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Quantification of hydraulic characteristics of swelling material

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Abstract

This paper presents a laboratory and numerical study to determine three hydraulic characteristic curves of a swelling material (soil or rock) in which montmorillonite is the predominant type of mineral. The first, the soil-water characteristic curve, represents the relationship between suction and moisture content that needs to be defined to solve the water flow problem and the accompanying change in the volume of the swelling unsaturated porous medium. The second curve presents hydraulic conductivity as a function of saturation or suction. The third curve represents the relationship between the volume change and the moisture content of the swelling material. These curves are crucial for understanding water flow and volume changes in swelling materials, with this study focusing on wetting regime behaviour. The aim of this research was to establish reliable methods for the definition of the hydraulic properties of the swelling material and to verify a proposed swelling model. While the swelling material shows significant hysteresis between the drying and wetting regimes, the hydraulic conductivity function shows little or no hysteresis between drying and wetting paths at equal moisture contents (coefficients).

Keywords:
swelling soil and rock; shrinkage curve; swelling curve; soil-water characteristic curve; model of swelling

1. Introduction

Swelling soils or rocks, which change their volume depending on whether they are exposed to drying or wetting conditions, pose a significant challenge in construction. This hazard, as documented by numerous authors (**Bell and Culshaw, 2001; Driscoll and Chown, 2001; Nelson and Miller, 1992; Grob, 1976; Jones and Jefferson, 2012; Harrison et al. 2012; Radevsky, 2001; Einstein, 1979; Houston et al. 2011; Zheng et al. 2009**), is particularly pronounced in regions with an arid and semi-arid climate. The urgent need to understand the behaviour of such materials is crucial to the successful prevention or resolution of these problems.

Swelling materials are dominated by clay minerals from the smectite group, in which montmorillonite is the primary representative. These minerals bind water very readily and thus multiply their volume. If such materials are present in the subsoil of the foundation, they can cause serious problems for lightweight structures and this risk should be adequately prevented. On the other hand, these materials are characterised by very low water permeability. Therefore, they are used for the construction of impermeable barriers in waste disposal sites that require low permeability and a high retention capacity for pollution.

The behaviour of the swelling material during drying and wetting was considered as a combined hydraulic-mechanical process that includes one-dimensional water flow in saturated and unsaturated conditions with a simultaneous change in the volume of the porous, deformable-expansive medium due to the change in moisture content. To provide the ability to analyse the drying and wetting process and forecast the behaviour of the swelling material under the assumed environmental conditions, appropriate assumptions were adopted for the practical solution of this problem.

The first assumption is that the problem of the swelling material drying or wetting can be treated entirely as a one-dimensional vertical flow of water in a deformable medium. Drying or wetting is simulated under isothermal conditions as one-dimensional water flow (diffusion

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of water vapour is not simulated directly) with a defined boundary condition in the form of evaporation or infiltration flow on the material's surface. The assumption of one-dimensional vertical flow is justified when the material is intact at the beginning of drying, i.e. uncracked, and for the conditions prevailing at the level of the laboratory sample in this research.

The second assumption is that the three-dimensional compression of the swelling material volume can be described by a simple model that simultaneously includes axial and lateral isotropic deformation of the skeleton (**Raats, 1969; Raats, 1984; Miller, 1975; Rijniersce,1983; Rijniersce,1984; Bronswijk, 1988; Bronswijk, 1990; Bronswijk and Evers-Vermeer, 1990; Kim et al., 1992a; Kim et al., 1992b; Kim et al., 1992c; Kime et al., 1999; Garnier et al., 1997a; Garnier et al., 1997b**).

The third assumption is that the material is homogeneous, its properties do not change in the horizontal direction, and the skeleton does not show time-intrinsic behaviour.

One-dimensional water flow in a swelling material is modelled based on Richards's equation (**Richards, 1931**) of water movement in an unsaturated medium, i.e. on its modified version (**Philip, 1969**), which is adapted for a deformable medium and enables simultaneous modelling of water flow and medium deformation. To solve this equation with defined initial and boundary conditions, it is necessary to know three hydraulic functions:

- soil-water characteristic curve (SWCC), which shows the dependence between suction and moisture content of the swelling material;
- hydraulic conductivity curve (HCC) in saturated and unsaturated conditions showing the relationship between hydraulic conductivity and swelling material suction;
- a shrinkage or swelling curve that shows the relationship between the volume change and the material's moisture content during drying and wetting.

The hydraulic functions SWCC and HCC are highly non-linear and show considerable hysteresis between drying and wetting. The third hydraulic function, which defines the change in volume as a function of the moisture content, also shows hysteresis between drying and wetting paths. Furthermore, this function depends on the normal stress variable that comes from the weight of the overburden and possibly some additional external load. Under drying conditions, this function represents a unique curve. While the shrinkage curve for the unloaded state of the sample has been studied in detail in the professional literature of modern soil physics and unsaturated soil mechanics, the swelling curve is often assumed to be identical in shape to the shrinkage curve, which is far from reality.

Experimental models of swelling material wetting (infiltration), e.g. **Kim et al. (1999) and Garnier et al. (1997a)**, usually interpret volume changes by taking a unique swelling curve (which they identify with a shrinkage curve) in wetting or starting infiltration at uniformly distributed moisture throughout the depth of the sample. This facilitates the interpretation but does not give an accurate picture of this problem.

A model that simultaneously includes water flow in saturated conditions and volume change was set up by **Terzaghi (1925)** in the form of the classical theory of one-dimensional soil consolidation with numerous approximations and limitations. The theory developed by **Gibson et al. (1967)** removes classical theory's restrictions and considers nonlinear changes in the compressibility and hydraulic conductivity of the soil. This theory also assumes the applicability of Darcy's law, which takes the relative velocity between the pore fluid and the skeleton (solid phase) and relates it to the gradient of the generated pore pressure.

The problem of one-dimensional consolidation, in theory, according to Gibson et al. (1967), considers an element whose solid particle mass does not change regardless of deformation, which assumes a coordinate system that is stationary about the material phase (which is called Lagrange's), and its coordinates are material. If the coordinate system is stationary in space, such a system is called spatial or Euler's. The Lagrange coordinate system is more acceptable in cases where the material boundary's movement problem is treated (**Gibson et al.**, **1967**).

Following the formulation of the differential equation for medium deformation and one-dimensional water flow (**Gibson et al.,1967**), **Abu-Hejleh and Znidarčić (1995)** developed the theory of the drying of soft cohesive soil. This theory encompasses consolidation and drying processes, where consolidation is treated as one-dimensional and drying as three-dimensional volume compression. The mentioned theories of one-dimensional consolidation and drying imply a state of complete saturation.

The formulation of the differential equation defined by **Philip (1969)** based on the Richards equation (**Richards, 1931**) and the use of material coordinates allows for simulating the flow of water and the deformation of the medium in saturated and unsaturated conditions.

Several numerical models of water flow in a deformable porous medium have been presented based on Richards and Philip's equations (**Narasimhan and Witherspoon, 1977; Bronswijk, 1988; Kim et al., 1992a; Garnier et al., 1997a**). **Perrier et al. (2002)** developed a software package called ECOUL to study the hydraulic behaviour of deformable or rigid media. ECOUL software was used in this research to simulate the drying and wetting of the swelling material numerically. It should be emphasized that the simulations of the wetting process could not be performed properly with this software due to its limitations in terms of hysteresis between drying and wetting. That is why the appropriate transformations of the calculated moisture content profiles into the corresponding void ratio profiles were performed using the developed swelling model (**Kavur et al., 2023**), which then enabled the implementation of valid simulations of the wetting of the swelling material.

The problem of shrinkage and swelling of soil materials has been extensively investigated in the past, but also in numerous recent studies (**Abd El-Latif et al., 2022; Onyelowe et al., 2022; Puppala et al., 2013; Lu and Dong, 2017; Li and Zhang, 2018; Khan et al., 2019; Ahmed et al., 2019; Shrestha et al., 2019; Vail et al., 2019; Menon and Song, 2019; Qi et al., 2022; Ivoke et al., 2021; Luo et al., 2023; Meshram et al., 2021; Rao et al., 2021**). The cited studies provide a good overview and insight into the current state of the main problem of unsaturated materials, which is the existence of hysteresis between the drying and wetting paths in the characteristic soil-water curves, the causes of which, despite the numerous studies that have been carried out so far, have not yet been sufficiently investigated and clarified. This study represents a contribution precisely in elucidating the problem of hysteresis and it focuses in particular on wetting regime behaviour of the swelling material. This research is mainly based on the study of **Kavur et al. (2023)**, which presented a conceptual model of the swelling of such materials, but also follows earlier work by various authors (**Kavur et al., 2011; Kavur, 2009; Vrkljan and Kavur, 2022; Vrkljan et al., 2006**).

This study includes laboratory procedures and numerical simulations using input data from the specifically designed sample test (**Kavur et al., 2023**) and aiming here to determine hydraulic characteristics of swelling material for wetting regimes, and to verify the swelling model proposed by **Kavur et al. (2023)**. A carefully planned, conducted and documented laboratory experiment of one-dimensional wetting of swelling material from the study of **Kavur et al. (2023)**, is here numerically simulated using ECOUL software. The moisture content profiles obtained using ECOUL software were interpreted into corresponding volume changes using the swelling model (**Kavur et al., 2023**), which also verified this model.

2. Material, procedures and test results

The research was carried out on samples of swelling material from the locality Muvrinski Jarak, located in the broader area of Gornja Jelenska, northeast of Popovača (Croatia). The mineral composition of the samples was determined using X-ray powder diffraction using a Philips diffractometer. The results of the analyses showed that the samples consist of clay minerals, quartz, clay minerals, K-feldspar, plagioclase, and there are indications of the presence of cristobalite, which is a common ingredient of bentonite. Montmorillonite was confirmed in the samples by different treatments. Diffraction images do not indicate interstratification of montmorillonite with illite. The value of the inter-lattice distance d (060), which defines the character of the octahedral network, is 1.504, which corresponds to dioctahedral smectites, i.e. montmorillonite. The performed mineralogical analyses enabled qualitative and semi-quantitative, but unfortunately not complete quantitative insight into the amount of active minerals. However, the granulometric analysis shows that the proportion of clay minerals is around 20%. The liquid limit ranges from 99 to 112%, and the plasticity index is around 54%. The natural water content of this material ranges from 45 to 71%, and the void ratio from 1.29 to 1.97. Basic geotechnical properties of swelling material from the locality Muvrinski Jarak are given in **Table 1**.

Table 1: Basic geotechnical properties of swelling material from the locality Muvrinski Jarak

Property in natural state	Value
Moisture content (%):	45.2 – 71.3
Saturation (%):	93 – 100
Void ratio:	1.29 – 1.97
Dry density [g/cm^3]:	0.92 – 1.19
Liquid limit (according to BS 1377: P2) (%):	99 – 112
Plastic limit (according to BS 1377: P2) (%):	45 – 58
Plasticity index (according to BS 1377: P2) (%):	54
Granulometric composition (acc. to ASTM D 422)	
Percentage of clay particles (C) %:	18 – 22
Percentage of silt particles (M) %:	65 – 69
Percentage of sand particles (S) %:	13
Percentage of gravel particles (G) %:	0
Specific gravity (according to ASTM D 854):	2.72

The experimental methodology adopted in this study was to use drying and wetting tests on laboratory samples prepared from natural, undisturbed swelling material and reconstituted samples with the aim of establishing clear and reliable procedures for defining key hydraulic characteristics. Hydraulic characteristics of swelling material for wetting regimes were determined through numerical simulations of water flow by using the inverse problem-solving technique. Wetting of the VU-3 sample described in **Kavur et al. (2023)** was numerically simulated here using ECOUL software.

Drying and wetting tests were performed on undisturbed samples of swelling material obtained from excavation and reconstituted samples. Undisturbed disc-shaped samples (see **Figure 1**) were subjected to drying and wetting experiments under laboratory conditions. **Table 2** provides an overview of the dimensions and wet mass of all undisturbed disc-shaped samples (11 pieces in total), as well as the state of dry density, moisture content, void ratio and saturation at the beginning of the test. The undisturbed samples in the form of a tall cylinder

Figure 1: Undisturbed samples of swelling material from the Muvrinski Jarak location

(see **Figure 2**) were also subjected to drying experiments in which only the upper base of the sample was exposed to drying. **Table 3** gives an overview of the dimensions and wet mass of all cylindrical undisturbed samples (6 pieces in total), as well as the state of dry density, moisture content, void ratio and saturation at the beginning of the test. The term reconstitution refers to forming a test sample by consolidating a paste prepared from a previously dried and disintegrated sample (**Kavur et al., 2023; Kavur et al., 2011**).

Tests were previously performed on the same material, which determined the hydraulic characteristics of the material for drying conditions (**Kavur et al., 2011**). Here, the characteristics of the same material for wetting regimes were determined and presented. Soil-water characteristic curves (see **Figure 3**) and hydraulic conductivity curves (see **Figure 4**) were determined based on the consolidation properties of the reconstituted material using the inverse problem-solving technique (**Kavur et al., 2011**).

Figure 3 shows the simulated SWCC curve in wetting together with the drying curve. **Table 4** shows the parameter values of the "van Genuchten" (VG) model of the SWCC curve in wetting.

The results of the wetting experiment of the sample VU-3 (**Kavur et al., 2023**) were used here to inversely determine HCC in wetting. The hydraulic conductivity function, *k(ϑ)*, was gradually adjusted so that the numer-

Table 2: Details on undisturbed samples in the form of a disk

Lab. No.	Specimen mass (g)	Diameter (mm)	Height (mm)	Dry density (g/cm³)	Moisture content, w	Void ratio, e	Saturation, S
1	65.88	50.50	20.00	1.02	0.620	1.68	1.00
2	121.91	49.81	38.20	1.01	0.620	1.69	1.00
3	120.11	69.83	19.25	1.01	0.620	1.68	0.99
4	205.86	69.77	33.25	1.00	0.620	1.72	0.98
5	134.73	59.95	30.40	0.92	0.713	1.97	0.99
6	135.43	59.95	30.57	0.93	0.703	1.93	0.99
7	127.56	69.90	19.40	1.17	0.460	1.32	0.95
8	127.38	69.90	19.27	1.18	0.452	1.30	0.95
9	127.49	69.90	19.55	1.17	0.452	1.33	0.93
10	126.70	69.90	19.25	1.18	0.452	1.31	0.94
11	148.41	59.90	30.50	1.19	0.452	1.29	0.95

Figure 2: Undisturbed samples of swelling material in the form of a tall cylinder

Table 3: Details on undisturbed samples in the form of a tall cylinder with diameter of 50 mm

Lab. No.	Specimen mass (g)	Diameter (mm)	Height (mm)	Dry density (g/cm³)	Moisture content, w	Void ratio, e	Saturation, S
1	324.42	196.94	100.92	1.035	0.580	1.629	0.968
2	317.15	189.93	96.93	1.049	0.580	1.592	0.991
3	298.79	180.35	92.53	1.040	0.580	1.614	0.977
4	266.23	157.25	80.73	1.064	0.580	1.557	1.000
5	256.21	152.48	78.01	1.054	0.580	1.580	0.999
6	240.27	144.55	73.47	1.044	0.580	1.606	0.982

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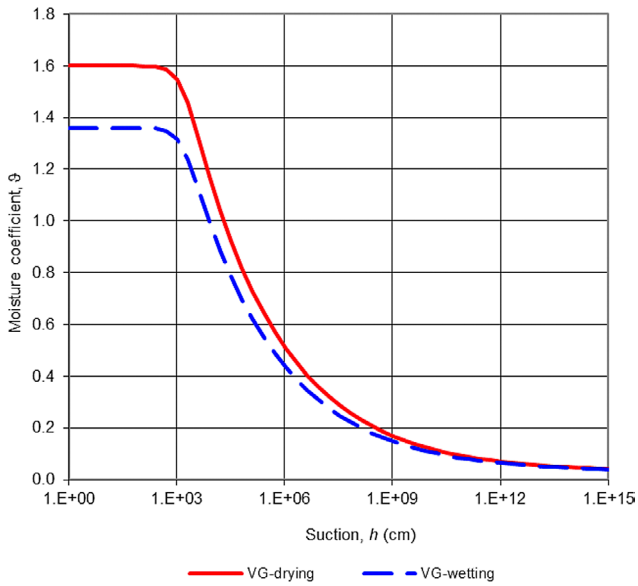

Figure 3: Soil-water characteristic curves in drying and wetting simulated by the VG model. Note: Data of BC(k)-drying curve are adopted from **Kavur et al. (2011)**.

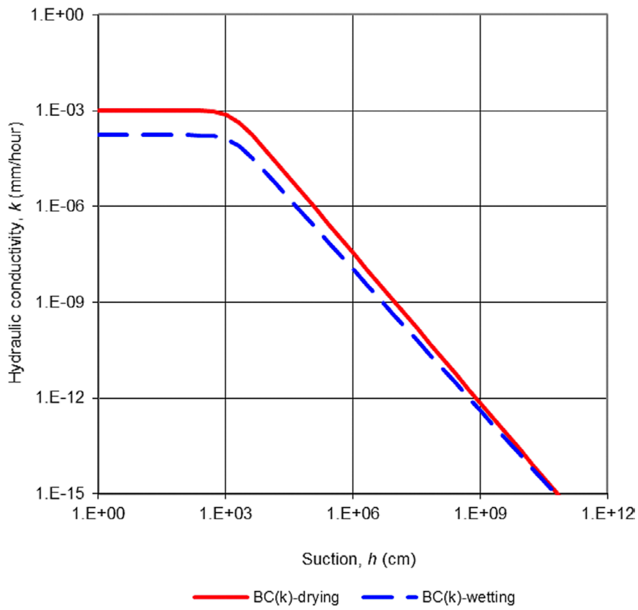

Figure 4: Hydraulic conductivity curves (simulated by BC model) in drying and wetting in relation to suction. Note: Data of BC(k)-drying curve are adopted from **Kavur et al. (2011)**.

ical simulation result corresponded to the measured data. The wetting function has relatively small corrections compared to the drying conductivity function.

The curve of hydraulic conductivity in wetting is shown in **Figure 4** and **Figure 5**, together with the drying curve depending on suction or moisture coefficient (ϑ). Here, instead of the volumetric water content (θ), commonly used in soil physics, the moisture coefficient (ϑ) was used, representing the ratio of the volume of water to the volume of solid particles in the sample. The

Table 4: Parameters of VG model of SWCC curve of swelling material in wetting

Parameter of *VG* model	Parameter value (-)
Moisture coefficient at full saturation, J_s	1.36
Residual moisture coefficient, J_r	0.03
Approximates the inverse value of suction at air entry, *a*	0.0007
Reflects the pore size distribution, *n*	2.18
Enables the symmetry of the entire curve, *m* = 1-2/n	0.08257

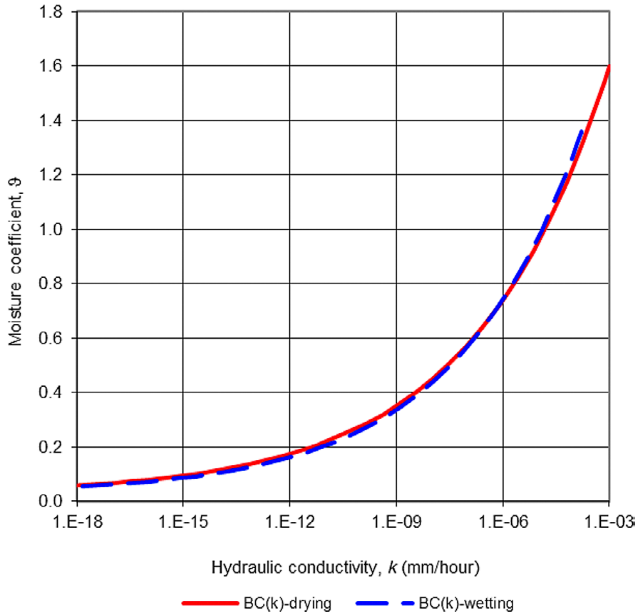

Figure 5: Hydraulic conductivity curves in drying and wetting in relation to moisture coefficient. Note: Data of BC(k)-drying curve are adopted from **Kavur et al. (2011)**.

Table 5: Parameters of the BC model of the hydraulic conductivity curve of swelling material in wetting

Parameter of *BC* model	Parameter value
Hydraulic conductivity, k_s	0.00017 mm/hour
Empirical curve fitting parameter, *B*	8.2 (-)

volume of solid particles is constant, unlike the volume of the sample itself, which is variable in the case of swelling materials. The curve shown in **Figure 4** is simulated by the parameter values of the BC model listed in **Table 5**.

The dried and disintegrated swelling material was mixed with distilled, deaerated water into a paste of high initial moisture content (w > 200%). The consolidation properties of the prepared paste were determined by analysing the results of the Seepage-Induced Consolidation Test (SICT) (see **Figure 6a-f**). This test technique was developed by Znidarčić and co-authors (**Znidarčić et al., 1986; Znidarčić et al., 1991; Znidarčić et al.,**

2021; Abu-Hejleh and Znidarčić, 1995; Abu-Hejleh et al., 1993; Abu-Hejleh and Znidarčić, 1996; Bicalho, 1999; Hwang, 2002; Yao et al., 2002). The laboratory pump (see **Figure 7**) enables precise control and a constant value of the selected flow rate through the sample. The differential transducer precisely measures the pressure difference between the reference value of the established back pressure and the pressure generated by the pump's operation below the sample's (see **Figure 8**) lower base.

The program of experimental and analytical procedures, which are applicable to define the hydraulic characteristics of the swelling material, first in drying and then wetting regime, should include the following:

- Classification tests to determine liquid limit, plasticity limit, plasticity index, specific density of solid particles, granulometric composition, natural water content, void ratio, and saturation of the material in natural state.
- The shrinkage curve should be determined by drying a saturated, undisturbed sample of the swelling material. The test sample should be formed with a standard oedometer ring to obtain the correct disc shape. The sample should be air-dried in the laboratory (see **Figure 1**). During drying, changes in mass and volume (by measuring the dimensions) of the sample should be recorded simultaneously. The frequency of these measurements should be sufficient to adequately define the curve. Towards the end of drying, the sample should be placed in a dryer at a temperature of up to 60°C and dried to a constant mass. After drying, its volume and mass should be determined immediately to determine the material's shrinkage limit.
- At least two tall cylindrical samples should be formed from a larger piece of undisturbed swelling material. The samples should be approximately equal in height and weight. The samples should be formed in a humidity chamber to preserve the saturation of the material. The sides and bottom of each sample should be protected with a rubber membrane (see **Figure 2**). The samples should be simultaneously, side by side, subjected to one-dimensional air drying in the laboratory. In doing so, the samples should be in approximately equal temperature and airflow speed conditions. During drying, the mass and volume of the samples should be periodically measured. Depending on the dynamics of mass changes, the samples should be dried for several days. When the upper surface of the sample becomes dry, drying should be stopped. After drying, the samples' final mass, height and volume should be determined. One sample should be cut into disks of equal height, and the water content should be measured for each disk to determine the water content profile. The second sample should be virtually divided into the same number of discs (as the first sample) by engraving marks. The diameter of each disc should be measured at the end of drying. The sample should then be subjected to one-dimensional wetting. It is important to keep the water level above the sample constant during the experiment. The experiment can be stopped once it is determined that the wet front has moved deep enough (more than half the height). It is necessary to determine the final mass of the wetted sample, the total height and total volume, and the diameter of each disc. The sample should be cut into discs according to the engraved markings, and the moisture profile determined after wetting.
- The SWCC in drying can be satisfactorily estimated based on the results of the SICT experiments. Although the suction variable is not measured concerning water content in this experiment, it is assumed that the effect of effective stress and suction on the change in the void ratio or water content in saturated conditions is approximately similar. The curve of the experimentally defined relationship between the effective stress and the void ratio should be simulated by the VG model so that the experimental and simulated SWCC curves match as well as possible in the saturated domain. In the unsaturated domain, the final part of the simulated curve is determined by selecting the residual water content parameter. The simulation of the SWCC curve in wetting is possible by taking the values of most parameters from the VG model of the curve in drying, while the value of the moisture coefficient (ϑs) should be determined from the wetting experiment.
- The HCC of the swelling material can also be estimated based on the results of SICT experiments. Hydraulic conductivity in unsaturated conditions can be determined using the inverse problem-solving technique. The quantitative model should simulate the drying and wetting experiments, and the hydraulic conductivity function should be adjusted by gradually changing the parameter B in the BC model until a satisfactory match between the simulated and measured values is obtained.

The data collected in the 1-D wetting experiments of the samples (**Kavur et al., 2023**) served here as a reliable basis for verifying the swelling model and evaluating the experimental and analytical procedures used to determine the hydraulic characteristics of the swelling material in wetting process.

2.1. Numerical simulation of wetting for the sample VU-3

The wetting (infiltration) experiment of the sample VU-3 (**Kavur et al., 2023**) was numerically simulated by the ECOUL program. The sample is simulated by one homogeneous layer whose hydraulic characteristics are represented by three different curves.

Figure 6: Stages of SICT preparation: a) pouring the suspension of the swelling material into the cylinder; b) suspension at the bottom of the cylinder; c) installation of the filter plate and filter paper on the sample in liquid state; d) view of the bottom of the cylinder with embedded sample and porous plate; e) installing the piston in the cylinder; f) sample cylinder and piston embedded in a triaxial cell.

Figure 7: Harvard '33' Syringe Pump

The name of the curve model is indicated by a keyword (e.g. "VanGenuchten", "BrooksCorey", "Braudeau") followed by the name of the variable given by the algorithm type (e.g. "Taux_humidite" represents the moisture coefficient, ϑ). The hydraulic characteristics of the sample are presented in the following order:

1) The SWCC using the VG model (**Table 4**); in the *.sim file, after the keywords of the model and variable, the values of the parameters follow: *r; Js, a* and *n*.

The VG model:

$$\vartheta = \vartheta_r + \frac{\vartheta_s - \vartheta_r}{\left[1+(\alpha h)^n\right]^m} \quad (1)$$

Where:

ϑr – residual moisture coefficient (-),

ϑs – moisture coefficient at full saturation (-),

h – suction (cm).

The VG model (**Equation 1**) includes three parameters for fitting the experimental data:

α – approximates the inverse value of suction at air entry (-),

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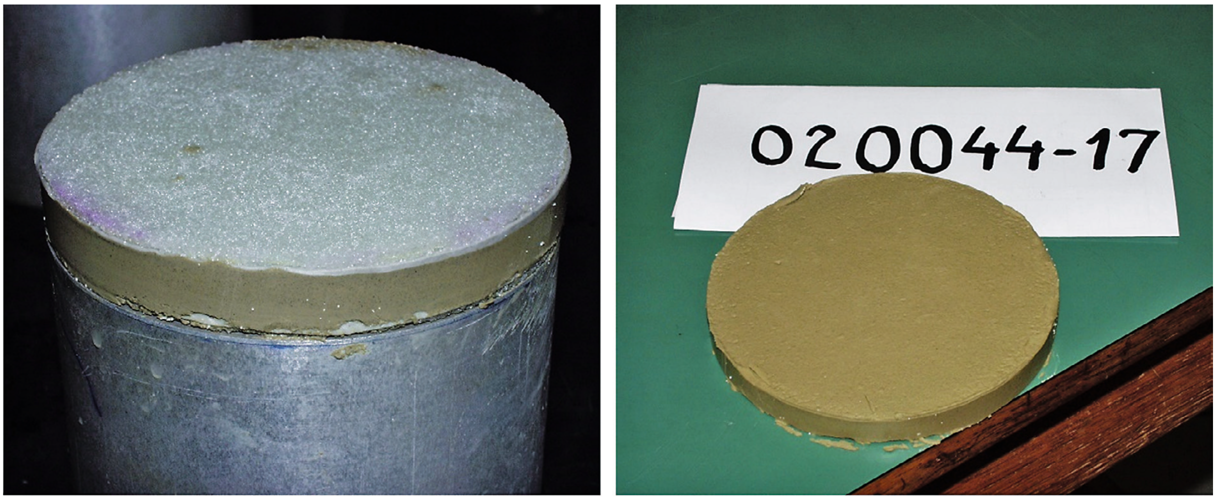

a) **b)**

Figure 8: Test sample (020044-17) of the swelling material used in the SICT experiment: a) sample taken out of the cylinder with a filter plate on top; b) sample after the seepage-induced consolidation test.

n – reflects the pore size distribution (-),

m – enables the symmetry of the entire curve (-).

Note: The file specifies the parameter α (from the VG model) as a negative value.

The relationship between the parameters m and n is defined by Burdine's condition in **Equation 2**.

$$m = 1 - \frac{2}{n} \tag{2}$$

2) The HCC using the BC model (**Table 5**); in the *.sim file, the model and variable keywords are followed by the parameter values: ϑr, ϑs, ks and B.

The BC model is expressed in **Equation 3**.

$$k(\vartheta) = k_s \left(\frac{\vartheta - \vartheta_r}{\vartheta_s - \vartheta_r} \right)^B \tag{3}$$

Where:

k_s – hydraulic conductivity (mm/h),

B – empirical curve fitting parameter (-).

3) The shrinkage or swelling curve using the "Braudeau" (BR) model (**Table 6**); in the *.sim file, the model and variable keywords are followed by the parameter values: r_s, G_s, K_o, ϑ_{SL}, e_{SL}, J_{AE}, e_{AE}, J_{LM}, e_{LM}, J_{MS}, e_{MS}.

Where:

r_s – geometric factor (-),

G_s – specific gravity (-),

K_0 – direction coefficient of line II in "e-ϑ" diagram (-),

J_{SL}; e_{SL} – shrinkage limit,

J_{AE}; e_{AE} – air entry to micropores,

J_{LM}; e_{LM} – limit of contribution of macropores to volume shrinkage,

J_{MS}; e_{MS} – limit of maximum volume of microaggregates.

Table 6: Parameters of the BR model of the quasi-swelling curve of sample VU-3

Parameter of BR model	Parameter value (-)
J_{SL}; e_{SL}	0.00 ; 0.84
J_{AE}; e_{AE}	0.00 ; 0.84
J_{LM}; e_{LM}	0.802 ; 1.035
J_{MS}; $_{eM}$S	0.802 ; 1.035
K_o	0.9
Geometric factor:	
r_s	3.00
Specific gravity:	
G_s	2.72

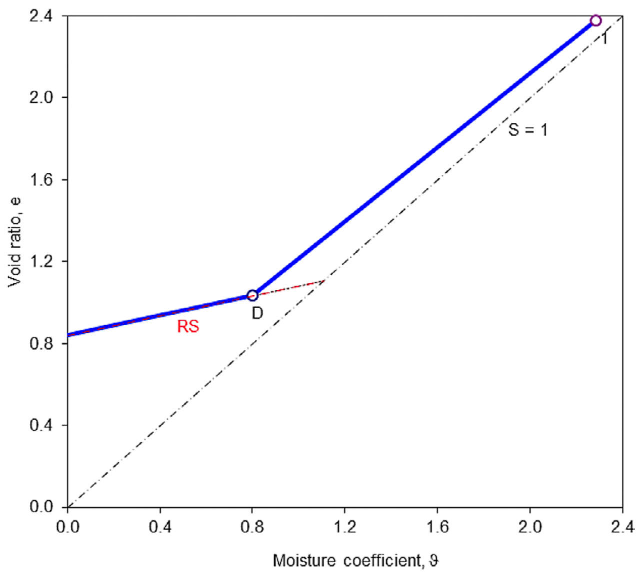

Figure 9: Quasi-swelling curve in the simulation of the wetting of the VU-3 sample by ECOUL (without modification)

Table 7: ECOUL file description of the simulation of wetting (infiltration) of sample VU-3

Sol: 14.48 Deformable 19.84 1 VU-3 0.00 14.48	
VanGenuchten2 Taux_humidite	
0.03 0 1.36 0 -0.0007 0 2.18 0	
BrooksCorey Taux_humidite	
0.00 0 1.36 0 0.00017 0 8.20 0	
Braudeau Taux_humidite	
3.00 0 2.72 0 0.00 0 0.84 0 0.00 0 0.84 0 0.802 0 1.035 0 0.802 0 1.035 0 0.90 0	
Profil: Teneur_en_eau 55	
0.00	0.026
0.27	0.031
0.54	0.042
0.81	0.066
1.08	0.093
1.36	0.114
1.63	0.131
1.90	0.145
2.17	0.157
2.44	0.167
2.71	0.176
2.98	0.184
3.25	0.192
3.52	0.199
3.79	0.205
4.07	0.211
4.34	0.216
4.61	0.221
4.88	0.226
5.15	0.230
5.42	0.234
5.69	0.238
5.96	0.242
6.23	0.245
6.50	0.249
6.77	0.252
7.04	0.255
7.31	0.257
7.58	0.260
7.85	0.262
8.12	0.265
8.39	0.267
8.66	0.269
8.93	0.271
9.20	0.273
9.47	0.275
9.74	0.276
10.00	0.278
10.27	0.279
10.54	0.280
10.81	0.282
11.08	0.283
11.34	0.284
11.61	0.285
11.88	0.286
12.15	0.286
12.41	0.287
12.68	0.288
12.94	0.288
13.21	0.289
13.47	0.289
13.74	0.289
14.00	0.290
14.26	0.290
14.48	0.290
ConditionSuperieure: Protocole 2	
30.0 Pluie 1.186	
29970.0 ChargeQuelconque 3.00	
PlaquePoreuse 0.00004	
ConditionInferieure: Protocole 1	
30000.0 FluxQuelconque 0.00	
NonPlaquePoreuse	
Environnement:	
Garnier 54 0.01	
Observation: 0	

The experimental curves of SWCC and HCC in saturated and unsaturated conditions are parameterised by the models above that can be selected in the ECOUL program. The so-called inverse problem-solving determines the part of the hydraulic conductivity curve that refers to the unsaturated area. The value of parameter B in BC model (**Brooks and Corey, 1964**) was gradually modified to match satisfactorily the calculated and experimental data.

The VU-3 sample was simulated as a homogeneous column. In the VG model of the SWCC curve, the value of the parameter ϑs is modified so that the moisture content obtained by the simulation is approximately limited to the level that was reached in the top parts of the sample VU-3 (disc no. 2) at the end of the wetting experiment. The values of other parameters of the VG model were not changed (see **Table 4**) compared to the same in drying.

To enable the simulation of the wetting experiment with the existing algorithm, the so-called quasi-swelling curve was defined (see **Figure 9**). This curve follows the

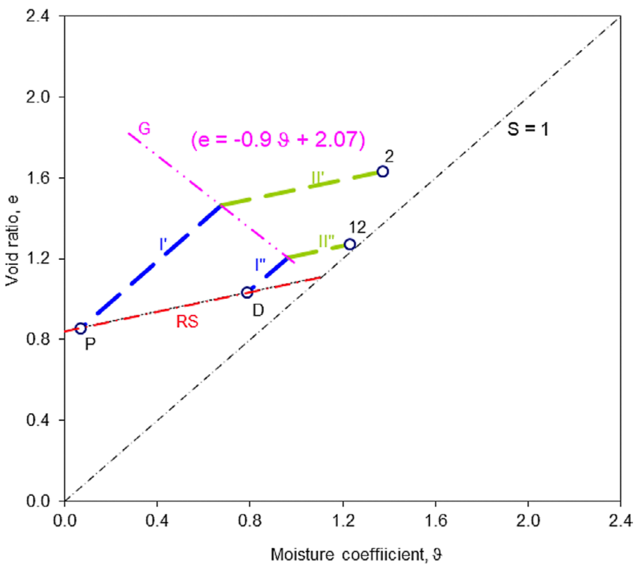

Figure 10: The swelling model used to reinterpret moisture profiles obtained by simulating the wetting of the VU-3 sample

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trace of the drying curve in the residual part (RS), starting from the dry state and reaching the moisture content (*w = 0.295* or *ϑ = 0.802*) that the sample has at the bottom (D) just before wetting. After reaching the specified moisture, the curve continues along the line with a direction coefficient of 0.9 in the "*e-ϑ*" diagram, i.e. towards the point (1) with the maximum value of moisture content and void ratio in the wetting experiment (*w = 0.84; e = 2.38*). The values of the parameters of the BR model of the quasi-swelling curve are shown in **Table 6**.

Data on the initial moisture distribution along the depth were obtained from the drying test of the VU-3 sample (**Kavur et al., 2023; Kavur et al., 2011**). In this simulation, the final moisture profile after the drying test was taken as the initial (input) profile (see **Table 7**).

In the initial 30 minutes of the wetting, the boundary condition on the sample's surface is defined as an infiltration flow with a velocity equal to that measured in the experiment. After that, the boundary condition is defined as a permanent column of water 3 cm high above the sample's surface (according to the infiltration performed) until the end of the experiment (total duration of 500 hours). At the bottom of the sample, the boundary condition is flow with a velocity equal to zero; the bottom is an impermeable boundary. The sample is spatially divided into 54 segments by depth. The minimum value of the time increment is 0.01 min.

Based on the quasi-swelling curve, the interpretation of the simulated moisture coefficients into the void ratios give a curve of the sample volume change with the opposite trend to the curve of the measured values. Therefore, the simulated moisture profiles are reinterpreted here using the defined swelling model (see **Figure 10**) so that each column segment (54 pieces) is associated with its swelling curve. In the simulation and reinterpretation, the material's specific behaviour at the very top of the VU-3 sample was ignored. Namely, at the very top during wetting, complete disintegration and disruption of the material structure occurs to a depth of only a few millimetres.

For the calibration of the swelling model, the data of discs no. 2 (near the top) and 12 (bottom), i.e. their final points in the "e-ϑ" diagram after wetting (see **Figure 10**) were used. The lines II' and II'' parallel to the residual part of the shrinkage curve (RS) is laid through the indicated points marked 2 and 12, respectively. In the same "e-ϑ" diagram, lines I' and I' are laid through point P, which represents moisture content (w = 0.026) on the surface and point D, i.e. moisture content (w = 0.29) at the bottom of the sample (see **Table 6**) parallel to the direction of full saturation (S = 1). Through the intersection of lines, I' and II', and the intersection of lines I'' and II'', line G is laid, which represents the border between the so-called primary and secondary stages of swelling. Each segment in the simulated column (sample) receives a swelling curve whose position in the "e-ϑ" diagram is determined by the moisture content that the segment has at the very beginning of wetting. The increase in the value of the void ratio (swelling) during wetting goes from the starting point, which is located on the shrinkage curve, in a direction parallel to the line of full saturation (primary phase of swelling) up to the boundary G. Then it continues in a direction parallel to the residual part of the shrinkage curve (secondary swelling phase).

Figure 11 shows the changes in the mass of the VU-3 sample measured and obtained by simulation of wetting. Initial and final measured and simulated moisture con-

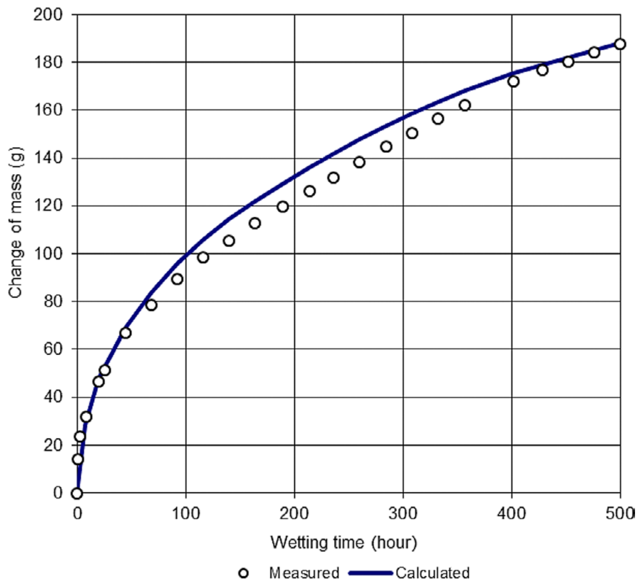

Figure 11: Calculated and measured mass changes of sample VU-3 during wetting. Note: Measured data are adopted from **Kavur et al. (2023)**.

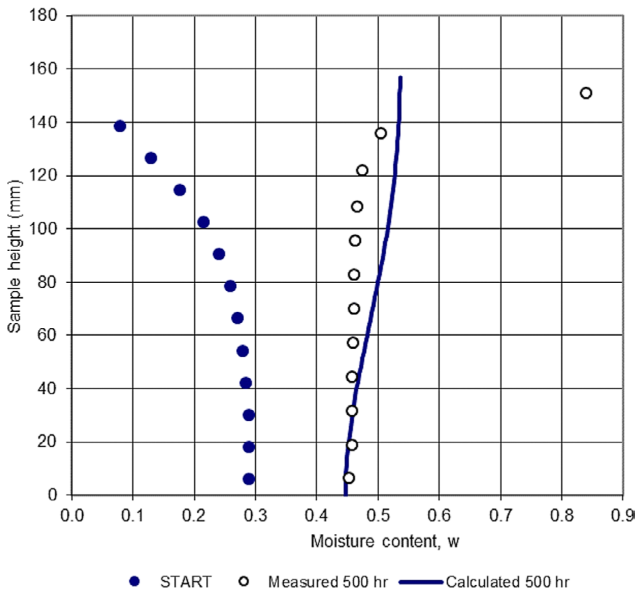

Figure 12: Initial and final (measured and calculated) moisture content profiles of sample VU-3 (before and after wetting for 500 hours). Note: Start and measured data are adopted from **Kavur et al. (2023)**.

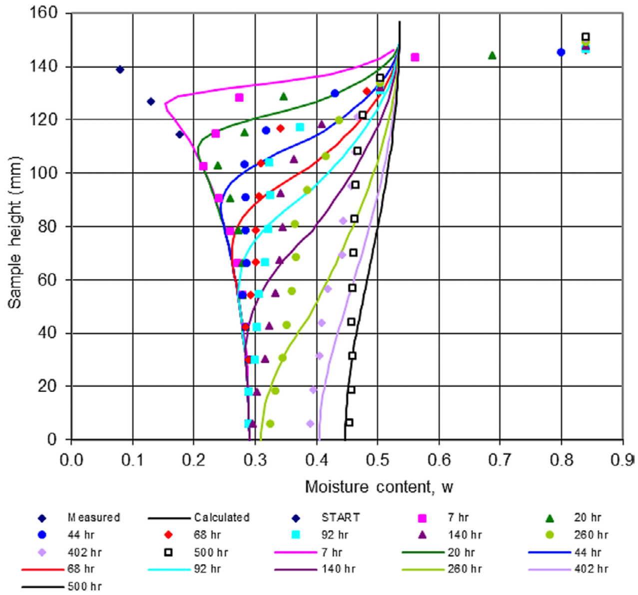

Figure 13: Calculated and measured moisture content profiles of sample VU-3 in wetting. Note: Start and measured data are adopted from **Kavur et al. (2023)**.

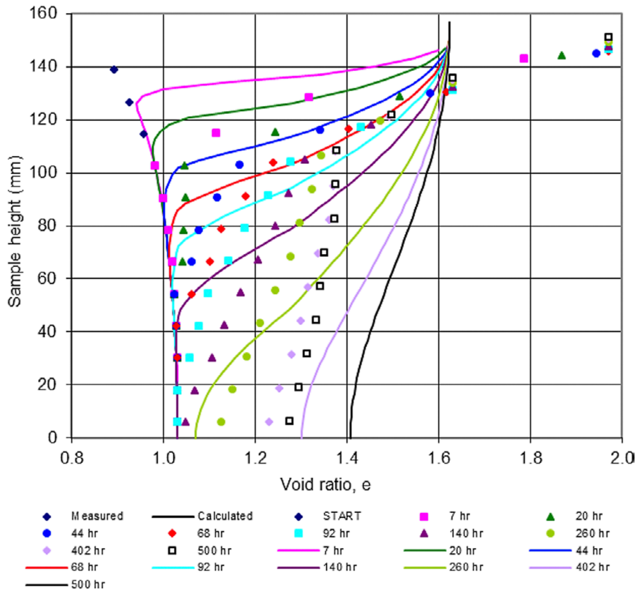

Figure 14: Calculated and measured void ratio profiles of sample VU-3 in wetting. Note: Start and measured data are adopted from **Kavur et al. (2023)**.

tent profiles are shown together in **Figure 12**. Simulated and interpreted moisture content profiles and void ratio profiles are shown in **Figure 13** and **Figure 14**, respectively.

3. Discussion

The conducted research obtained the basic hydraulic characteristics of the swelling material for wetting regimes. Previous tests (**Kavur et al., 2011**) on the same material determined hydraulic characteristics for drying conditions. The experiments were planned to cover a wide range of moisture content, from full saturation to residual conditions. That is, to define the main or limiting hydraulic curves of the material, for the drying and wetting regimes. The resulting curves, which are shown in **Figure 3** and **Figure 4**, indicate the existence of significant hysteresis between drying and wetting. In real conditions, it is to be expected that drying and wetting processes, i.e. changes in suction and hydraulic conductivity of the swelling material occur in the space between these main curves.

The wetting experiment's results (**Kavur et al. 2023**) were used to determine the parameters of the BC model (see **Table 5**). The function k(ϑ) was gradually adjusted to bring the simulation result close to the measured data. About the parameter values of the BC model of function in drying (**Kavur et al., 2011**), the values of the same for the function in wetting (see **Table 4**) underwent relatively small corrections.

The comparison of the curves of hydraulic conductivity in relation to the moisture coefficient of the material (see **Figure 5**) shows small or no differences in conductivities between drying and wetting. Based on the experience gained in this research, the hydraulic conductivities in drying and wetting should be approximately the same at the same moisture coefficients of the material (see **Figure 5**).

The specific behaviour of the top of the VU-3 sample, during wetting, was ignored in the simulation due to the limitations of the model used. Despite this, it is possible to assess that the calculated profiles of moisture content (see **Figure 13**) and void ratio (see **Figure 14**) satisfactorily agree with the measured data. Also, the calculated amount of infiltrated water through the calculated changes in the mass of the sample (see **Figure 11**) during wetting corresponds well to the measured data.

The swelling curve is not a unique curve like the shrinkage curve. This means that each spatial segment of the column (sample) in the simulation should have a separately defined swelling curve. The algorithm for deformable media in ECOUL software does not have this option. Attempts to solve the problem by dividing the column into enough layers with separately defined swelling curves resulted in the "cracking" of the program.

No code modifications to the algorithm were made as part of this research. However, they are recommended for simulating infiltration into a swelling material. The existing algorithm enables an adequate infiltration simulation, provided that the swelling material at the beginning of the simulation has a uniform moisture distribution along the depth. In such a case, the swelling curve could be defined as unique.

The quality of the results obtained by simulation depends on the quality of the experimentally determined material properties and the flexibility of the model for quantifying the material properties to adapt to the experimental data. In addition, the quality of numerical simulations naturally depends on the quality of the algorithm used for the numerical solution of the partial differential equation that describes the spatiotemporal distribution of water and potential in a porous medium, that is, on the size of the error that arises due to numerical approximations.

4. Conclusions

The experimental results of one-dimensional wetting of a sample (labels VU-3) of a swelling material (**Kavur et al., 2023**) were successfully numerically simulated here. The swelling model proposed by **Kavur et al. (2023)** is now verified. A numerical simulation was performed based on experimentally determined material properties determined for wetting conditions and not, as is usual, for drying conditions.

At the beginning of the wetting (infiltration) simulation, a variable distribution of the moisture content across the swelling material's depth was defined to present and realistically analyse the problem. This significantly complicates the numerical simulation. However, this is precisely what makes this study valuable and sets it apart from similar studies that started from a uniform moisture distribution throughout the swelling material's depth. Such conditions at the beginning of the experiment of wetting are necessary to get a realistic picture of the problem through the experiment.

The results of this research showed significant hysteresis between drying and wetting on all three hydraulic characteristic curves. However, it is important to notice that the hydraulic conductivity in drying and wetting regimes remains approximately the same at the same moisture content of the swelling material.

The proposed swelling model was successfully used to interpret the moisture content profile, which provided a good picture of the swelling material behaviour during wetting. Based on this, it is concluded that the presented quantitative model realistically describes the behaviour of the swelling material during the wetting experiment. The results of the performed simulations also confirm that the hydraulic characteristics of the material are relatively well measured and estimated based on the established procedures.

The used numerical model can be refined so that each segment of the column has a separately defined swelling curve in wetting and to enable the definition of different hydraulic characteristics for drying and wetting during the same simulation. This also opens up the possibility of conducting further research into the problem of hysteresis between drying and wetting of the swelling material.

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SAŽETAK

Kvantificiranje hidrauličkih značajki bubrivoga materijala

U radu je prikazana laboratorijska i numerička studija za određivanje triju hidrauličkih karakterističnih krivulja bubrivoga materijala (tla ili stijene) u kojemu je montmorilonit prevladavajući tip minerala. Prva, karakteristična krivulja tlo-voda predstavlja odnos između usisa i vlažnosti koji je potrebno definirati za rješavanje problema tečenja vode i prateće promjene volumena bubrivoga nezasićenog poroznog medija. Druga je krivulja funkcija hidrauličke provodljivosti u ovisnosti o saturaciji ili usisu. Treća krivulja predstavlja odnos između promjene volumena i vlažnosti bubrivoga materijala. Poznavanje ovih krivulja presudno je za razumijevanje tečenja vode i rezultirajućih promjena volumena pri čemu se studija posebno usredotočuje na ponašanje bubrivoga materijala u režimu vlaženja. Cilj istraživanja bio je utvrditi pouzdane metode za određivanje hidrauličkih svojstava bubrivoga materijala i obaviti verifikaciju predloženoga modela bubrenja. Iako bubrivi materijal pokazuje znatnu histerezu između režima sušenja i vlaženja, funkcija hidrauličke provodljivosti pokazala je malu ili nikakvu histerezu među putevima sušenja i vlaženja pri jednakim sadržajima (koeficijentima) vlažnosti.

Ključne riječi:
bubrenje tla i stijene, krivulja stezanja, krivulja bubrenja, karakteristična krivulja tlo-voda, model bubrenja

Author's contribution

Boris Kavur (1) (PhD in mining engineering, Associate Professor at the Faculty of Geotechnical Engineering, University of Zagreb) performed: tests, data analysis, conceptualisation, interpretation and presentation of the results. **Jasmin Jug (2)** (PhD in mining engineering, Assistant Professor at the Faculty of Geotechnical Engineering, University of Zagreb) assisted in data analysis and presentation. **Biljana Kovačević Zelić (3)** (PhD in mining engineering, Full Professor at the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb) provided conceptualization and drafting of the research, advised and supervised this study. **Ivan Vrkljan (4)** (PhD in civil engineering, Professor Emeritus at the Faculty of Civil Engineering, University of Rijeka) provided conceptualization and drafting of the research, advised and supervised this study.