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Determination of soil hydraulic properties of potential low and intermediate level waste disposal sites in Bulgaria

Assistance to site selection and site evaluation for low- and intermediate level waste disposal in Bulgaria

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Abstract

In the framework of selecting a suitable site for final disposal for low- and intermediate level short-lived radioactive waste in Bulgaria, a determination of soil hydraulic properties of two potential sites was made. The investigated samples are from the vadoze zone of the unsaturated deep soil profiles, which are considered as a pathway of eventual radionuclide migration from the disposal facility to the biosphere. The hydraulic parameters are determined from the relationship ”soil water content – pressure head” (*soil water retention curve*). The traditional method of determining the retention function was used - establishing a series of equilibria between water in the soil sample and a body of water at known potential. According to the pressure head value, two types of apparatuses were used – a sand bath and a pressure cell. The hydraulic parameters of the samples were obtained by implementing the optimization procedure for retention curves available in the computer code RETC. The resulting hydraulic parameters can now be used in the simulation models for the prediction of variably saturated water flow and concomitant radionuclide transport in the deep unsaturated sediments of the potential disposal sites. This is important input to an evaluation of the suitability of potential sites for developing a near surface disposal facility.

Key words: low- and intermediate level short-lived radioactve waste, site evaluation, unsaturated hydraulic properties, retention curve, RETC, optimization procedure

1. Introduction

A procedure for selection of a site for a National repository for low and intermediate level radioactive wastes is forthcoming in Bulgaria. At the present state, after subsequent analysis of elimination, from 24 initially selected terrains only three potential sites remained - all situated in the Northwest part of the country. The State Enterprise 'Radioactive Wastes', the Bulgarian state organization responsible for the final disposal of the radioactive wastes, appointed the GI-BAS for further investigations of these sites.

Two of the sites (*Marichin Valog* and *Brestova Padina*) are close to the Kozloduy Nuclear Power Plant and they are with almost similar geomorphologic and geological conditions, namely undulating landscape developed on Pliocene clays covered by Quaternary sediments - loess and clayey gravel layers. The third potential site (*Varbitza*) is located at about 60 km in South-Southeast direction and it is placed in the Fore-Balkan marl sediments weathered at the upper part. At the three sites, the water table is at relatively great depth, so an unsaturated (vadoze) zone exists. The thickness of the unsaturated zone is about 10-15 m at *Varbitza* and *Brestova Padina* sites and up to 30 m in *Marichin Valog*.

From the long-term safety point of view, the movement of water and dissolved contaminants in the saturated and unsaturated zones of the subsurface environment is a basis for comparison of the sites in order that the best suitable one be selected. Also, the proper knowledge about unsaturated water flow and concomitant radionuclide transport is key input to safety assessment calculations.

Computer models for the prediction of variably saturated flow and transport properties of the medium require accurately estimation of a number of parameters which appear in those models. These hydraulic parameters can be determined from the relationship ”soil water content – soil water suction”, which is indentified in the literature by various names, including *water retention* function (Klute, 1986).

The main task of the following investigations is the measurement of the soil hydraulic characteristics, notably the *soil water retention curve* (*capillary pressure - water content* relationship). Laboratory tests will be set up using soil samples from two potential sites - *Marichin Valog* and *Varbitza*. Data collected will be mathematically analyzed using RETC inverse optimization computer code and will be compared with previous studies of that kind (Mallants et al., 2005; Mallants et al., 2006; Mallants et al., 2007). The resulting parameters can be used as input to variably saturated water flow codes, with which predictive calculations can be made on the hydraulic regime of unsaturated sediments underlying a surface repository.

2. General Principles and Experimental Methodology

2.1. Theoretical remarks.

The traditional method of determining the water retention function involves establishing a series of equilibria between water in the soil sample and a body of water at known potential. The soil-water system is in hydraulic contact with the body of water via a water-wetted porous plate or membrane but in certain cases it could be a uniform sand medium. At each equilibrium point, the volumetric water content, θ, of the soil is determined and paired with a value of the matric pressure head, h_m, determined from the pressure in the body of water and the gasphase pressure in the soil. The data pair (θ, h_m) is one point on a retention function. A drainage curve is mapped by establishing a series of equilibria by drainage from zero pressure head. A wetting curve is obtained by equilibrating samples wetted from a low water content or low pressure head (large negative value) (Klute, 1986).

The retention curve is hysteretic, i.e. the water content at a given pressure head for a wetting soil is less than that for a drained soil. The principle features of the hysteresis of the retention function are shown in *Fig. 1*. The drainage curve that starts at complete saturation of the porous medium is the initial drainage curve (IDC). In many porous media, as water is removed, the matric pressure head decreases and the water content approaches a limit called the residual water content, θ_r. The main wetting curve (MWC) is obtained by wetting the sample from low water content. Usually, the MWC is determined starting at the residual water content θ_r or the so-called "air-dried condition". As the soil is wetted along the MWC and the pressure head approaches zero, the water content approaches a value, θ_o, that is less than the total porosity, θ_s, due to the presence of entrapped air. Usually, θ_o is about is about $0.8\times\theta_s$ to $0.9\times\theta_s$. The water content, θ_o, is called the *natural saturation* or the *satiated* water content. The drainage curve obtained beginning at θ_o is called the main drainage curve (MDC). It merges asymptotically with the IDC as the pressure head decreases. An infinite set of scanning curves lies inside the envelop of the IDC and the MWC (*Fig. 1*).

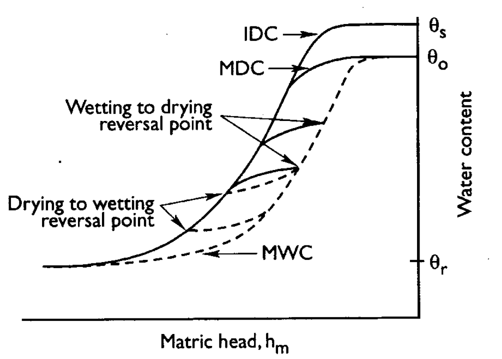

Fig. 1. Diagram of hysteresis in the water retention function (by Klute, 1986)

2.2. Experimental stage.

The equipment for determining the retention function could be two types – suction apparatus (sand bath) or pressure cell apparatus. The sand bath method is used for the pressure head values up to -100 cm (100 cm of suction tension) and the pressure cell method is used for equal or more than -100 cm values of the pressure head.

The main details of the sand bath method apparatus are shown on *Fig. 2* and a general view of the system is shown on *Photo 1*.

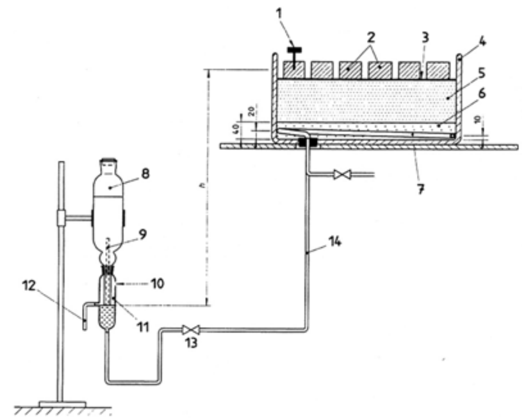

Fig. 2. Example of sand suction table, dimensions in mm (by Di Bonito, 2005): 1- tensiometer, 2-soil core sample, 3-nylon or cotton voile, 4-ceramic sink, 5-fine sand (60-100 *μm*), 6-coarse sand, 7-drain system, 8-250 cm^3 reservoir, 9-thin nylon tube, 10-air inlet, 11-levelling bottle, 12-overflow, 13-tap, 14-flexible 7 *mm* id nylon tubing

Note: It is important that the sand has to be very uniform so not to interrupt the water flow from the bottom of the sink to the soil samples.

Photo 1. A sand bath apparatus (courtesy: Guido Rentmeester, UCL, 2007)

The main details of the pressure cell apparatus are shown on *Fig. 3* and a general view of the system is shown on *Photo 2*.

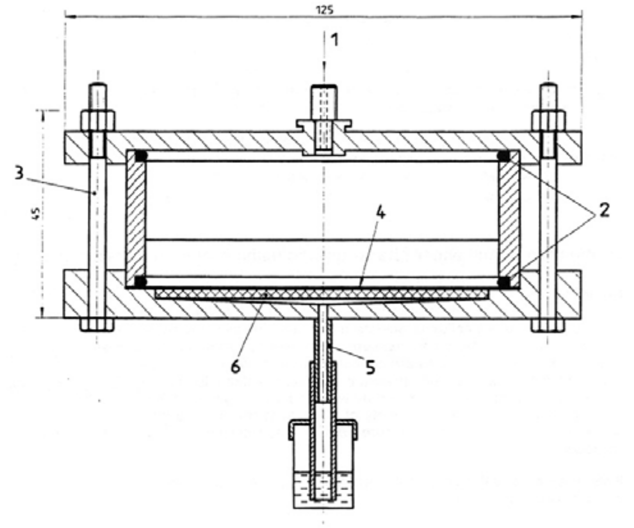

Fig. 3. Pressure membrane cell, dimensions in mm (by Di Bonito, 2005): 1-air from compressor, 2-O-rings, 3-bolts, 4-visking membrane, 5-outflow pipe, 6-sintered bronze plate

Photo 2. Pressure cell apparatus (courtesy: Guido Rentmeester, UCL, 2007)

3. Quantifying the hydraulic functions from water retention curve determination

3.1. General remarks

Twenty-one undisturbed soil samples in steel rings were prepared for estimation of the soil water retention curve, resp. for the hydraulic parameters determination. A brief description of the samples from the *Marichin Valog* site is as follows:

- one sample /Lab N 3527/ from the red clayey gravel layer (transition zone) at 4.35-4.50 m depth;
- eleven samples /Lab NN 3529, 3530, 3663-71/ from the Pliocene clay layer from different depths. All the samples are from the vadoze zone of the profile.

The soil samples from the *Varbitza* site are as follows:

- nine samples /Lab NN 3673-81 or S1-S9/ from the upper weathered part of the marl sediments. It is assumed that this zone is unsaturated up to 15 m in depth.

The boreholes from which the samples were taken are shown on Appendix A, *Fig. A-1 and Fig. A-2*, respectively for the *Marichin Valog* and the *Varbitza* sites. The detailed description and some physical parameters of all samples are given at Appendix A, *Tabl. A-1*.

For the aim of the plotting of the soil water retention curve, the estimation of the samples' volumetric water content after saturation is done at nine points of the pressure head, namely at 1.0, 1.85, 2.0, 2.4, 3.0, 3.5, 4.0 and 4.2 pF. Note that pF = -log(h) [cm], for instance 1.85 pF is equal to -70 cm of a pressure head. As it was mentioned above, for the pF 1.0 and 1.85 data points, the sand bath method has been used after the saturation in the same apparatus (*Photo 3*). For the other data points the pressure cell apparatus has been used. In the case of pF 3.5 and above (i.e. high pressure values), as the results of the volumetric water content are mostly dependent on the sample`s grain size and not so much on its texture, disturbed samples (in a state of a paste) have been used (*Photo 4*). A detailed scheme of the measurements is given in Appendix B of this report.

Photo 3. Saturation and measurement of the pF 1.0 and pF 1.85(courtesy: Guido Rentmeester, UCL, 2007)

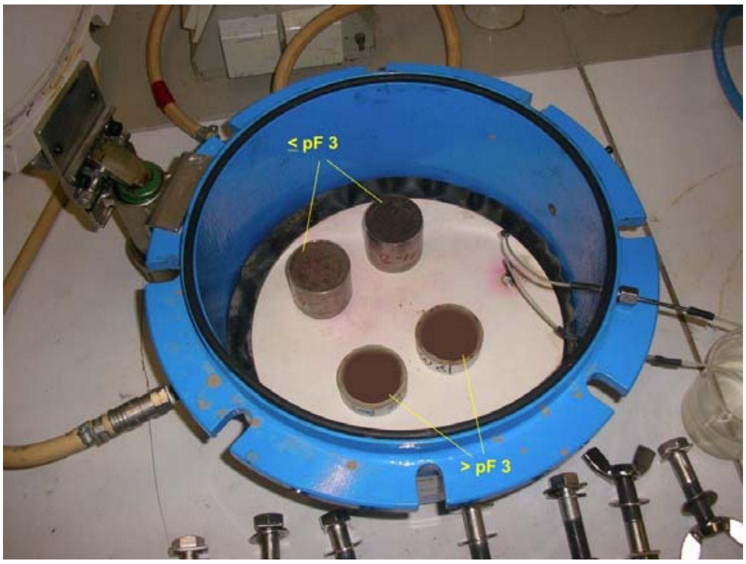

Photo 4. Preparation for measurements in the pressure cell: undisturbed samples in steel rings (up to pF3) and disturbed samples-paste in 2 cm high rings (above pF 3)(courtesy: Guido Rentmeester, UCL, 2007)

3.2. Soil water characteristic

Various models have been defined to describe the soil water characteristic, but the model defined by van Genuchten (1980) is the most commonly used. One of the advantages of the van Genuchten model is that it provides a predictive closed-form equation for the unsaturated hydraulic conductivity function by using the statistical pore-size distribution model of Mualem (1976), see further. First, the degree of water saturation is defined:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{1}$$

where θ is soil water content (cm^3/cm^3), θ_r and θ_s are the residual and saturated water contents (cm^3/cm^3), respectively. As a first approximation and on intuitive ground, $\theta_s = \eta$ and $\theta_r = 0$. In reality, however, the saturated water content θ_s of soils is smaller than the total porosity η because of entrapped air and the presence of large pores which drain too rapidly to become saturated. The residual water content θ_r is likely to be larger than zero, because of the presence of adsorbed water. Most often θ_r is treated as a fitting parameter without physical significance. Rather than using the matric potential in the parameterization of the water characteristic, the matric head h is used instead:

$$h = -\frac{\psi_m}{\rho_w g} \tag{2}$$

where h has units of length (m). Note that h was named pressure head in a saturated soil because of the positive pressure. The original van Genuchten equation for the soil water characteristic, $\theta(h)$, is defined as (van Genuchten, 1980):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{(1+(\alpha|h|)^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{3}$$

where θ, θ_r and θ_s were defined previously, and α (1/m), n, and m are constants which define the shape of the curve, with $m = 1-1/n$ (with the requirement $n > 1$ if Eq. (3) is used in combination with $K(h)$, see further). The dependency of the van Genuchten model on the parameters α and n is shown in Fig. 4.

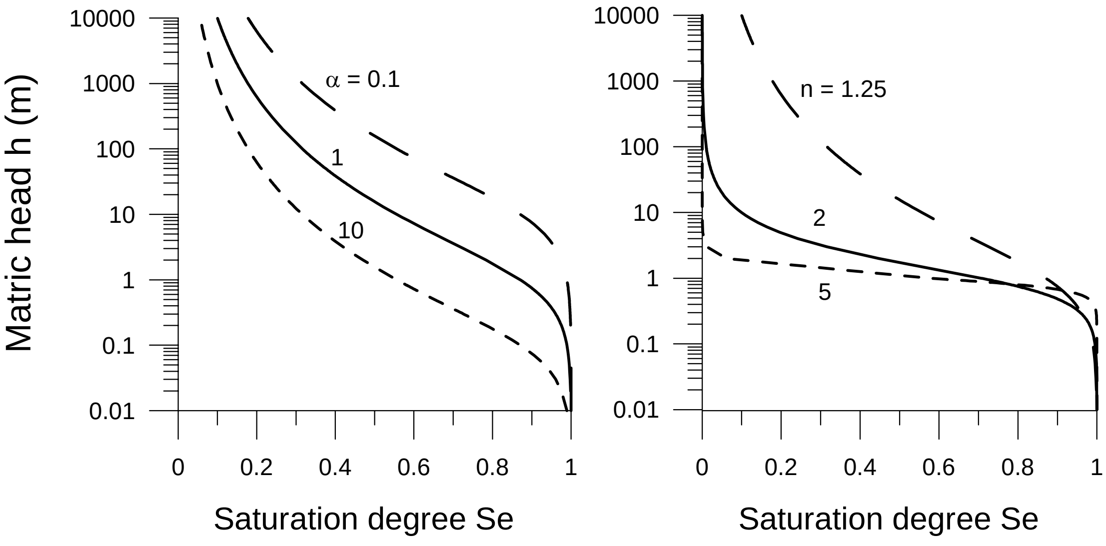

Fig. 4 Dependency of van Genuchten soil water characteristic on parameter α (keeping n fixed at 1.25) (left) and n (keeping α fixed at 1) (right). Saturation degree S_e is used rather than water content.

3.3 Unsaturated hydraulic conductivity

In addition to the parameterisation of $\theta(h)$, description of water flow through unsaturated soil also requires the parameterisation of $K(h)$. Most models for $K(h)$ assume that the water-filled pore space consists of a set of capillaries with the distribution of pore radii being determined by the soil water characteristic. One very attractive unsaturated hydraulic conductivity function is that derived by van Genuchten (1980), and is based on the statistical pore size distribution of Mualem (1976). The van Genuchten-Mualem $K(h)$ model is defined as follows:

$$K(h) = \begin{cases} K_s\, K_r(h) & h < 0 \\ K_s & h \geq 0 \end{cases} \tag{4}$$

where

$$K_r = S_e^{\tau} \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{5}$$

and K_s and K_r are saturated and relative hydraulic conductivity (m/s), respectively, τ is an empirical constant assumed equal to 0.5 (Mualem, 1976), and S_e is as defined previously. The advantage of the van Genuchten-Mualem $K(h)$ model is that nearly all its parameters, except K_s, can be determined from the soil water characteristic. In other words, a complete description of $\theta(h)$ and $K(h)$ may be obtained with five parameters, i.e. θ_r, θ_s, α, n, and K_s. Two types of measurements therefore suffice to determine the hydraulic functions: measurements of the soil water characteristic and saturated hydraulic conductivity.

3.4 Hydraulic functions for typical soils

Different soil types exhibit quite different hydraulic functions. This is illustrated by considering three different soil textures, sand, silt, and loam, where the sand is composed of much coarser particles compared to the fine-textured silt and loam. The soil water characteristic and the unsaturated hydraulic conductivity relationship are shown in Fig. 5.

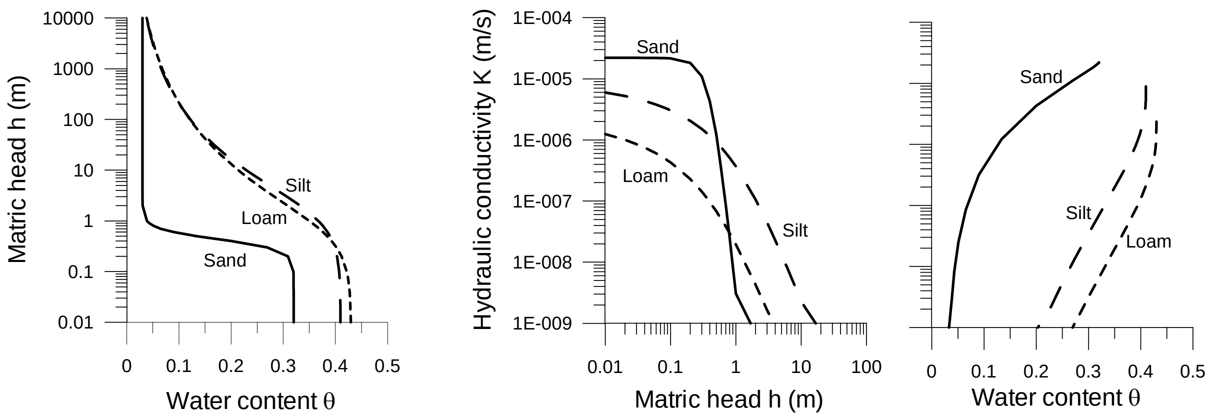

Fig. 5 Hydraulic functions of typical soils using the van Genuchten soil water characteristic and the van Genuchten-Mualem hydraulic conductivity model. Sand: $\theta_r = 0.03$, $\theta_s = 0.32$, $\alpha = 2.3$ (m^{-1}), $n = 4.17$, $K_s = 2.2\times10^{-5}$ ($m\ s^{-1}$); Silt: $\theta_r = 0.01$, $\theta_s = 0.41$, $\alpha = 0.7$ (m^{-1}), $n = 1.30$, $K_s = 1\times10^{-5}$ ($m\ s^{-1}$); Loam: $\theta_r = 0.00$, $\theta_s = 0.43$, $\alpha = 1.6$ (m^{-1}), $n = 1.25$, $K_s = 0.3\times10^{-5}$ ($m\ s^{-1}$).

Carsel and Parish (1988) estimated a set of average van Genuchten parameters for a large variety of soil textural groups (see Table 1). These data may be used, when initial estimates of the soil water characteristic are not available.

Table 1 Average values for van Genuchten soil water characteristic for textural groups according to the USDA classification (Soil Survey Staff, 1998) as estimated by Carsel and Parish (1988).

Texture	θ_r	θ_s	α (m^{-1})	n	K_s (m d^{-1})
Sand	0.045	0.43	14.5	2.68	7.13
Loamy sand	0.057	0.41	12.4	2.28	3.50
Sandy loam	0.065	0.41	7.50	1.89	1.06
Loam	0.078	0.43	3.60	1.56	0.25
Silt	0.034	0.46	1.60	1.37	0.06
Silt loam	0.067	0.45	2.00	1.41	0.11
Sandy clay loam	0.100	0.39	5.90	1.48	0.31
Clay loam	0.095	0.41	1.90	1.31	0.06
Silty clay loam	0.089	0.43	1.00	1.23	0.02
Sandy clay	0.100	0.38	2.70	1.23	0.03
Silty clay	0.070	0.36	0.50	1.09	0.005
Clay	0.068	0.38	0.80	1.09	0.05

3.5 Results from the analysis

Measured retention data for the Mariching Valog and Varbitza site are shown in Fig. 6 and 7, respectively.

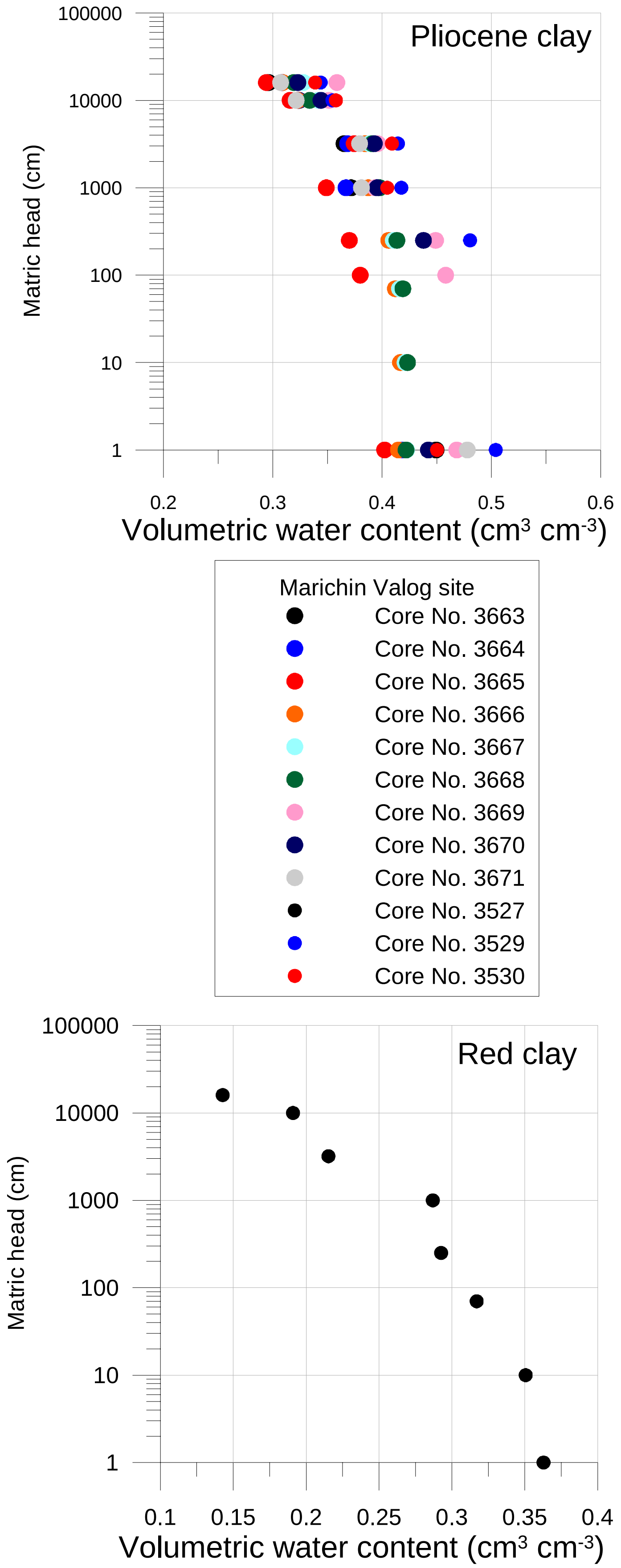

Fig. 6 Measured retention data for cores taken from the Marichin Valog site.

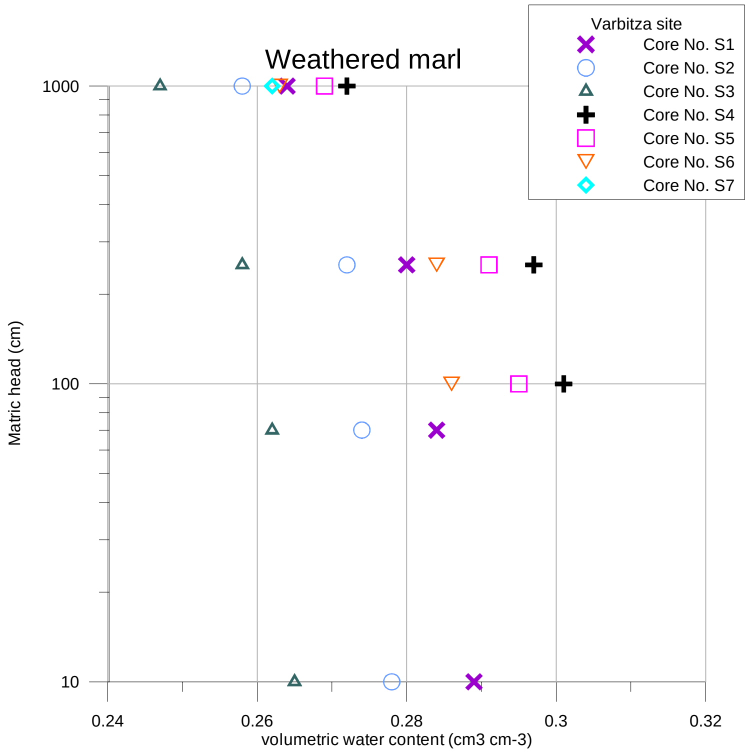

Fig. 7 Measured retention data for cores taken from the Varbitza site.

The raw laboratory data determined by the above mentioned experimental procedures are given in Appendix B, *Table B-4*. The so received soil water retention curves were optimized by the computer program RETC. One of the programme`s options is a simultaneous fit of pooled retention data (van Genuchten et al., 1991). This option results in a simultaneous fit of the van Genuchen model parameters (*Eq. 3*) to a set of observed soil water retention data from different samples (pooled data). The results from the computer analyses are presented in Tables 2, 3 and 4, respectively for the clayey gravel, Pliocene clay and weathered marl samples.

Table 2. Parameter values for the clayey gravel (Pliocene clay) sample from the inverse optimization using RETC code. Parameter θ_r was fixed at zero

Parameter	***Best fit value***	***S.E. coefficient***	***Lower 95%***	***Upper 95%***
θ_s [$cm^3.cm^{-3}$]	0.346	0.0136	0.311	0.382
α [m^{-1}]	0.408	0.3512	-0.494	1.310
n [-]	1.180	0.0474	1.058	1.302
R^2	0.9490			

Table 3. Parameter values for the Pliocene clay samples from the inverse optimization using RETC code. Parameter θ_r was fixed at zero

Parameter	Best fit value	S.E. coefficient	Lower 95%	Upper 95%
θ_s [$cm^3.cm^{-3}$]	0.432	0.005	0.421	0.443
α [m^{-1}]	0.131	0.073	-0.0161	0.279
n [-]	1.095	0.018	1.058	1.133
R^2	0.757			

In order to have one more common (representative) result for the Pliocene clay samples the data for the volumetric water content were firstly averaged for the respectively pF value. The same procedure was applied for the weathered marl samples.

Table 4. Parameter values for the weathered marl samples from the inverse optimization using RETC code. Parameter θ_r was fixed at zero

Parameter	Best fit value	S.E. coefficient	Lower 95%	Upper 95%
θ_s [$cm^3.cm^{-3}$]	0.282	0.0043	0.273	0.291
α [m^{-1}]	0.347	0.553	-0.791	1.485
n [-]	1.033	0.016	0.999	1.066
R^2	0.409			

Observed and fitted retention curves are shown in Fig. 8.

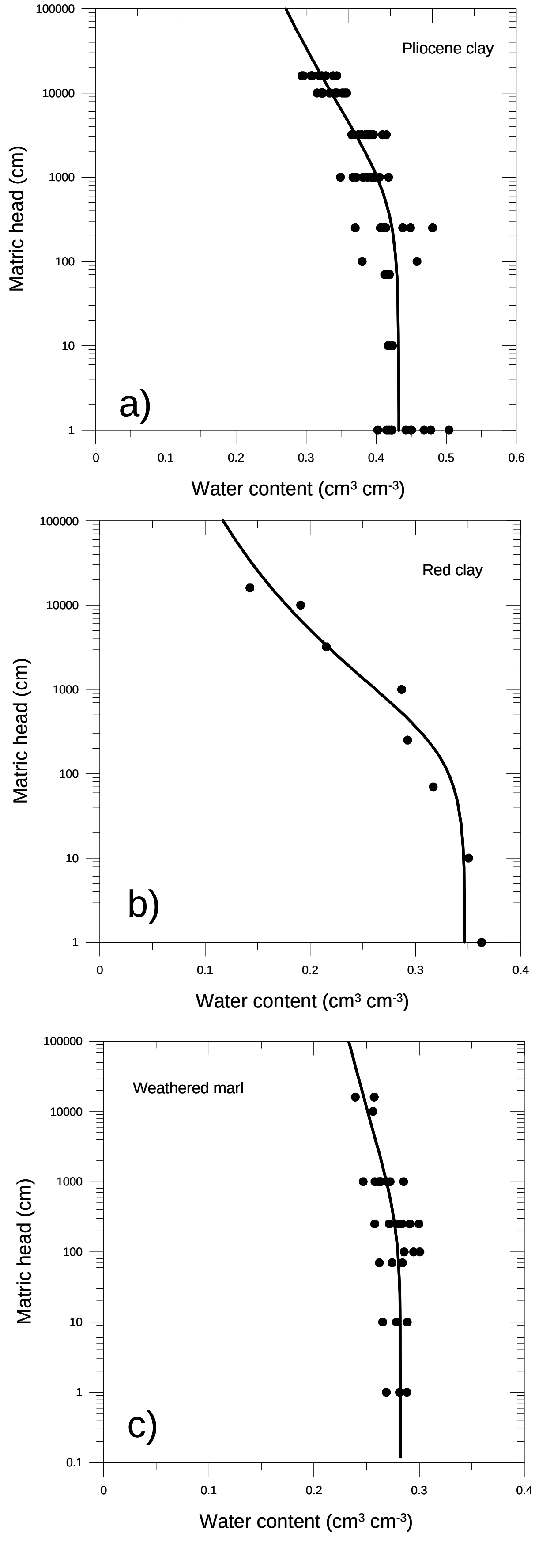

Fig. 8. Observed and fitted retention curves. (a) : Pliocene clay; (b): Red clay; (c) Weathered marl.

3.6. Results from the previous investigations

In the framework of a site characterization campaign at the *Marichin Valog* site performed 2005, with assistance to site selection and site evaluation for low- and intermediate level waste disposal, thirteen undisturbed core samples from the vadose zone of the profile were analyzed according to the above mentioned methodology by the SCK•CEN (Mallants et al., 2005). A description, some soil physical parameters and the raw laboratory results of the measurements ”*volumetric water content – pressure head*” are shown in Appendix C, *Table C-1*. The results after the inverse optimization with the computer program RETC are presented in *Table 5.*

Table 5. Fitted van Genuchten moisture retention parameters (θ_s, α and n); parameter θ_r is fixed at zero, K_s is measured(Mallants et al., 2005)

Sample No	θ_s	α	n	K_s
	cm³ cm⁻³	***cm⁻¹***	**-**	***m s⁻¹***
U2	0.402	0.033	1.177	1.75E-07
U4	0.331	0.003	1.368	3.88E-07
U5	0.442	0.006	1.356	4.63E-07
U6	0.418	0.229	1.082	1.25E-06
U7	0.420	0.228	1.071	5.02E-07
U8	0.377	0.691	1.044	5.29E-08
U9	0.410	0.021	1.081	2.12E-08
U10	0.304	0.120	1.032	N.A.
U11	0.361	0.017	1.039	N.A.
U12	0.334	0.030	1.076	3.67E-06
U14	0.298	0.080	1.105	N.A.
U15	0.312	0.074	1.074	N.A.
U16	0.387	0.065	1.045	N.A.

Table 6. Fitted van Genuchten moisture retention parameters (θ_s, α and n) from two investigation campaigns

Type of soil	Parameter	Results 2005	Results 2007
Red clayey gravel	θ_s [$cm^3.cm^{-3}$]	0.410	0.347
”	α [m^{-1}]	2.1	0.408
”	n [-]	1.081	1.180
Pliocene clay	θ_s [$cm^3.cm^{-3}$]	0.387	0.432
”	α [m^{-1}]	6.5	0.131
”	n [-]	1.045	1.095

A comparison between the results obtained in 2007 and 2005 investigations for the similar type of soils (for the *Marichin Valog* site) is presented in *Table 6*.

The comparison shows a good correspondance in the *n* optimazed value but quite dispersive results for the α one for the both type of soils. Of course, the spatial variety has to be taken into account but further studies (*e.g.* large scale field investigations) are needed for more reliable estimates of the α value.

4. Conclusions

The hydraulic properties of three types of soil samples were evaluated. The samples originate from the potential radwaste disposal sites vadoze zone. After the optimization procedure of the retention curves with the code RETC, van Genuchten model parameters were obtained. For the soils from the *Marichin Valog* site (red clayey gravel and Pliocene clay), the optimized retention curves were in good agreement with the data. According to the relatively short period of equilibrum established for the weathered marls, the parameters are not fitted very well and their further use must be carefully considered. The comparison between the results of 2005 and 2007 campaigns shows very good correspondence for the values of the saturation water content and the parameter n, taking into account the spatial variability. The values of parameter α are quite dispersive and an additional calibration is needed. The presented investigation is a very important step in the prediction of the movement of water and dissolved contaminants in the saturated and unsaturated zones of the subsurface environment from the long-term safety point of view, and it is a basis for comparison of the radwaste disposal sites in order that the best suitable one be selected. In addition, the study has also been very instructive for the staff of the Geological Institute of the Bulgarian Academy of Sciences in terms of technology transfer about new measurement techniques important in for the characterization of the deep unsaturated sediments in potential disposal sites.

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Appendix A

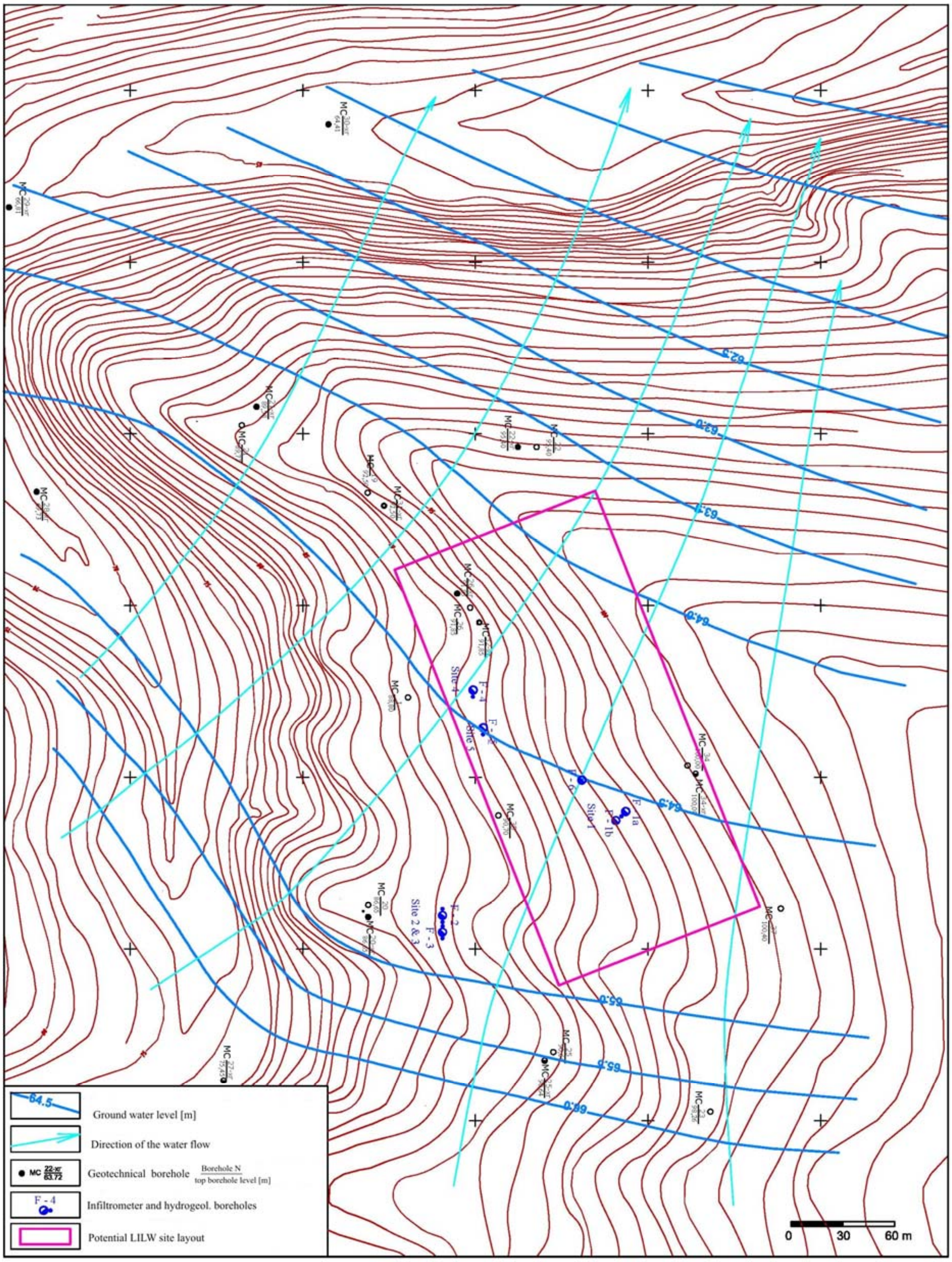

Fig. 1-A. Marichin Valog site with indication of the boreholes (after Evstatiev et al., 2003 and Mallants et al. 2005)

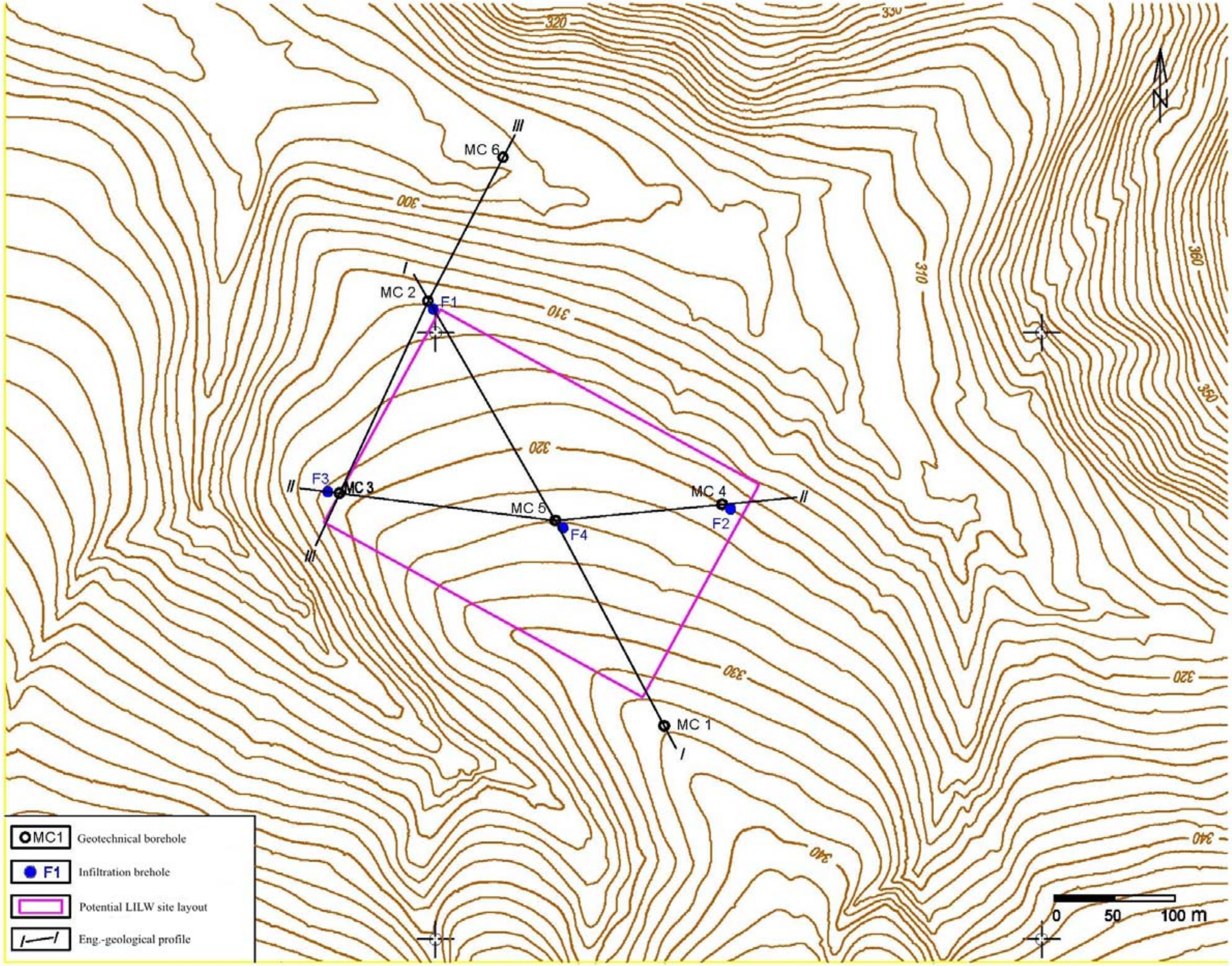

Fig. 2-A. Varbitza site with indication of the boreholes (by Karastanev et al., 2007)

Tabl. A-1. Description and physical parameters of the measured samples

SITE	Borehole	Lab. N	Description	Depth	Gravimetric water content, W	Wet bulk density	Dry bulk density
				[m]	[%]	[g/cm^3]	[g/cm^3]
Marichin Valog	F 5	3527	Red clay /gravel/ (transition zone)	4.35 – 4.50	16.5	1.95	1.67
Marichin Valog	MB I	3663	Pl clay	2.40 - 2.70	21,4	1,95	1,61
"	MB I	3664	"	2.40 - 2.70	21,8	2,03	1,66
"	MB I	3665	"	2.40 - 2.70	20,9	2,02	1,67
"	MB I	3666	"	2.70 - 3.00	21,8	2,06	1,69
"	MB I	3667	"	2.70 - 3.00	22,7	2,05	1,67
"	MB I	3668	"	2.70 - 3.00	22,8	2,03	1,65
"	MB I	3669	"	3.00 - 3.30	21,7	2,03	1,67
"	MB I	3670	"	3.00 - 3.30	21,4	2,06	1,70
"	MB I	3671	"	3.00 - 3.30	21,6	2,05	1,69
"	MB I	3529	"	3.30 – 3.60	22.8	2.04	1.66
"	MB I	3530	"	3.30 – 3.60	22.3	2.05	1.68
Varbitza	MB 2	3679	Weathered marl	10.30 - 10.60	11,9	2,30	2,06
"	MB 2	3680	"	10.30 - 10.60	12,5	2,31	2,05
"	MB 2	3681	"	10.30 - 10.60	12,2	2,32	2,07
"	MB 1	3673	"	15.20 - 15.50	14,0	2,28	2,00
"	MB 1	3674	"	15.20 - 15.50	13,1	2,30	2,04
"	MB 1	3675	"	15.20 - 15.50	12,4	2,30	2,05
"	MB 1	3676	"	16.70 - 17.00	13,8	2,28	2,00
"	MB 1	3677	"	16.70 - 17.00	14,2	2,22	1,95
"	MB 1	3678	"	16.70 - 17.00	17,3	2,15	1,83

Appendix B

Tabl. B-1. Scheme for the order of measurement of the soil samples – Pliocene clay

Method	**Pressure state**	**Laboratory number of the sample**											**Duration. minimum**
	[pF]	*3529*	*3530*	*3663*	*3664*	*3665*	*3666*	*3667*	*3668*	*3669*	*3670*	*3671*	*days*
Sand bath. undisturbed sample	***saturation***	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	7
	1	**-**	**-**	**-**	**-**	**-**	**x**	**x**	**x**	**-**	**-**	**-**	7
	1.85 /-70 cm/	**-**	**-**	**-**	**-**	**-**	**x**	**x**	**x**	**-**	**-**	**-**	7
Start/End of the method		*The beginning of the experiment/Approx. 21 days after the beginning of the experiment*											
Pressure cell. undisturbed sample	2	**-**	**-**	**-**	**-**	**x-I**	**x-II**	**x-II**	**x-II**	**x-I**	**-**	**-**	2
	2.4	**x-I**	**-**	**-**	**-**	**-**	**x-II**	**x-II**	**x-II**	**-**	**x-I**	**-**	2
	3	**-**	**x-I**	**-**	**-**	**-**	**x-II**	**x-II**	**x-II**	**-**	**-**	**x-I**	2
Start/End of the method		*Approx. 7 days after the beginning/Approx. 13 days after the beginning*											
Pressure cell. disturbed sample	3.5	**1/3x-I**	**1/3x-II**	**1/3x-I**	**1/3x-I**	**1/3x-I**	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-II**	2
	4	**1/3x-I**	**1/3x-II**	**1/3x-I**	**1/3x-I**	**1/3x-I**	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-II**	2
	4.2	**1/3x-I**	**1/3x-II**	**1/3-I**	**1/3-I**	**1/3-I**	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-II**	2
Start/End of the method		*Approx. 11 days after the beginning/Approx. 17 days after the beginning of the experiment*											

Note 1: The "1/3x" means one-third of the sample´s length
Note 2: The "x-I" and "x-II" show the serial number of the batches for the pressure sells

Tabl. B-2. Scheme for the order of measurement of the soil samples – weathered marl

Method	**Pressure state**	**Laboratory number of the sample**									**Duration. minimum**
	[pF]	***3673***	***3674***	***3675***	***3676***	***3677***	***3678***	***3679***	***3680***	***3681***	***days***
Sand bath. undisturbed sample	***saturation***	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	7
	1	**-**	**-**	**-**	**-**	**-**	**-**	**x**	**x**	**x**	7
	1.85 /-70 cm/	**-**	**-**	**-**	**-**	**-**	**-**	**x**	**x**	**x**	7
Start/End of the method	*The beginning of the experiment/Approx. 21 days after the beginning of the experiment*										
Pressure cell. undisturbed sample	2	**x**	**x**	**x**	**-**	**-**	**-**	**x-II**	**x-II**	**x-II**	2
	2.4	**x**	**x**	**x**	**-**	**-**	**-**	**x-II**	**x-II**	**x-II**	2
	3	**x**	**x**	**x**	**-**	**-**	**-**	**x-II**	**x-II**	**x-II**	2
Start/End of the method	*Approx. 7 days after the beginning /Approximately 13 days after the beginning*										
Pressure cell. disturbed sample	3.5	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-I**	**1/3x-I**	**1/3x-I**	**1/3x-II**	**1/3x-II**	**1/3x-II**	2
	4	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-I**	**1/3x-I**	**1/3x-I**	**1/3x-II**	**1/3x-II**	**1/3x-II**	2
	4.2	**1/3x-II**	**1/3x-II**	**1/3x-II**	**1/3x-I**	**1/3x-I**	**1/3x-I**	**1/3x-II**	**1/3x-II**	**1/3x-II**	2
Start/End of the method	*Approx. 7 days after the beginning /Approximately 13 days after the beginning*										

Note 1: The "1/3x" means one-third of the sample´s length
Note 2: The "x-I" and "x-II" show the serial number of the batches for the pressure sells

Tabl. B-3. Scheme for the order of measurement of the soil samples – Red clay /transition zone/

Method	**Pressure state**	**Laboratory number of the sample**	**Duration. minimum**
	[pF]	***3527***	***days***
Sand bath. undisturbed sample	***saturation***	x	7
	1	x	7
	1.85 /-70 cm/	x	7
Pressure cell. undisturbed sample	2	x	2
	2.4	x	2
	3	x	2
Pressure cell. disturbed sample	3.5	x	2
	4	x	2
	4.2	x	2

Tabl. B-4. Measured soil hydraulic properties of undisturbed and disturbed soil samples

Sample	Depth from the surface [m]	Volumetric water content θ [$cm^3.cm^{-3}$]								
		pF 0	pF 1	pF 1.85	pF 2	pF 2.4	pF 3.0	pF 3.5	pF 4.0	pF 4.2
Red clay /gravel /3527/	4.35 – 4.50	0.363	0.351	0.317	-	0.293	0.287	0.215	0.191	0.143
Pl clay /3663/	2.40 – 2.70	0.449	-	-	-	-	0.372	0.365	0.324	0.296
Pl clay /3664/	2.40 – 2.70	0.419	-	-	-	-	0.367	0.368	0.323	0.309
Pl clay /3665/	2.40 – 2.70	0.402	-	-	0.380	0.370	0.349	0.374	0.316	0.294
Pl clay /3666/	2.70 – 3.00	0.415	0.417	0.412	-	0.406	0.387	0.384	0.323	0.309
Pl clay /3667/	2.70 – 3.00	0.422	0.421	0.416	-	0.410	0.394	0.388	0.342	0.328
Pl clay /3668/	2.70 – 3.00	0.422	0.423	0.419	-	0.414	0.398	0.391	0.334	0.319
Pl clay /3669/	3.00 – 3.30	0.468	-	-	0.458	0.449	0.393	0.396	0.351	0.359
Pl clay /3670/	3.00 – 3.30	0.442	-	-	-	0.438	0.396	0.393	0.344	0.323
Pl clay /3671/	3.00 – 3.30	0.478	-	-	-	-	0.381	0.379	0.321	0.307
Pl clay /3529/	3.30 – 3.60	0.504	-	-	-	0.481	0.418	0.414	0.355	0.344
Pl clay /3530/	3.30 – 3.60	0.450	-	-	-	-	0.405	0.409	0.358	0.339
Weathered marl /S1/	10.30 – 10.60	0.288	0.289	0.284	-	0.280	0.264	0.358	0.321	0.278
Weathered marl /S2/	10.30 – 10.60	0.281	0.278	0.274	-	0.272	0.258	0.326	0.256	0.257
Weathered marl /S3/	10.30 – 10.60	0.269	0.265	0.262	-	0.258	0.247	0.332	0.340	0.239
Weathered marl /S4/	15.20 – 15.50	0.305	-	-	0.301	0.297	0.272	0.410	0.331	0.382
Weathered marl /S5/	15.20 – 15.50	0.303	-	-	0.295	0.291	0.269	0.406	0.327	0.390
Weathered marl /S6/	15.20 – 15.50	0.289	-	-	0.286	0.284	0.263	0.432	0.351	0.322
Weathered marl /S7/	16.70 – 17.00	0.302	-	-	-	-	0.262	0.389	0.313	0.300
Weathered marl /S8/	16.70 – 17.00	0.340	-	-	-	-	0.285	0.400	0.318	0.281
Weathered marl /S9/	16.70 – 17.00	0.411	-	-	-	-	0.334	0.404	0.326	0.321

Appendix C

Tabl. C-1. Measured soil hydraulic properties of undisturbed soil samples from borehole N37 (Mallants et al., 2005)

Sample No	***Soil Description***	***Depth from the surface***	***Bulk density***	***Total porosity***	***Volumetric water content (cm^3 cm^{-3}) at***								
					pF 0	***pF 0.5***	***pF 1***	***pF 1.5***	***pF 2***	***pF 2.3***	***pF 2.8***	***pF 3.4***	***pF 4.2***
		m	*$g.cm^{-3}$*	cm^3 cm^{-3}	-	-	-	-	-	-	-	-	-
U2	paleosoil	7.5	1.386	0.477	0.402	0.394	0.384	0.365	0.330	0.275	0.209	0.191	0.141
U4	silty loess	10.0	1.397	0.473	0.470	0.444	0.435	0.423	0.393	0.333	0.222	0.136	0.100
U5	silty loess	11.5	1.378	0.480	0.451	0.441	0.435	0.423	0.398	0.346	0.285	0.136	0.104
U6	clayey loess	13.0	1.339	0.495	0.413	0.398	0.384	0.361	0.335	0.289	0.263	0.247	0.228
U7	clayey loess	14.0	1.356	0.488	0.413	0.404	0.391	0.371	0.344	0.315	0.268	0.262	0.256
U8	red clay	15.0	1.586	0.402	0.369	0.357	0.350	0.331	0.314	0.299	0.281	0.270	0.258
U9	red clay (gravel)	16.3	1.546	0.417	0.411	0.403	0.402	0.400	0.393	0.359	0.313	0.294	0.266
U10	clay (Pl)	17.5	1.714	0.353	0.303	0.302	0.292	0.292	0.287	0.277	0.253	0.247	0.246
U11	clay (Pl)	18.0	1.741	0.343	0.360	0.359	0.358	0.358	0.354	0.349	0.314	0.310	0.295
U12	sandy clay (Pl)	20.5	1.897	0.284	0.293	0.282	0.280	0.278	0.273	0.246	0.227	0.223	0.219
U14	silty sand (Pl)	22.3	1.652	0.377	0.299	0.286	0.282	0.271	0.234	0.220	0.185	0.179	0.141
U15	clay (Pl)	28.5	1.738	0.344	0.317	0.300	0.298	0.293	0.271	0.254	0.227	0.208	0.192
U16	clay (Pl)	31.3	1.749	0.340	0.391	0.379	0.376	0.373	0.361	0.342	0.316	0.310	0.286