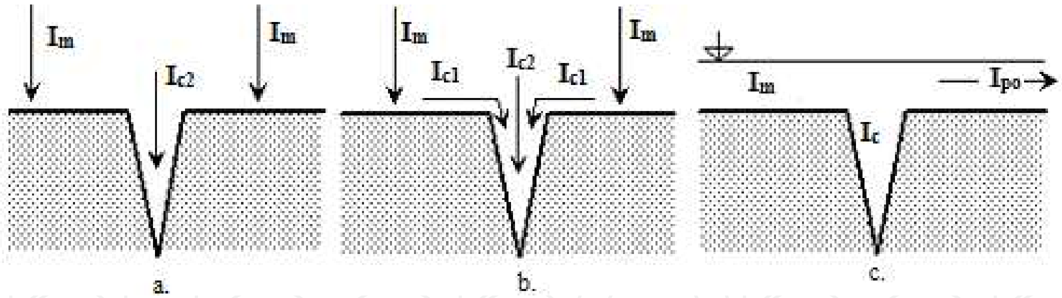

Figure 4. Different ways of water penetration through cracks and soil matrix surface depending on the rainfall intensity.

During water transfer from the surface to lower soil horizons or ground water level (GWL, rainwater can permeate directly under the root zone. As a result no efficient water contact with root zone occurs. This effect reduces the efficiency of irrigation and fertilizing. At the same time, cracks can accelerate soil water evaporation to atmosphere and crack networkwork anticipates the permeation of pollutants through soil to GWL.

2.4.2. Water balance in two-domain soil structure

The basic equation for determining the water balance in aeration zone is [7]:

$$W_t = W_0 + I_k + I_i + Q_{hp} - E - T - Q_{ho} - I_h \tag{1}$$

W_0 - initial overall soil content in aeration zone [m], W_t - overall soil water content in aeration zone at time *t* [m], I_k - capillary water inflow [m], I_i - water inflow by infiltration from rainfall [m], Q_{hp} – subsurface lateral water inflow [m], E - water losses by evaporation [m], T - water losses by transpiration [m], Q_{ho} – subsurface lateral water drainage [m], I_h - infiltration into GWL or lower horizons [m].

For the purposes of cracking soils, it is necessary to adapt some members of the balance equation, mainly I_i, representing water inflow by infiltration from precipitations. This shall be split to I_c – water inflow by infiltration through cracks, and I_m – water inflow by infiltration through soil matrix surface ($I_i = I_c + I_m$).

Similarly, water losses by evaporation E shall be split to the evaporation from soil matrix surface E_m and evaporation from sectional area of cracks E_c ($E = E_m + E_c$). However, the evaporation from the sectional area of cracks is disputable. On one hand, it could be objected that water does not evaporates merely from the narrow area of cracks sectional surface but from the whole surface of crack walls, which is larger. On the other hand, evaporation from the surface of crack walls is very limited due to high moisture levels and little air circulation inside a crack. Air inside the cracks that reach the depth of groundwater table is supposed to be saturated with water vapours. Evaporation from plant cover (transpiration) T occurs only on the area of soil matrix surface $T_m = T \,.\, S_m$. Modified balance equation shall be:

$$W_t = W_0 + I_k + I_c + I_m + Q_{hp} - E_m - E_c - T_m - Q_{ho} - I_h \tag{2}$$

In lowland areas, subsurface inflow and drainage (Q_{hp}, Q_{ho}) can be disregarded.

3. Methods and material

3.1. Texture of the analysed soil profiles

The research in heavy soils water regime on ESL was performed on 11 soil profiles. In this paragraph, results from three typical areas on ESL are presented: Senné (48°39'48,19"; 22°02'53,90"; 97 m), Milhostov (48°40'11,08"; 21°44'18,02"; 100 m) and Sírnik (48°3033,01"; 21°48'51,18"; 98 m). Grain-size analysis to various depths was performed on each of these three soil profiles- in Senné to 0.8m, in Milhostov to 2.0m and in Sírnik to 1.2m, in the layers 0.10m thick. The results were processed into USDA soil textural triangles [8], which are shown at fig.5.

It is obvious that the heaviest soil is in Senné, where clay is the predominant soil constituent. Soil profile is homogeneous and the fraction of sand is significantly lower compared to the other two areas. In Milhostov, where in addition to clay, silt can be found as the second most dominant soil type, ranging from clay silt to silty loam. Upper horizons of soil profile to 0.60m are heavier (36% of clay) than the lower horizons. Sírnik soil profile shows two markedly different layers along the vertical line. In the depth of 0.40m and downwards to 1.20 m clay fraction doubles from 25% to 50%. Apart from clay, the second more dominant constituent is silt.

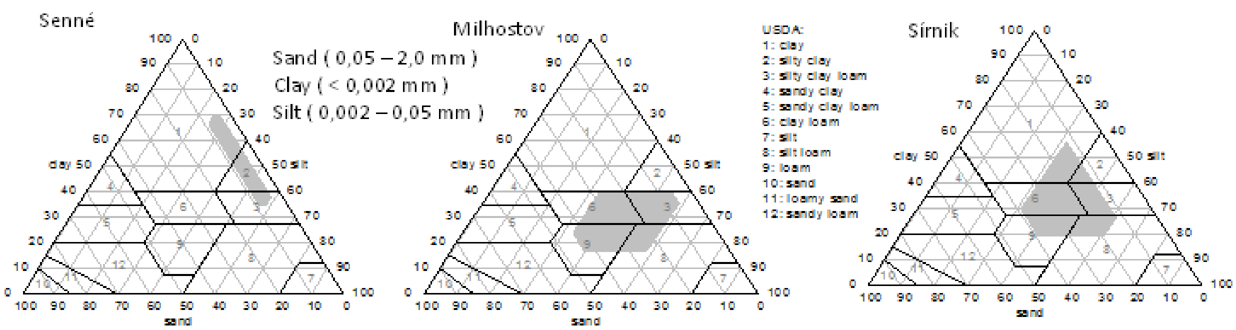

Figure 5. Classification of selected soil profiles according to the triangular classification diagram USDA

3.2. Field measurements and experiments

Field measurements included continual monitoring of the observed areas once every week. During the winter, field measurements were not performed because of possible imprecisions due to snow cover and frozen upper layer of soil.

The following parameters were monitored fig.6.:

- GWL position,
- volumetric soil moisture along the vertical line to the depth of 0.8m in the layers 0.1m thick.
- vertical movement of soil surface – these measurements were performed by the method of surface levelling in three points situated in the shape of equilateral triangle with 2m sides. For the details of one such point see fig.6. Casing pipe is used as a fixed point. It is supposed that due to deep embedding, the pipe is stable with regard to the vertical movements of soil surface through the active layer of a soil profile.

- lump-sum takings of undisturbed soil samples by the method of dug probe fig.7, in Kopecký cylinders, for the purpose of determining moisture retention curves, hydraulic conductivity, COLE values (Coefficient of Linear Extensibility) and PLE values (Potential Linear Extensibility). Undisturbed soil samples were taken as well to perform grain-size analysis. Furthermore, in Milhostov area, geometric parameters of crack networkwork such as length, width, specific length and soil matrix area were measured.

3.3. Laboratory measurements and experiments

Laboratory measurements were based on the evaluation of soil samples taken during the regular monitoring and lump-sum takings. The following analyses were performed:

- Grain-size analysis – on disturbed soil samples by hydrometer-method. On the ground of this, soils were classified according to USDA texture diagram.
- Analysis of soil shrinking properties – on undisturbed soil samples. Firstly, the samples were fully saturated with water and on the basis of geometric parameters measurements their original volume and measured weight were calculated. The samples were then dried at laboratory temperature and their volume and weight were regularly measured. When the weight loss had almost reached measurement error, samples were dried up in a laboratory dryer at 105°C and then measured again for their final volume and weight. Measured parameters were evaluated from the point of view of dependencies between soil volume, grain soil structure and volumetric moisture, shrinking properties in the form of shrinkage curve and COLE and PLE values and geometric factor r_s.

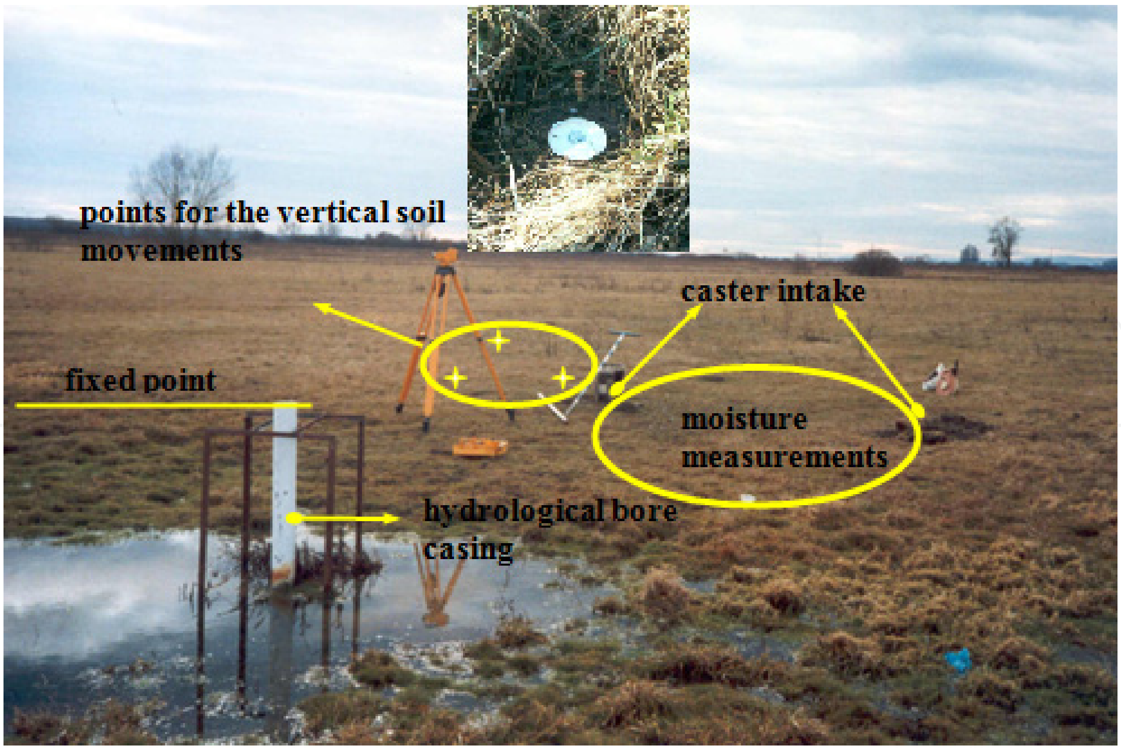

Figure 6. Sampling area (Senné area) and a detail of a point where vertical water movements are measured

Figure 7. Collection of untouched soil samples

- Analysis of volumetric soil moisture – gravimetric method was used.
- In the IH SAS laboratory in Bratislava, overpressure method was used for measuring moisture retention curves and courses of hydraulic conductivities on the solid soil samples.

3.4. Determination of the selected heavy soils characteristics

3.4.1. Determination of the soil shrinkage basic characteristics

Heavy soils shrinkage is often described with regard to the relationship between the volume of the soil and its moisture. This relation has been subject to numerous studies worldwide. The shrinkage characteristic used most is based on the relation between a soil water ratio - ν and a void ratio – e, where ν = soil water content / volume of soil solid phase [-] e = volume of pores/volume of soil solid phase [-]. Soil water ratio and void ratio are determined on the basis of volumetric soil moisture - θ and porosity – P. The following equations are used:

$$P = \frac{e}{1+e}; \;\; \theta = \frac{\nu}{1+e} \, [-] \tag{3}$$

General relationship between soil water ratio and void ratio is figured in the graph in fig.8. Auxiliary diagonal line in the fig.8 represents the state of saturation when soil water ratio equals void ratio and the total volume of pores is filled with water. Curve divides shrinkage process to four domains.

- **Strucural domain** – occurs in saturated soils. Water is drained from macropores. Soil volume remains unchanged or changes very slightly;
- **Normal domain** – changes in soil volume are equal to the changes in water content and micropores remain saturated with water (part of the curve paralel to the diagonal line);
- **Residual domain** – changes in soil volume are lower than changes in water content , air starts to enter the micropores (curved part of the curve);
- **Zero domain** – there are no changes in volume (horizontal part of the curve).

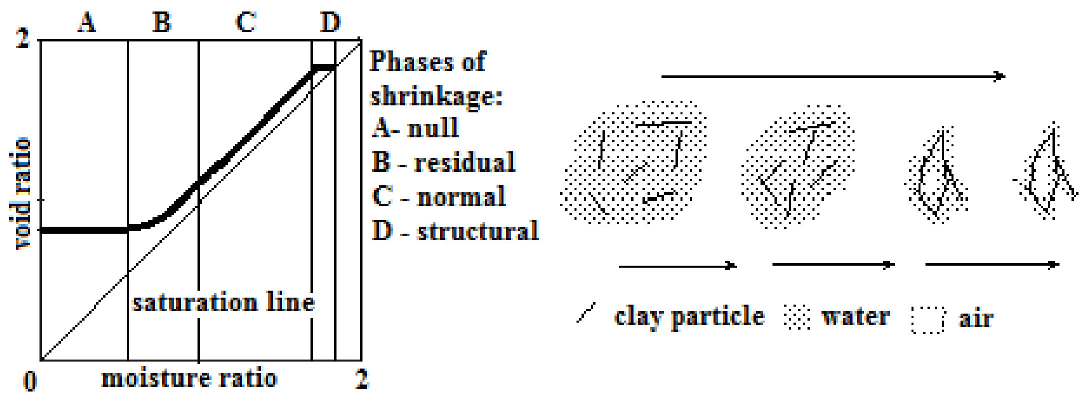

Figure 8. General form of expression of shrinkage characteristics of heavy soils and position of clayey particles during drying [9].

3.4.2. Shrinkage potential of heavy soils

When studying shrinkage characteristics of heavy soils, it is practical to quantify the potential of this phenomena. For this purpose two parameters were introduced in soil science: COLE (Coefficient of Linear Extensibility) and PLE (Potential Linear Extensibility). COLE was introduced by Grossman [10] and it is used for quantifying shrink-swell potential of soil:

$$COLE = \left(\frac{V_{wet}}{V_{dry}} \right)^{\frac{1}{3}} - 1\,[-] \tag{4}$$

where V_{wet} is the volume of wet soil and V_{dry} is the volume of dry soil.

The second parameter expressing shink-swell soil potential is PLE, which is the potential for soil swelling and shrinking in field conditions. It considers swelling and shrinking properties of the individual soil horizons in the studied soil profile.

$$PLE = COLE_{(1)}.\ Z_{h(1)} + COLE_{(2)}\ .\ Zh_{(2)} + \ldots + COLE_{(n)}\ .\ Z_{h(n)} \tag{5}$$

where $COLE_{(n)}$ is a COLE value for n- horizon, $z_{h(n)}$ is the width of n-horizon [cm], and $z_{h(1)} + z_{h(2)} + \ldots + z_{h(n)} = 100$.

PLE is the value of maximum (potential) change in length of a 100cm thick soil profile due to swelling and shrinkage process. After COLE and PLE has been set, a soil can be classified according to COLE value [11], tab.2 or PLE values [12], tab.2.

shrinkage - swelling potential	COLE
low	< 0.03
medium	0.03 - 0.06
high	0.06 - 0.09
very high	> 0.09

Shrinkage according to the PLE potential	PLE value [cm]
high shrinkage	> 14
medium shrinkage	9 - 14
low shrinkage	< 9

Table 2. Classification of shrink-swell potential by COLE and PLE values

3.4.3. Formulation of relationships between volumetric changes and vertical subsidence of soils

Soils volumetric change is a three-dimensional process. In nature, drying of soils is partly reflected in cracks formation and partly in the soil surface subsidence. Therefore soil changes are horizontal, caused by opening and closure of cracks, and vertical as soil surface movement. In laboratory, soil volumetric changes are visible as changes in geometric dimensions of an undisturbed specimen of soil. Calculations are based on the following equations fig.9.:

$$\Delta V = \Delta Vv + \Delta Vh \tag{6}$$

where

$$\Delta Vv = z_s^2 \, . \, \Delta z \quad [m^3] \tag{7}$$

Mathematical expression of the relationship between soil volumetric change and vertical subsidence is as follows [13]:

$$\Delta z = z_s - \left[\left(\frac{V}{V_s} \right)^{\frac{1}{r_s}} \right] z_s, [m^3] \tag{8}$$

where

ΔV total volumetric change of a soil specimen $[m^3]$;
ΔV_v vertical volumetric change of a soil specime $[m^3]$;
ΔV_h horizontal volumetric change of a soil specimen $[m^3]$;
V soil volume after shrinkage $[m^3]$;
V_s volume of a saturated soil specimen $[m^3]$;
Δz change in height of a soil specimen [m];
z_s height of a saturated soil specimen [m];
z height of a soil specimen after shrinking [m];
r_s geometric factor [-].

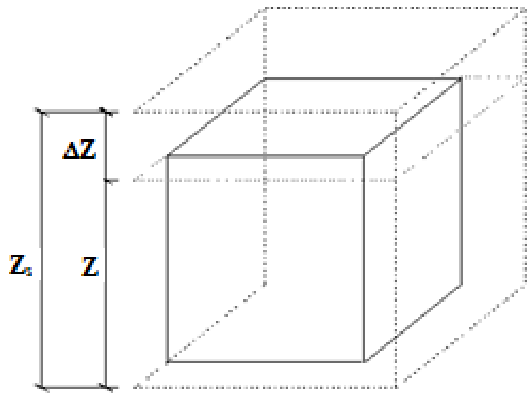

Figure 9. Volume change of isotropic soil sample in shaper of cube during drying process, (dashed line express the sample in saturated state (sample height Z_s), continuos line express the sample after shrinkage (sample height Z)

The equation above (8) is implemented in the mathematical simulation model FLOCR [14], which is designed to calculate the thickness of each layer. Horizotal volumetric change can be expressed by the following combination of equations (6,7,8):

$$\Delta V_h = V_s \left[\left(\frac{V}{V_s} \right)^{\frac{1}{r_s}} - \frac{V}{V_s} \right] \left[\mathrm{m}^3 \right] \tag{9}$$

Experimental measurements of the dependency ΔV = f(θ) in the vertical line of a soil profile allow for the calculation of crack porosity volume and the overall subsidence or lift of soil surface induced by moisture changes. With the knowledge of geometric characteristics of crack networkwork, cross-sectional surface and avg thickness (rate of openness) of cracks can be calculated.

3.4.4. Geometric factor of volumetric changes

Non-dimensional geometric factor r_s is the ratio of participation in soil volumetric changes of both crack formation and vertical movements. It can be influenced by external load and possibly by terrain settling process, which occurs when the clay sheet particles are orientated in one predominant direction. r_s can reach the following values:

$r_s = 1$ no cracking process, all soil volumetric changes are vertical;
$1 < r_s < 3$ vertical movement predominates over crack formation
$r_s = 3$ isotropic shrinking;
$r_s > 3$ crack formation predominated over vertical movement;
$r_s \to \propto$ all soil volumetric changes are horizontal; i.e. only cracks are formed.

In nature, isotropic shrinking with $r_s = 3$ can occur in most soils. Provided that during drying the vertical change in height of a soil specimen and the volume of water saturated soil are measured, the equation (8) can be used to calculate the geometric factor r_s. This factor can be calculated from the equation mentioned previously in its analytical form:

$$r_s = \frac{\log(\frac{V}{V_s})}{\log\left[\frac{-(\Delta z)+z_s)}{z_s}\right]} \; [-] \qquad (10)$$

3.4.5. Measurements of crack networkwork characteristics

Cracks represent horizontal volumetric changes of soil. On the soil surface they form a mosaic that reminds a network. Stability of soil matrix walls is ensured by cohesive forces in soil. It is enforced by humic and other organic substances. It is a well-known fact that cracks are formed in places where mechanical strength is lower, usually in the same area not only during one year but also in more consecutive seasons. It means that if a crack networkwork was created in an area, cracks shall open repeatedly, unless significant changes occurred in mechanical characteristics of the soil [15], [7]. Study of cracks geometry and determination of their characteristic has been increasingly important with regard to physical structure of soil which is characterised by physical soil properties. This relationship may be useful for formulating predictions about cracks formation in a soil type. With a view to define geometric properties of cracks the following characteristics can be used: L_c – length (total length of cracks on a measured surface) [m], d_c – width (avg crack openness) [m], z_c – depth [m], - specific length (length of cracks on a measured surface) [$m.m^{-2}$], R_c – specific density (number of cracks on a unit of length) [$m^2.m^{-2}$], $S_{pr} = L_c \,.\, d_c$, S_c – internal surface of cracks (“wall surface” of cracks on a unit of soil surface area) [$m^2.m^2$], $S_c \cong 2 \,.\, L_c \,.\, z_c$, P_c – crack porosity (crack volume in a unit of soil volume) [$m^3.m^{-3}$], P_{ac} – crack porosity of aeration zone (crack volume on a unit of soil surface to GWL depth) [$m^3.m^{-3}$]. Geometric characteristics of crack networkwork were studied in Milhostov area. From 3m above the ground photodocumentation was made, on the ground of which geometric characteristics of crack networkwork were evaluated.

3.4.6. Numerical simulation of heavy soils water regime

Numerical simulation of water movement through the unsaturated soil is based on the interrelation of this sub-system with other sub-systems of the system: atmosphere – plant cover – unsaturated zone – groundwater. When coming in contact with water, impacted unsaturated zone responds by water regime changes in time and space. With a view to authentically simulate the results of such water movement, so that the model approaches reality as much as possible, very precise input data are vital. The input data are of five types: metheorological and climatic conditions, plant cover characteristics, hydrological conditions, topographic data of the observed area and initial and boundary conditions. In case of numerical simulation of water regime in heavy soils, shrinking and swelling characteristics must be included as well. Outputs from the model provide information on the development of soil water content in every horizon in unsaturated soil, on water flow through upper and lower boundary of unsaturated zone during the whole modelled period. The model can be verified by comparing the outputs from the model with the data monitored on-site.

In this particular case of heavy soils water regime, FLOCR model was used (FLOw in CRacking soils) [14]. The model was developed in The Netherlands and it simulates one-dimensional vertical water flow in aeration zone of a two-domain soil profile. It assumes that water flow through soil matrix in unsaturated zone can be calculated by Richards`equation and volumetric changes by the formula (6). A soil profile is divided in layers, there can be max. 30 layers in a soil profile. For each layer, the model calculates water inflow and drainage, volumetric changes, crack volumes, changes in layer width, moisture potential as a pressure height and volumetric moisture. For a soil profile as a whole, the model calculates total volume of cracks, vertical movements of soil surface, GWL, drainage, actual evapotranspiration and surface runoff. The model can be used also for the soils with more horizons of different hydrophysical properties. Max. Number of horizons is 5.

The input data entering the model are: hydrophysical properties of a soil profile (moisture retention curve, saturated and unsaturated hydraulic conductivity, shrinking characteristics), upper and lower boundary condition, precipitations, potential evapotranspiration, spacial determination of a soil profile, setting of a computational step.

4. Results

4.1. Quantification of volmetric changes in ESL soils

Altogether, 90 samples of different gran-size structure were analysed. Time-course of volumetric changes of soils with varying clay particles ratio is pictured in fig. 10. The graph shows considerable impact of clay particles ratio in soil on the rate of volumetric changes with regard to the conditions of saturation. When the content of particles of the I. fraction (I. fraction (I.fr.) is colloidal clay - particles < 0,001 mm, I. kat.- particles < 0,01 mm) exceeds 25%, this increase shoots up other volumetric changes (difference between upper and lower line). Therefore water desorption from soil during drying requires different time interval for every soil sample.

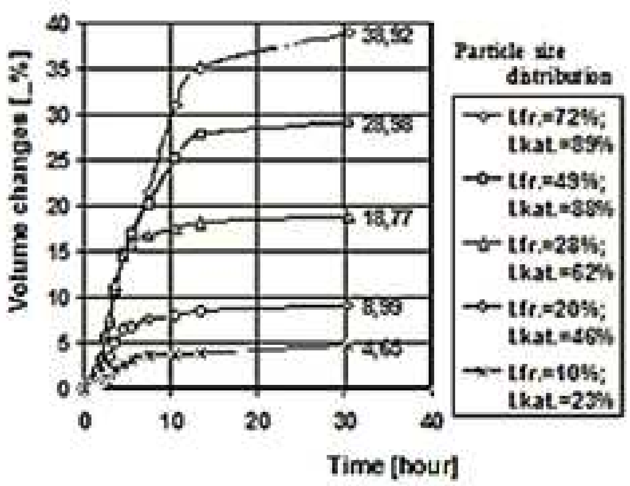

Figure 10. Processing the courses of the volume changes of the soil with the different particle size Distribution, I.fr. < 0.001 mm.

Fig. 11 shows the course of volumetric changes of soils of various grain-size structure with regard to volumetric moisture. The differences in volumetric changes in each part of I. fraction are obvious. It can be seen that volumetric changes can reach 40 % of the saturated soil volume. In fig.11 volumetric changes at different moisture levels for different soil samples are considered. Thus the lines in the graph represent volumetric changes measured simultaneously in various soil samples with different moisture values. Initially, all the lines of the first fraction are in one bundle.

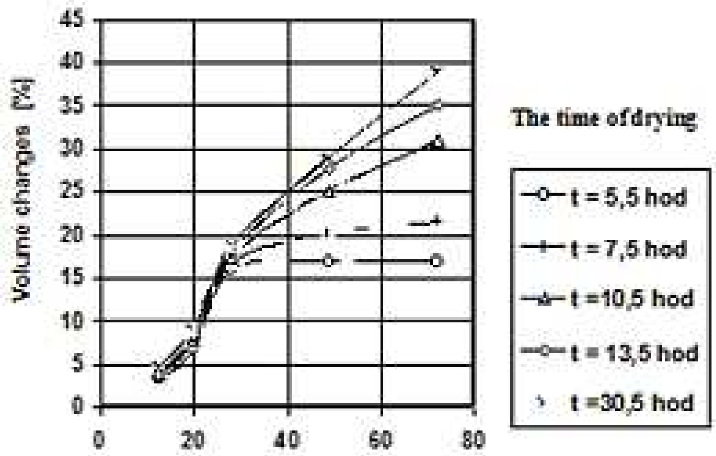

Figure 11. The course of the volume changes of the soils with the different particle size distribution during drying depending on the bulk water content. Differences at individual levels of 1. Fraction content are obvious.

When the particle content in the I. fraction is less then 20 %, important volumetric changes occured during the first 5.5h and in the following 25h there were just slight changes in soil volume.

Fig. 12 shows the course of volume changes in soils of different textural composition, with regard to soil volumetric moisture. The differences in volumetric changes in soils with various ratio of fraction I. are evident. On the grounds of the stated results, it is obvious that physical clay content and soil moisture have a decisive impact on soil volumetric changes.

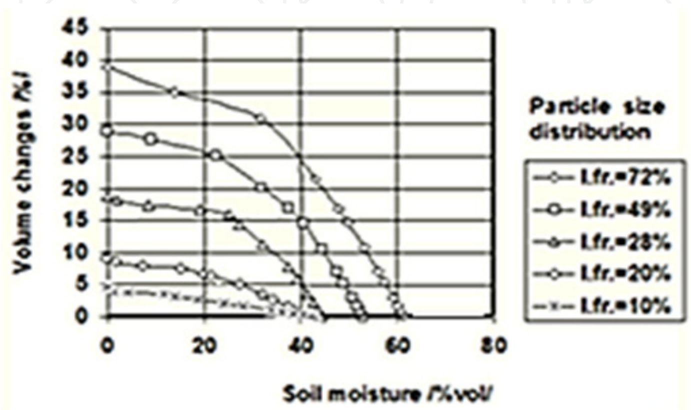

Figure 12. The soil volume changes at different water contents (bulk water content θ is expressed by the time of drying) with the different content of particle of 1. fraction

Fig.13 shows a three-dimensional visualisation of the measured results. It is a three - dimensional axionometric representation of 190 measurements of dependencies between volumetric soil changes with regard to the content of physical clay and volumetric moisture. Fig. 13 on the left is a graphical representation of the measured data. On the right there is a graphical representation of the same values by means of 3rd order polynomials.

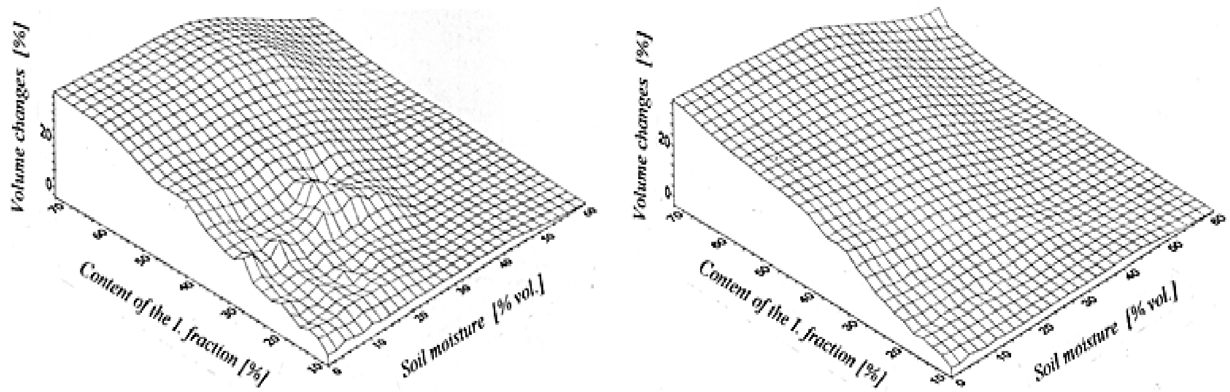

Figure 13. The three-domain representation of the measured volumetric changes of soil in dependence on the humidity and the grain structure and polynomial representation of this dependency.

4.2. Shrinkage characteristics

In the soil profiles mentioned in paragraph 3.1, shrinkage properties were determined in layers 0.1m thick by means of the method described in paragraph 3.4.1. Fig. 14 shows the comparison between the soil profiles with different clay minerals content, which has considerable impact on the course of shrinkage characteristics. Shrinkage process in clay soils comprise three distinct shrinkage phases. In light soils (on the right) shrinkage is very slight. Knowledge of shrinking characteristics is vital for precise numerical simulating of heavy soils water regime.

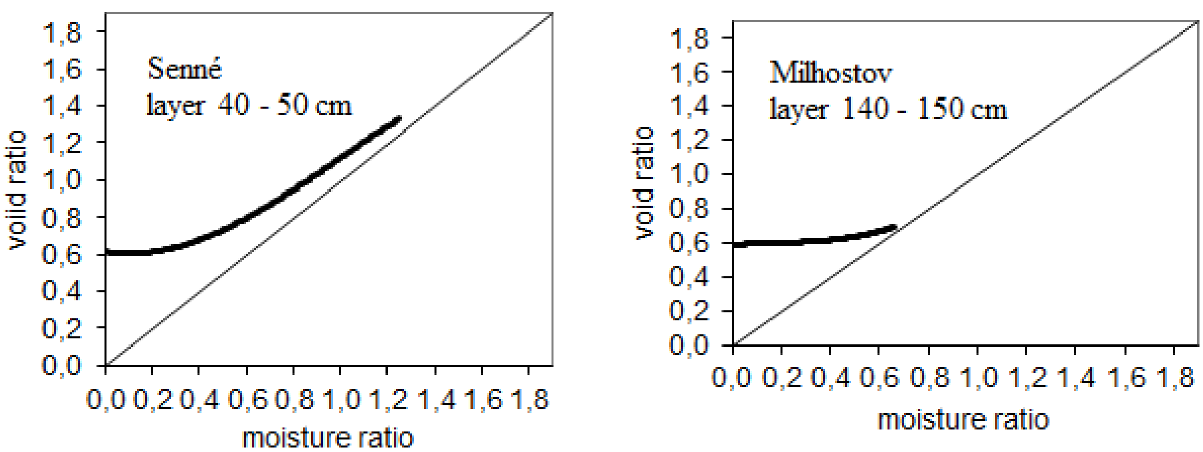

Figure 14. Comparison of shrinkage characteristics of heavy clay (Senné, clay 49%) and lighter loam (Milhostov, clay 23%).

4.3. Evaluation of shrink-swell potential of ESL soils

The quantification of volumetric change potential was performed in laboratory on the examined profiles by means of COLE and PLE coefficients.

Value of PLE=15,30cm in Senné classifies the soil profile as "High shrinkage" in Reeve classification. It means that soil profile can potentially change its thickness by 15,30cm into the depth of 1m. However, it is only theoretical assumption which is very unlikely to occur in nature. The highest vertical movement measured in Senné locality during research works was 5,51cm.

Dependency between COLE and clay minerals measured on ESL was compared to the results gained in the Netherland and USA [9], [11], [16] fig. 15. Comparison indicates that examined dependency measured on ESL has slightly steeper slope comparing to the data from literature. It is probably related to spatial variability of mineral structure of clay particles, mainly by presence of illite and montmorillonite group of clay minerals.

4.4. Field measurements of vertical soil surface movements

Vertical soil surface movement is one of the signs of volumetric changes. Fig. 16 shows the results of vertical water movement in 2003. Results indicate that the largest soil surface movements occured in Senné locality (5.51cm). It was 4.08cm in Sírnik area and 3.18cm in the Milhostov area. Results comply with the analysis based on PLE and COLE values. It is possible to calculate water storage in active layer of soil profile by vertical movements. Value of the geometric factor – r_s (that is dependent on the ratio of horizontal and vertical part of shrinkage) was laboratory determined. In every analysed profile the value of r_s was dentified for 0.10 m thick layers. In the Senné avg value $r_s = 2.85$ was measured. It means that the vertical soil surface movement dominates over creation of soil cracks. In Milhostov the avg measured value was $r_s = 3.1$ is. Horizontal changes slightly dominate over vertical changes with regard to the total volumetric change. In Sírnik profile to 0.80m depth r_s value was isotropical, r_s=3.

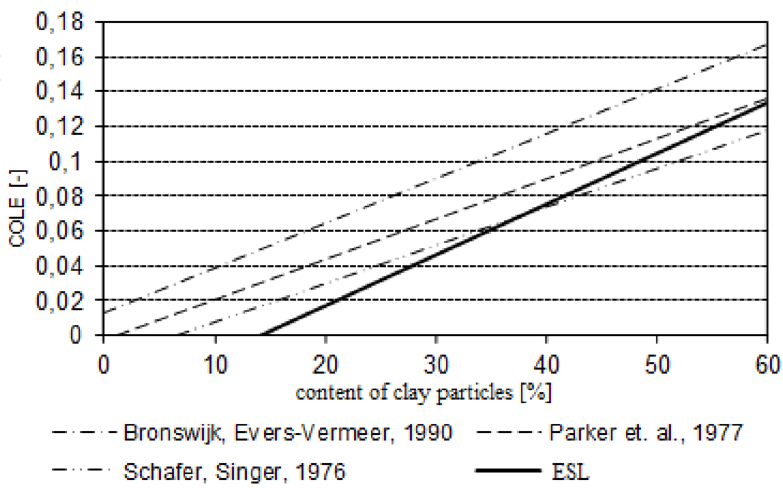

Figure 15. Comparison between cole dependency on clay particles content on ESL and dependencies measured in heavy soils in Netherlands and USA.

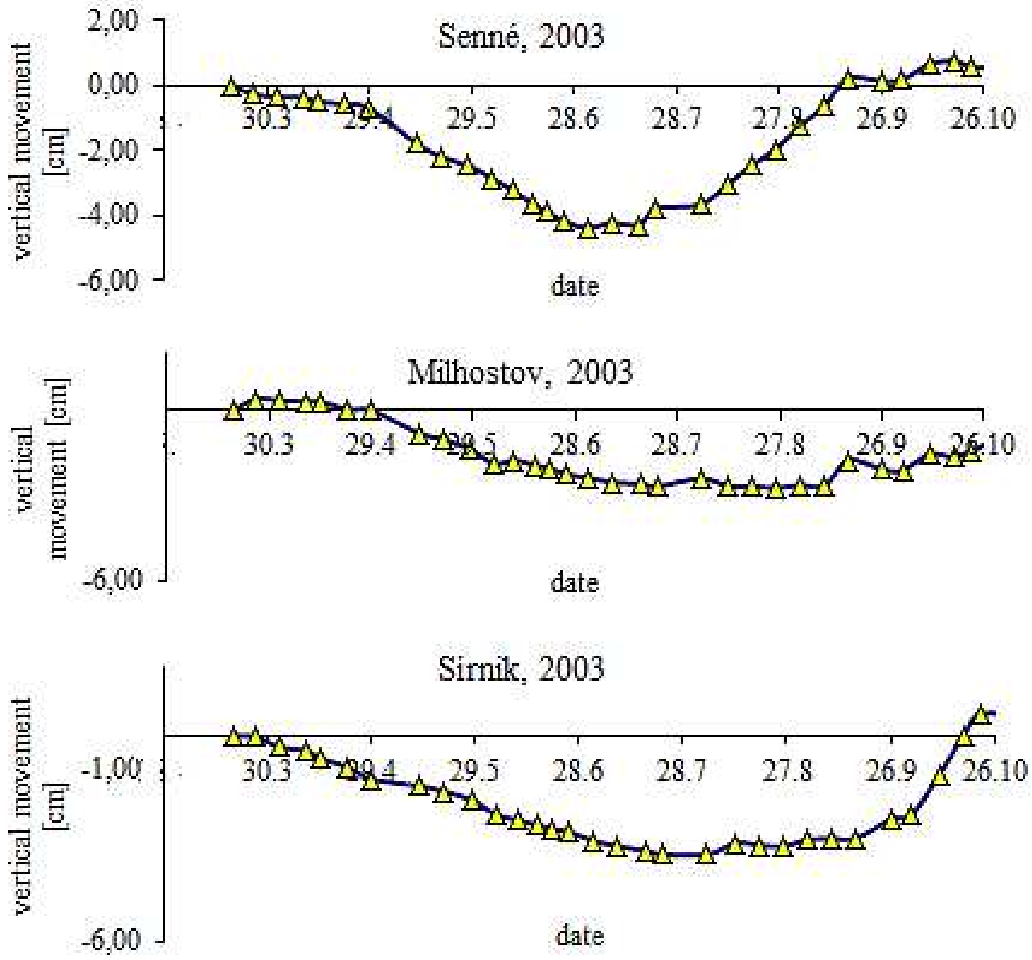

Figure 16. Results of vertical movements of soil surface measurements in 2003

4.5. Structure of crack network in the locality of Milhostov

In Fig.3 you can see the types of crack network structure identified in this work on the basis of common particular features [7]. The most common structure is *characteristic structure of crack network*, fig. 17a, which occurs in the soils cultivated by common agrotechnology. Another structure is a sporadic crack structure of *linear typ,* fig. 17b. It is an accidental structure occurring on seedbeds or on paths between them. It is a separate element on the surface of agriculturally cultivated fields. The third type is a sporadic structure of *cluster type,* fig. 17c**.** It is formed by small clusters of cracks on small areas which are caused by enormous soil drying in these areas. Crack network structure of *anthropogenic character,* fig. 17d, is a network which is caused by sowing mechanisms blades. It has a regular square structure. In comparison with preceding structure it is characterised by relatively smaller values of specific length and crack density.

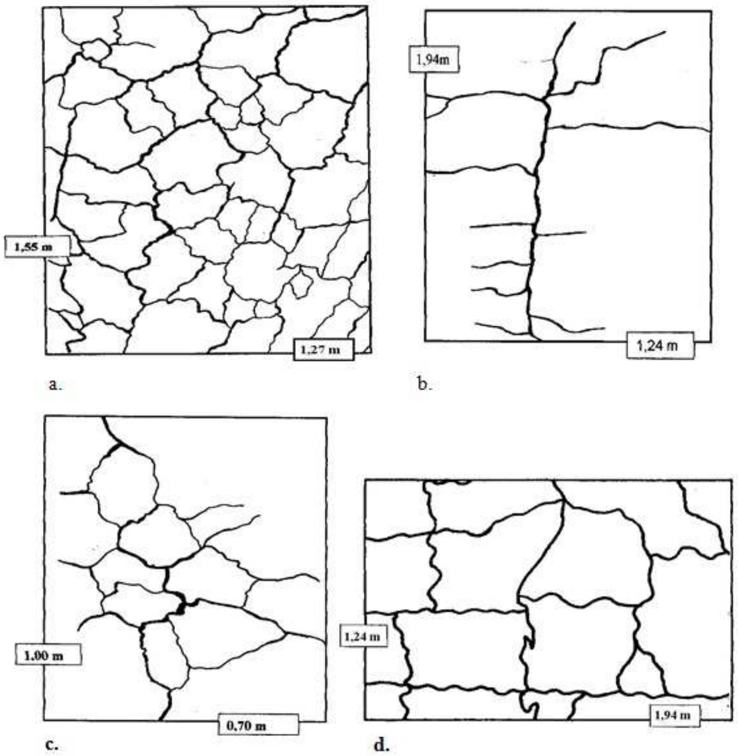

Figure 17. Structure of heavy soil crack net (locality Milhostov)

The analysis of photographs from Milhostov area showed that total length of cracks in the observed areas L_c was 123m, specific length was L_{mc} = 5.65 m.m^2, specific density was R_c = 3.1 cracks.m^{-1}. Depth of the cracks was estimated on 1.20m based on a dug probe. Therefore the average area of internal walls with neglected turtuzoity is 13.56 m^2.m^{-1}. At the occurrence of sudden and extreme rainfall, the infiltration is realised not only by soil matrix surface but also by water permeation through cracks as the cracks are filled with water. Fig. 18 shows the evaluation of 234 soil matrices. The distribution indicates that the most occurring soil matrix area is within the interval 0.05-0.10 m^2. The average area of the soil matrix is 0.121m^2.

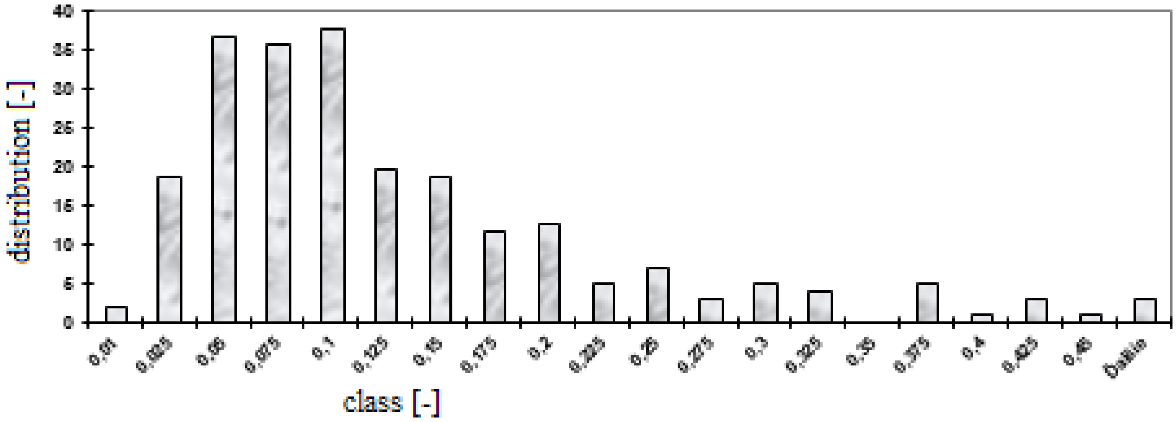

Figure 18. Distribution abundance of soil matrix area in the locality Milhostov

4.6. Selected results of numerical simulation of soil water regime on ESL

In the figure below, the results of 2003 numerical simulation of water regime are described. This year has been one of the driest years in Senné area in terms of soil water storage since 2007. Therefore the impact of the clay minerals on hydrological processes in soil environment can be proved. The schemes graphically represent the results of moisture volume measurements in the examined profiles. The depth to which the soil profiles are dried can be seen.

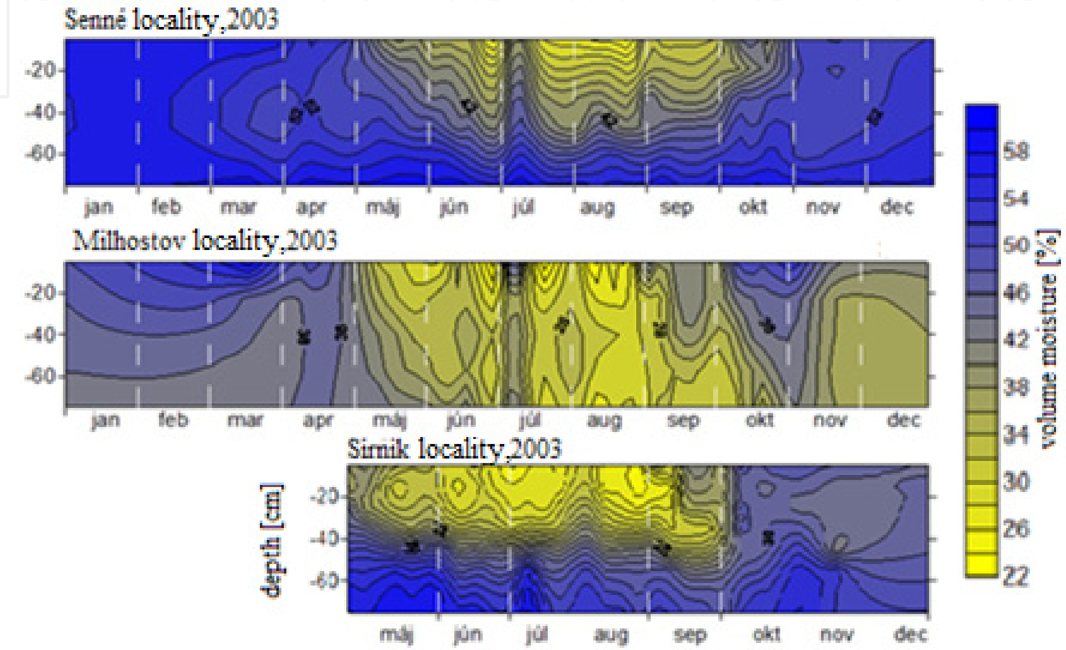

Figure 19. Monitored moisture regime of examined soil profiles in 2003 in Senné, Milhostov and Sírnik locality.

After the verification of the numerical simulation results, the simulation of water regime into the depth of 3.0 metres could be started. The targets of the verification were the measurements of the soil moisture regime, GWL course and soil surface vertical movement. The results of moisture regime numerical simulation of the observed profiles into the depth of 3m during 2003 vegetation period are shown in Fig. 20.

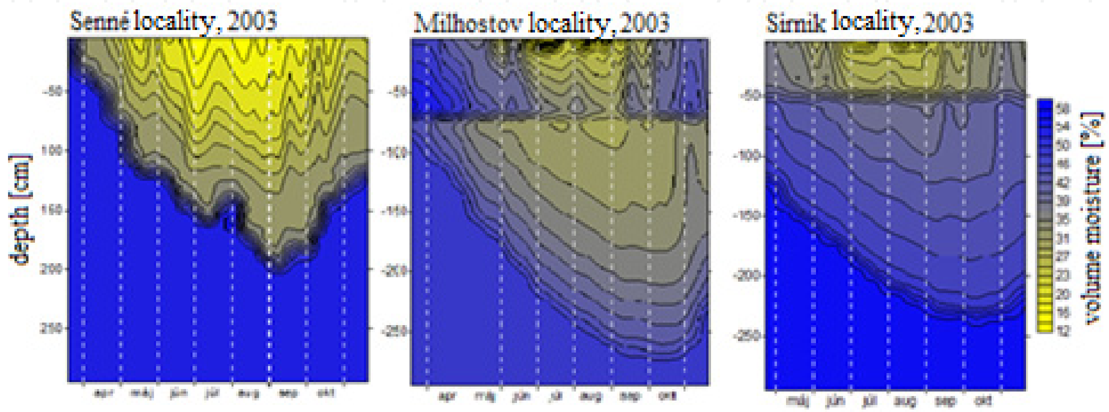

Figure 20. Numerical simulation of moisture regime of examined profiles

In Milhostov and Sírnik the influence of material interface along the vertical line of soil profiles is clearly manifested. In Milhostov the upper soil horizons are heavier with higher content of clay compared to the lower horizons. In Sírnik the situation is just the other way round and in Senné the soil profile is homogenous. Balance values illustrated in tab. 3 (based on fig. 21) confirm that the heavy soil profile in Senné can absorb rainwater through the cracks better then the Milhostov profile. Surface runoff did not occur in 2003. Its occurrence was observed only once, in Milhostov in 2001. It was induced by heavy rain in July 2001 when the daily rainfall accrual was 82mm. This rain event provoked 17mm surface runoff. The rest was absorbed by soil matrix and cracks.

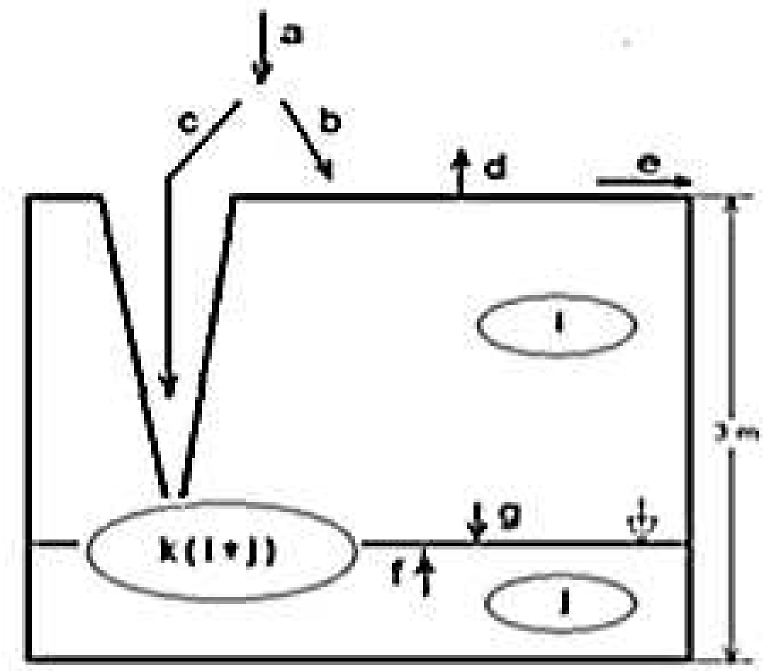

Figure 21. Balance scheme for simulated soil profile (explanations are listed in table 3).

4.7. Simulation of extreme rainfall influence on the water regime in unsaturated zone

The network of soil cracks represents a retention volume which is available for rainwater retention in case of extreme rainfall incidents. This effect is manifested most under extreme rainfall incidents. 2001 water regime of soil a profile (from February 14, 2001 to December 18, 2001) was simulated by numerical simulation using the mathematical model FLOCR (FLOw in Cracking soils). The profile is a specimen of extremely heavy soil with a two-domain structure. During the simulation the soil profile to a 3 m depth was defined. The course of groundwater level, volumetric moisture of the observed soil profile and the values of surface runoff were obtained by the simulation. Monitoring process, including the measurements of groundwater level and takings of soil samples in order to define volumetric moisture, took place in the observed locality. Measured data were used to verify the results of the simulation.

Profile water balance			Senné 2003	Milhostov 2003	Sirnik* 2003
precipitation	(b+c)	(a)	300	315	295
rainfall absorbed bzysoil matrix		(b)	287	305	293
rainfall absorbed by cracks		(c)	13	10	2
actual ET		(d)	462	504	473
Surface runoff		(e)	0	0	0
flow from GW (to the zone of areation)		(f)	177	56	155
flow to GW (from the zone of areation)	(h-c)	(g)	92	30	90
flow to GW (from the zone of areation+from the cracks)		(h)	105	40	92
water content change in the zone of aeration	(b-d-g+f)	(i)	-90	-173	-115
water content change in the zone of saturation	(h-f)	(j)	-72	-16	-63
water content change in the soil profile	(i+j)	(k)	-162	-189	-178

*values are listed for the Sírnik locality for period from 1.5. to 30.9.

Table 3. Balance table (values according to the model (mm) for vegetal period: 1.4 to 30.9.

The other step was to analyse a 30-year series of daily rainfall accrual, from which the rainfall event with the periodicity of 0.01 was calculated, i.e. the probability of its repetition is once in every 100 years. The value of extreme rainfall daily accrual was 76mm, fig. 22. This datum was incorporated to the inputs entering the model on the day when the soil profile was the driest, which was calculated to September 5th, 2001. Then he consequent output from the model, based on the added fictitious rainfall event, was evaluated and its influence on the soil profile water regime was analysed. The model showed a very sensitive response of the soil profile to the added fictitious rainfall. It proves the differentiation of volumetric moisture states along the vertical line of the soil profile and the course of groundwater level fig. 22, 23, 24. Surface runoff had a zero (0) value when the simulation considered real rainfall (no extreme rainfall). The addition of extreme rainfall resulted in surface runoff while the soil profile absorbed 56mm of water. At the very limited infiltration ability of the soil matrix surface it means that the significant part of this water content was absorbed immediately by soil cracks. Crack network represents an important retention volume available in heavy soils mainly during dry periods.

Maximum rainfall accrual that the soil profile would be able to absorb is app. 56 mm, provided the periodicity of rainfall is 0.02, fig. 25. This value disregards surface runoff. From the retention point of view, crack network of a two-domain soil structure has a significant influence on the water regime in immediate high rainfall accruance. This fact is of great importance for the future investigation of two-domain soil structures influence on the water regime as the periodicity of heavy rainstorms occurence continually rises at present.

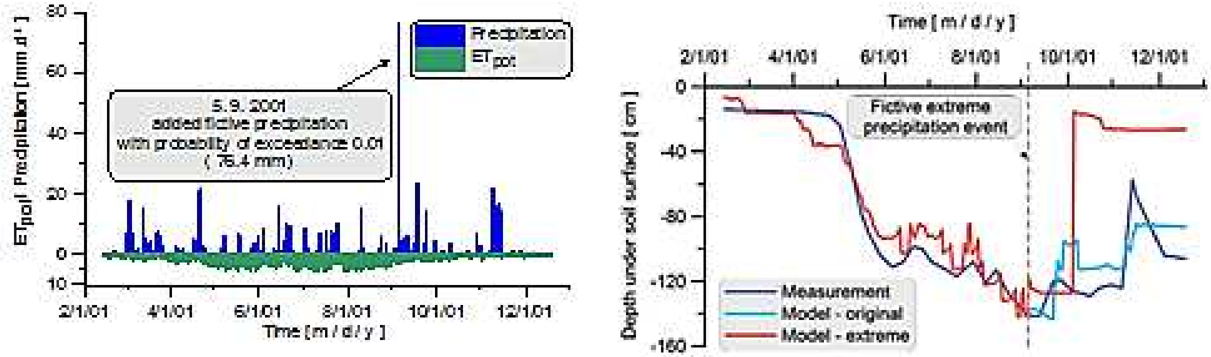

Figure 22. Meteorological inputs to the model with the added fictious extreme rainfall and observed and calculated courses of groundwater level

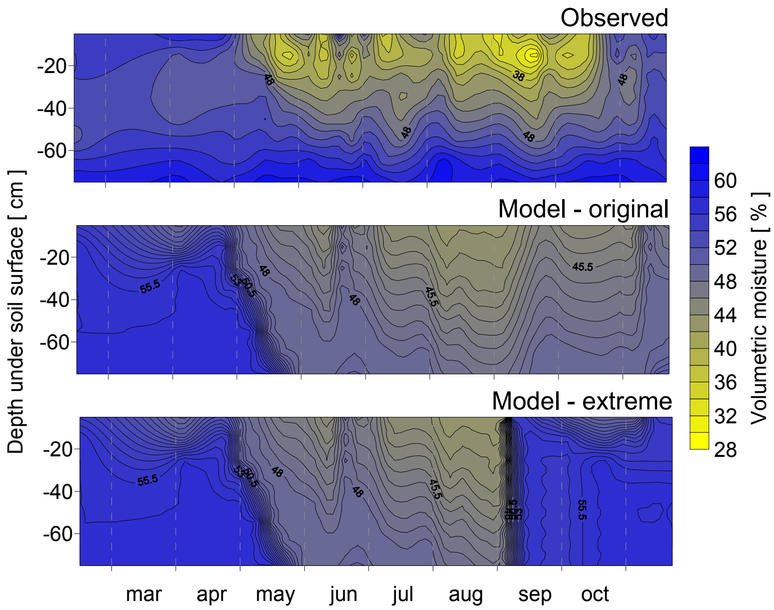

Figure 23. Redistribution of volume moisture in soil profile

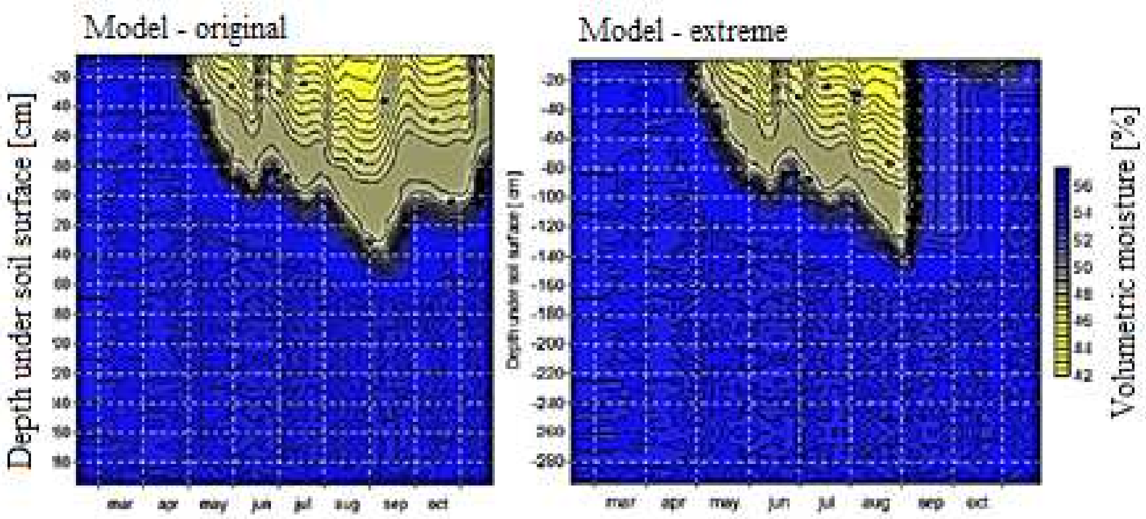

Figure 24. Redistribution of volume moisture in soil profile (model – original), (model – extreme).

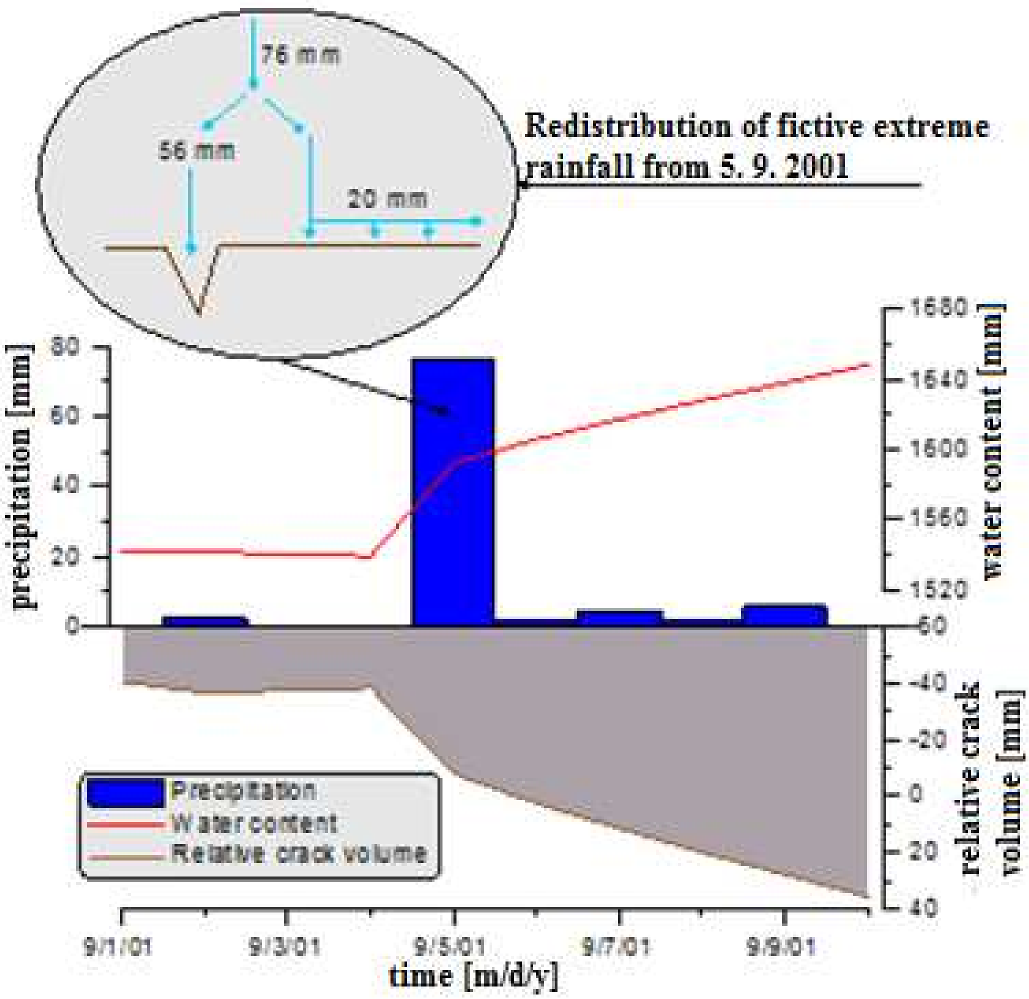

Figure 25. The reaction of model at the time of fictious rainfall event

4.8. Creation of soil cracks as a soil drought indicator

One of the evidence of an extreme hydrological processes is the creation of soil drought. In general, soil drought is defined as a shortage of the soil water used by plant cover for its growth. During water shortage plants get into the state of stress and all their physiological processes are focused on plant survival. To assess soil water storage available for plant cover, we conventionally use the following characteristics: moisture retention curve (soil-water content); wilting point (WP) - represents the value of pF = 4.18; threshold point (TP) - represents the value of pF = 3.3; field water capacity (FWC) - represents the value of pF = 2.0 to 2.7. Water drought starts when the water supplies in the root zone of a soil profile are on the TP level. TP is a soil moisture state when the physiological processes in plant cover are restricted by water shortage. WP is a soil moisture state when plant cover is in a constant lack of water what finally leads to wilting [17], [18],

Heavy soils contain higher percentage of clay minerals. With the changes in soil moisture, these minerals cause the changes in soil volume. During soil profile drying, volumetric changes are manifested by cracks creation. Volume of cracks depends on soil moisture. Soil moisture is thus an indicator of a soil profile moisture conditions. The aim of the presented part is to quantify one of the stress factors on the selected soil profile. [19], [20]. In other words, we focus on quantifying water drought by monitoring volume of soil cracks [21], [22], [23], [24].

The study of this problem is based on the analysis of soil moisture regime with regard to cracks volume and the position of TP and WP on the retention curve. For thew purposes of the analysis, Milhostov area soil profile was used. Numerical simulation was calculated with a computational time of 1 day step in 38 year time series of the 1970-2007 vegetation periods.

Fig. 26 shows shrinkage characteristics. These are expressed in the form of a dependency between a void ratio and a moisture ratio and between the overall soil volumetric changes and moisture. Both expressions include TP and WP values. The development of the dependency between a void ratio and a moisture ratio it is assumed that plants get into stress when shrinkage characteristics shifts from normal domain to residual domain. During the shrinkage process non-linearity is observed. Descrease in soil volume is lower than water reduction. That means that the air penetrates into micropores. Moisture ratio has the value of 0.56 for TP and 0.26 for WP. From the development of overall soil volumetric change (shown in the second part at fig. 26) it is assumed that overall soil volumetric change at TP is 6.7% and at WP 14% with regard to the saturated state. This shrinkage induces crack formation in the upper layer of a 1m- thick soil profile i.e. double domain soil structure is formed. Volume of the created cracks at TP moisture is 43mm and at WP moisture 85mm.

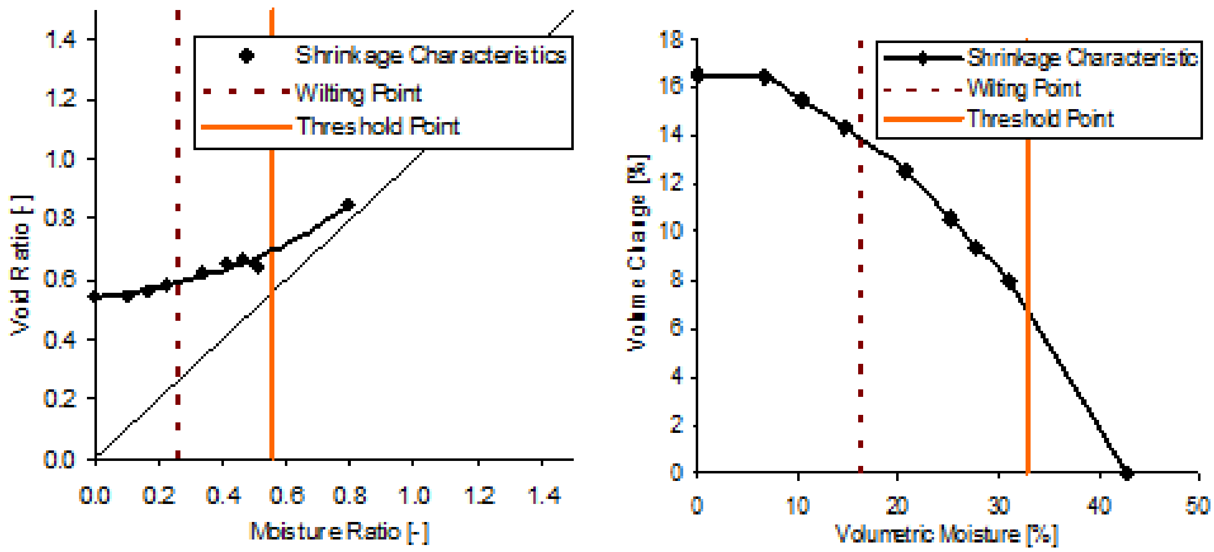

Figure 26. Basic shrinkage characteristics of heavy soil (Milhostov, Slovakia)

5. Conclusion

Sources of clay minerals impact on soil hydrological processes consist in their capacity to bind water and subsequently change their volume. Changes in soil hydrological processes result in the change in soil water regime.

This phenomena was studied in the soils of the East Slovakian Lowland. Research of mineralogical structure in ESL soils showed a predominant presence of illite and montmorillonite type of clay minerals. Therefore it was possible to identify percentual content of clay with percentual content of particles smaller than 0,002mm (colloidal+physical clay) without a need to distinguish between individual types of clay minerals during determination of percentual content of clay in soil.

Significant dependency of volume changes on clay minerals was demonstrated. Maximum volumetric changes reached up to 40% of saturated soil volume. Varying time intervals of water desorption from the soil samples were identified depending on content of clay particles. The intervals varied between 5 and 80 hours. In shrinkage characteristics of ESL heavy soils all shrinkage phases are contained very distinctly. The soils in Senné area show the highest shrink-swell potential on ESL. The potential compared to Reeve classification is of a high value: PLE = 15.3cm. Maximum values of 5.51cm were identified by field measurements of vertical movements. Assessment of soil isotropy in relation to their volumetric changes and based of the geometric factor r_s showed that its values are about 3.0. This value represents isotropy of volumetric changes. Research of geometric characteristics identified 4 types of crack network. It shall be noted that specific length of cracks on a unit of area was L_{mc} = 5.65 m.m^2 and avg soil matrix surface is 0.121 m^2.

Selected components of soil water regime were monitored in the field. Numerical simulation results were verified by comparison with the monitored results. This paper presents assimilation measurements of heavy soils moisture regime in homogeneous profile and two materially heterogenous profiles. Moisture distribution at the interface of material layers are illustrated as well.

The impact of water retention in a two-domain soil structure on rainfall-runoff processes during sudden and intensive rainfall in dry periods was quantified. There is a theory in which cracks are used as an indicator of soil drought creation in the end.

Clay minerals presence in soils and consecutive review of their influence on hydrological processes course in the soils is a very extensive issue. Due to limited extent of the present paper only basic approaches to the quantification of clay minerals impact on hydrological processes could be studied and illustrated in this chapter.

6. Further research

Clay minerals content in soil is stable. Their impact on hydrological processes is manifested in changes in soil water storage. This is most significant during extreme hydrological incindents such as soil drought or extreme rainfall.

In the last years, the increased occurence of crack network formation has been observed. It can be probably accounted for the ongoing climatic changes whose primary manifestation is in the change in rainfall distribution throughout the year- more frequent dry periods and subsequent extreme rainfall. With regard to this, the study of clay minerals impact on the dynamics of soil hydrological processes has an increasing importance.

The future research should be focused on the prognostics of the occurence of a two-domain soil structure in an area and on the study of its impact on soil water regime. The prognostics should be based on the numerical simulation and the outputs of the available climatic scenarios. It is advisale that the occurence of a two-domain soil structure be quantified. Mathematical models can be used to numerically simulate the effects of cracks retention volume on water drainage from an area during extreme rainfall incidents. In addition to this, further research into the knowledge of cracks temporal and spacial characteristics, water flow within a crack, into a crack, and flow between cracks and soil matrix should be developed. On the grounds of numerical simulations and field observations, the quantification of crack network influence on the transfer of water, other substances and solutions in soil should be performed. The results of this can be used for proposing the measures for the mitigation of cracks negative impacts and, on the contrary, for using their positive sides in water management in the countryside.

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7. References

[1] Richards, L. A.: Capillary conduction of liquids through porous mediums. In: Physics 1, 1931, pp.318-333.

[2] Ross, G. J.: 1978. Relationships os specific surface area and clay content to shrink – swell potential of soils having different clay mineralogical composition. In: Canadian Journal Soil Science. 1978, č. 58, s. 159-166.

[3] Olive, W. W. – Chleborad, A. F. – Frahme, C. W. et al.: 1989. Swelling Clays Map Of The Conterminous United States. U.S. Geological Survey. 1989.

[4] Velde, B.: 1995. Composition and mineralogy of clay minerals. In: Origin and mineralogy of clays. New York : Springer-Verlag. 1995, s. 8-42.

[5] Tall, A.: 2002. Porovnanie klasifikačných systémov pre určovanie textúry pôd so zameraním na ťažké pôdy. In: Acta Hydrologica Slovaca, roč. 3, 2002, č. 1, s. 87-93, (in Slovak).

[6] Čurlík, J. 1977. Pedograficko-mikroskopické a mineralogické štúdium pôd Slovenska : Kandidátska dizertačná práca. Bratislava : Katedra mineralógie a kryštalografie PriFUK. 1977, 301 s.,(in Slovak)

[7] Šútor, J. – Gomboš, M. – Mati, R. - Ivančo, J.: 2002. Carakteristiky zóny aerácie ťažkých pôd Východoslovenskej nížiny. Monografia, ISSN 80-968480-8, ASCO pre ÚH SAV a OVÚN, , 215 s., (in Slovak).
[8] Soil Survey Division Staff.: 1993. Soil survey manual : USDA Handb. 18. Washington, DC. : U.S. Gov. Print Office.
[9] Bronswijk, J. J. B. – Evers-Vermeer, J. J.: 1990. Shrinkage of Dutch clay soil aggregates. In: Netherlands Journal of Agricultural Science. 1990, č. 38, s. 175-194.
[10] Grossman, R. B. – Brasher, B. R. – Franzmeier, D. P. et al. 1968. Linear extensibility as calculated from natural-clod bulk density measurements. In: Soil Science Society of America Proceedings. 1968, č. 32, s. 570-573.
[11] Parker, J. C. – Amos, D. F. – Kaster, D. L.: 1977. An evaluation of several methods of estimating soil volume change. In: Soil Science Society of America Journal. 1977, č. 41, s. 1059-1064.
[12] Reeve, M. J. – Hall, D. G. M. – Bullock, P.: 1980. The effect of soil composition and environmental factors on the shrinkage of some clayey British soils. In: Journal of Soil Science. 1980, č. 31, s. 429-442.
[13] Bronswijk, J. J. B.: 1989. Prediction of actual cracking and subsidence in clay soils. In: Soil Science. 1989, č. 148, s. 87-93.
[14] Oostindie, K. – Bronswijk, J. J. B.: 1992. Flocr – A simulation model for the calculation of water balance, cracking and surface subsidence of clay soils : Report 47. Wageningen : The Winand Staring Centre for Integrated Land, Soil and Water Research. 1992, 65 s.
[15] Novák, V. - Šimunek, J. – Genuchten Van, M. Th.: 2000. Infiltration of Water into Soil with Cracks. In: Journal of Irrigation and Drainage Engineering, roč. 126, 2000, č. 1, s. 41-47.
[16] Schafer, W. M. – Singer, M. J.: 1976. Influence of physical and mineralogical properties on swelling of soils in Yolo County, California. In: Soil Science Society of America Journal. 1976, č. 40, s. 557-562.
[17] Kotorová, D. - Mati, R.: 2008. Properties and moisture regime of heavy soils in relation to their cultivation. Cereal Research Communications 36. 5: 1751-1754.
[18] Stehlová, K.: 2007. Assessment of the soil water storage with regard to prognosis of the climate change at lowlands. Cereal Research Communications, 35. 2: 1093-1096
[19] Velísková, Y. (2010) Changes of water resources and soils as components of agro-ecosystem in Slovakia. Növénytermelés, Vol. 59, suppl., pp. 203-206, ISSN 0546-8191, http://www.gabcikovo.gov.sk
[20] Nagy, V. – Sterauerova, V. – Neményi, M. – Milics, G. – Koltai, G.: 2007. The role of soil moisture regime in sustainable agriculture in both side of river Danube in 2002 and 2003. Cereal Research Communications, 35. 2: 821-824.
[21] Šoltész, A. - Baroková, D.: 2004. Analysis, prognosis and control of groundwater level regime based on means of numerical modelling. In: Global Warming and other Central European Issues in Environmental Protection: Pollution and Water Resources, Columbia University Press, Vol.XXXV, Columbia, pp.334-347, ISBN 80-89139-06-X

[22] Tall, Andrej - Pavelková, D.: 2010, Dana. Predpokladaný vplyv klimatických zmien na hladinu podzemnej vody na Východoslovenskej nížine. In Acta Hydrologica Slovaca, 2010, roč. 11, č. 1, p. 162-166. ISSN 1335-6291.
[23] Šútor, J. - Gomboš, M. - Mati, R. - Tall, A. – Ivančo, J. : 2007. Voda v zóne aerácie pôd Východoslovenskej nížiny. ISBN 80-89139-10-8, Bratislava:Michalovce, Ústav hydrológie SAV, 279 s.
[24] Kandra, B.: 2010. The creation of physiological stress of plants in the meteorological conditions of soil drough. Növénytermelés, Vol. 59, ISSN 0546-8191, Supplement, p. 307-310.