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TEMPERATURE CHANGES IN THE VICINITY OF THERMALLY LOADED STRUCTURE EMBEDDED IN THE SOIL: EFFECT OF SAND CONTENT AND SATURATION DEGREE

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Abstract: Due to the rapid development of geothermal technologies, the problem of efficient and proper evaluation of soil thermal conductivity becomes extremely important. Factors mostly affecting the soil conductivity are the conductivity of solid phase and the degree of saturation. The former one is mainly affected by the mineral composition, in particular, by the content of quartz whose conductivity is the highest one among all the minerals forming soil skeleton. Organic matter, because of its relatively low conductivity, influences the solid conductivity as well. The problem addressed in the paper is the influence of mentioned factors on temperature changes in the vicinity of thermally loaded structure embedded in the soil medium. Numerical simulations are carried out for different values of soil thermal conductivity resulting from various quartz contents and degrees of saturation. In addition, a weak coupled – heat and water transport – problem is considered.

Key words: *transient heat flow, temperature, quartz, organic matter, degree of saturation*

1. INTRODUCTION

Soil, as a typical geomaterial, exhibits relatively high capability to store the so-called geothermal energy which can be extracted, e.g., by the application of reinforced concrete energy piles (e.g., Laloui et al., 2006; Gao et al., 2008; Murphy et al. 2015; Khosravi et al., 2016). Geothermal energy has also some other applications, such as: ground source heat pumps, borehole thermal energy storage, geological carbon dioxide sequestration and geothermal heated bridge/pavement (Zhang and Wang, 2017).

Since heat transfer in soils is commonly described as the conductive flow, the key parameter, from the point of view of aforementioned applications, is the soil thermal conductivity. This particular soil parameter can be determined either by in situ/laboratory measurements (e.g., Mohsenin, 1980; Farouki, 1981; Bristow et al., 1994; Gehlin, 2002) or by making use of existing empirical or theoretical models (e.g., Mickley, 1951; De Vries, 1963; Johansen, 1975; Coté and Konrad, 2005; Lu et al., 2007). In general, thermal conductivity of soils depends on mineral composition, texture, dry density, moisture content, porosity, etc. (Johansen, 1975; Farouki, 1980). Some of these parameters affect more, while others less, on the overall value of soil thermal conductivity.

The greatest influence on the soil conductivity is due to the content of quartz minerals in the soil solids and the content of water which is usually defined in terms of the degree of saturation (Różański and Stefaniuk, 2016b; Zhang and Wang, 2017). The former effect is caused by the fact that thermal conductivity of quartz is around 7.7 $Wm^{-1}K^{-1}$, which is the highest value among all the minerals forming soil skeleton (Johansen, 1975). The quartz content is, therefore, directly affecting the conductivity of solid phase. A considerable effect on solid conductivity, and as a consequence on the overall soil conductivity, is also due to the content of organic matter which is characterized by relatively low value of thermal conductivity, i.e., 0.25 $Wm^{-1}K^{-1}$ (Bristow, 2002). The effect of both quartz and organic matter content on the solid conductivity was investigated in earlier author's work (Różański and Stefaniuk, 2016b); based on the micromechanical approach, the model for evaluation of solid conductivity was proposed.

As mentioned, water content is another one factor strongly influencing the overall thermal conductivity of soils. At dry state, the pores are occupied by air whose conductivity is very low, around 0.025 $Wm^{-1} K^{-1}$. On the contrary, at full saturation state, the pores are filled with water characterized by 24 times higher conductivity than the one of air. Thermal conductivity of water is usually assumed as 0.6 $Wm^{-1} K^{-1}$ (at room temperature). It triggers that overall soil conductivity at dry state can be even one order less than the one at saturation. The conductivity of soil at intermediate states of saturation is usually evaluated from the conductivities in dry and saturated states by the application of the normalized conductivity, the so-called Kersten number (Johansen, 1975).

From the engineering point of view a very important aspect is the influence of such factors as quartz and organic matter content or saturation degree on the temperature distribution in the vicinity of thermally loaded structure embedded in the soil medium, e.g., in case of energy piles, temperature changes imply thermal expansion and contraction of the pile as well as the surrounding soil. Therefore, proper prediction of temperature changes in the soil is of primary importance.

In the paper, numerical simulations are performed in order to visualize how the aforementioned factors affect the distribution of temperature around the pipeline which is thermally loaded with respect to assumed temperature–time path. The structure is embedded in a homogenous subsurface; computations are performed for different values of thermal conductivity of soil resulting from various contents of quartz. The effect of water is also investigated. Different states of saturation, i.e., dry soil, 50% saturation, and fully saturated soil, are also investigated. In addition, the weak coupled problem, transient water and heat transport, is solved. Then, the pipeline is assumed to be located in the area of vadose zone, so the changes of saturation degree in time imply the variation of the soil thermal conductivity.

The paper is organized as follows. In Section 2, existing models estimating the conductivity of solid phase are presented. Next, some empirical and theoretical models estimating overall soil conductivity of soils are provided. The results of numerical simulations showing the effect of solid conductivity as well as water content on the temperature distribution in the vicinity of thermally loaded structure are provided in Section 4. Here, the results are also discussed. Final conclusions end the paper.

2. THERMAL CONDUCTIVITY OF SOLID PHASE

Soil is a porous material composed of a skeleton (solid phase, usually referred to as the matrix) and pore space that is occupied by air and/or water. The conductivities of air and water are generally known, and can be easily evaluated for different temperature ranges. Thermal conductivity of solid phase varies from soil to soil, e.g., depending on the mineral composition of skeleton. Furthermore, there is no laboratory method allowing direct measurement of this parameter. Thus, thermal conductivity of solid phase is usually estimated using empirical or theoretical models. A brief review of existing models is provided below.

Gemant (1952) proposed the linear relation between thermal conductivity of the solid phase, λ_s, and the volumetric proportion of clay in the soil solids, ϕ_{Cl}, i.e.:

$$\lambda_s = -3.3 \cdot \phi_{Cl} + 5.84 \tag{1}$$

Equation (1) lacks the conductivity of quartz, so it is quite commonly known that it gives too small a value for quartz sand by about 25% (Farouki, 1981).

Johansen (1975) proposed the geometric mean model for the estimation of solid conductivity based on the quartz content:

$$\lambda_s = \lambda_q^{\phi_q} \lambda_o^{1-\phi_q} \tag{2}$$

where ϕ_q denotes the quartz content of the total solids content and λ_q and λ_o are the thermal conductivities of quartz and other soil forming minerals, respectively. Johansen assumed that the conductivity of quartz is λ_q = 7.7 $Wm^{-1}K^{-1}$ and that of other soil forming minerals should be established with respect to the following condition:

$$\lambda_o = \begin{cases} 3.0 & \text{if} \quad \phi_q \le 0.2 \\ 2.0 & \text{if} \quad \phi_q > 0.2 \end{cases} \tag{3}$$

The use of Eq. (3) requires the recognition of mineral composition of soil, and the volume fraction of quartz, in particular. It is the reason for commonly used simplification, namely the assumption, that quartz content is "more or less" equal to the sand content, ϕ_{Sa} (cf. Peters-Lidard et al., 1998; Lu et al., 2007; Różański and Stefaniuk, 2016b). With this assumption Eq. (2) takes the form:

$$\lambda_s = \lambda_q^{\phi_{Sa}} \lambda_o^{1-\phi_{Sa}} \tag{4}$$

In previous author's work (Różański and Stefaniuk, 2016a) it was found that solid conductivity can be estimated using the information on the microstructural, intrinsic soil property, namely the specific surface area (*SSA*). The relation between λ_s and *SSA* was postulated to be characterized by the modified power function:

$$\lambda_s = a_1 \cdot a_2^{SSA} + a_3 \tag{5}$$

where a_1, a_2, a_3 are the parameters to be fit. The empirical model was established based on thirty-four laboratory measurements of thermal conductivity performed on silt and clay soils. The values of fitting parameters are: $a_1 = 5.7$, $a_2 = 0.988$, $a_3 = 2.0$. The basis for evaluation of Eq. (5) is, in some sense, similar to the proposition of Gemant – Eq. (1). The latter one is based on the fact that the conductivity of clay minerals is relatively small (e.g., compared to the conductivity of quartz). So, it is evident that as the content of clay minerals is increasing the conductivity of solid phase should decrease. On the other hand, although the clay minerals have small sizes, their shape is platy and therefore it is the reason why they mainly contribute to the overall value of specific surface area. One can expect the following relation: the greater the value of *SSA* the greater the content of clay minerals. Therefore, a higher value of SSA corresponds to the higher content of clay minerals, and, consequently, to lower values of solid conductivity, as it is revealed by Eq. (5). The practical use of Eq. (5) is, however, limited – the assessment of *SSA* is not a common practice and the model was validated for small number of data.

It is evident that even the same minerals can possess their own unique internal structure resulting in different values of thermal conductivity. For example, the quartz minerals has the highest thermal conductivity among all the soil minerals, however, as reported by Clauser and Huenges (1995), the thermal conductivity of quartz minerals might be in the range from 6 to 11 $\mathrm{Wm^{-1}K^{-1}}$. It was the motivation for the application of the random field theory and modelling the thermal conductivity as a random variable, with prescribed probability density function (Różański and Stefaniuk, 2016b). Furthermore, the effect of organic matter content (whose conductivity is relatively small (Bristow, 2002), i.e. 0.25 $\mathrm{Wm^{-1}K^{-1}}$) on solid conductivity was taken into account as well. Based on the computational micromechanics approach, the following formula for λ_s estimation was proposed (Różański and Stefaniuk, 2016b):

$$\lambda_s = \frac{a + b \cdot \phi_{OM}}{1 + c \cdot \phi_{Sa} + d \cdot (\phi_{Sa})^2}. \tag{6}$$

In the equation above a, b, c and d are fitting parameters (the values were evaluated as: $a = 3.67$, $b = -0.074$, $c = -0.006$, $d = 1.2 \times 10^{-5}$) and ϕ_{OM} is the organic matter content (in the formula above, the contents of sand and organic matter should be percentage values [%]). Utilizing own data as well as those available in literature, it was shown that predictions of overall soil conductivity are substantially improved when the solid conductivity is estimated with Eq. (6). Furthermore, estimation by Eq. (6) is efficient and, what is most remarkable, it requires information on the sand fraction and organic matter content only.

Solid conductivity is an input parameter for the majority of existing empirical or theoretical models evaluating overall soil conductivity. Selected models, available in the literature, are described in the next Section.

3. OVERALL THERMAL CONDUCTIVITY OF SOIL

Rough estimate of overall soil conductivity can be performed with the use of existing bounds. In 1912 Wiener proposed upper and lower bounds for thermal conductivity of the porous medium composed of three phases: solid, liquid and gas (Wiener, 1912). The lower bound λ^L on thermal conductivity corresponds to the series arrangement of phases, whereas the upper bound λ^U is obtained when the constituents' arrangement is parallel, i.e.:

$$\lambda^L = \left(\sum_i \frac{\phi_i}{\lambda_i} \right)^{-1} \tag{7}$$

$$\lambda^U = \sum_i \phi_i \cdot \lambda_i \tag{8}$$

where ϕ_i and λ_i are the volume fraction and thermal conductivity of i phase, respectively.

Kersten (1949) tested 19 different soils and crushed rocks and established empirical formula for estimation of overall soil conductivity in terms of moisture content, w (%), and dry density, γ_d ($\mathrm{g/cm^3}$):

$$\lambda = 0.1442 \cdot (0.9 \log w - 0.2) \cdot 10^{0.6243 \gamma_d}, \quad \text{for silts or clays} \tag{9}$$

$$\lambda = 0.1442 \cdot (0.7 \log w + 0.4) \cdot 10^{0.6243 \gamma_d}, \quad \text{for sandy soils} \tag{10}$$

Equations (9) and (10) are valid for moisture contents higher or equal to 7% and 1%, respectively.

Mickley considered the unit cube of soil as the volume composed of subdomains (columns) being a solid, water and air (Mickley, 1951). For the given direction of heat flow the contributions of each subdomain are added and the thermal conductivity for partially saturated soil is given by the following equation:

$$\lambda = \lambda_a c^2 + \lambda_s (1-a)^2 + \lambda_w (a-c)^2$$

$$+ \frac{2\lambda_w \lambda_a c(a-c)}{\lambda_w c + \lambda_a (1-c)}$$

$$+ \frac{2\lambda_s \lambda_w \lambda_a c(1-a)}{\lambda_w \lambda_s c + \lambda_s \lambda_a (a-c) + \lambda_w \lambda_a (1-a)}$$

$$+ \frac{2\lambda_w \lambda_s (a-c)(1-a)}{\lambda_s a + \lambda_w (1-a)} \tag{11}$$

The lengths a and c are calculated from the soil porosity, n, and the degree of saturation, S_r:

$$3a^2 - 2a^3 = n \quad \text{and} \quad 3c^2 - 2c^3 = n \cdot (1 - S_r) \tag{12}$$

Due to the complicated formulas, the application of Mickley equation in engineering practice is rather cumbersome.

Theoretical model proposed by De Vries (1963) assumed both solid particles and air voids are dispersed in a continuous water medium. The thermal conductivity of an unsaturated soil is given as:

$$\lambda = \frac{\sum_i F_i \cdot \phi_i \cdot \lambda_i}{\sum_i F_i \cdot \phi_i} \tag{13}$$

where factor F_i is expressed by the following relation:

$$F_i = \frac{1}{3} \sum_j \left[1 + \left(\frac{\lambda_i}{\lambda_w} - 1 \right) g_j \right]^{-1}, \quad j = a, b, c \tag{14}$$

In the equation above the g_j values, which were originally intended to be shape factors, are used rather as parameters to fit empirical data. Note that the g values sum to unity, i.e., $g_a + g_b + g_c = 1$.

Johansen (1975) expressed the thermal conductivity of partially saturated soil as a function of both thermal conductivity at saturated state (λ^{sat}) and the one at dry state (λ^{dry}):

$$\lambda = (\lambda^{sat} - \lambda^{dry}) K_e + \lambda^{dry} \tag{15}$$

where K_e is the so-called Kersten number being a function of the degree of saturation:

$$\begin{aligned} K_e &\cong 0.7 \cdot \log S_r + 1.0, \text{ for coarse soils and } S_r > 0.05 \\ K_e &\cong \log S_r + 1.0. \text{ for fine soils and } S_r > 0.1 \end{aligned} \tag{16}$$

Johansen (1975) used the following relation to estimate λ^{dry}:

$$\lambda^{dry} = \frac{0.135\rho_d + 64.7}{2650 - 0.947\rho_d} \tag{17}$$

where ρ_d is the dry density of soil, kg/m^3. It was proposed to estimate the conductivity at saturated state by the geometric mean equation:

$$\lambda^{sat} = \lambda_w^n \lambda_s^{(1-n)} \tag{18}$$

Donazzi et al. (1979) considered the dependence of the soil thermal resistivity on two parameters, namely the porosity and the saturation degree. The following relation for evaluation of soil conductivity was proposed:

$$\lambda = \lambda_w^n \lambda_s^{(1-n)} \exp[-3.08n(1-S_r)^2] \tag{19}$$

Since 1979, when the original $K_e - S_r$ relation (Eq. 16) was first published by Johansen (Johansen, 1975), the formula has undergone some important changes. Coté and Konrad (2005) proposed a new formula for Kersten number which, in addition, incorporates the soil type effect revealed by parameter κ:

$$K_e = \frac{\kappa S_r}{1 + (\kappa - 1) S_r} \tag{20}$$

The suggested values of κ are: 1.69 for silt and clay; 3.55 for median and fine sand; 4.5 for gravel and coarse sand.

Lu et al. (2007) proposed the following equation relating K_e to S_r:

$$K_e \cong \exp\{\psi[1 - S_r^{(\psi - 1.33)}]\} \tag{21}$$

where ψ is the parameter whose value depends on the soil texture, i.e., 0.96 and 0.27 for coarse- and fine-textured soil, respectively.

4. TEMPERATURE DISTRIBUTION IN THE SOIL: NUMERICAL SIMULATIONS

4.1. THE EFFECT OF SOLID CONDUCTIVITY

In Fig. 1 (left) the values of solid conductivity evaluated with Eqs. (4) and (6) are plotted against the content of sand. Since Eq. (4) does not take into account the content of organic matter, the results correspond to the case of no organic matter in the soil. In general, within full range of sand content, prediction by Eq. (6) overestimates the one obtained with Eq. (4). This is mainly due to the sudden loss of conductivity at threshold value of $\phi_{Sa} = 0.2$. It was however shown in the previous work (Różański and Stefaniuk, 2016b) that, for considered soils, better prediction of overall conductivity was obtained with the use of Eq. (6). The influence of organic matter content on the solid conductivity (using Eq. (6)) is graphically presented in Fig. 1 (right). It is evident that as the organic matter content is increasing the conductivity of solid phase is decreasing.

For practical applications, the most important is, however, how the value of solid conductivity influences the overall soil conductivity, and as a consequence, the temperature distribution in the soil, in particular situations. In order to investigate this problem the numerical simulation of unsteady-state heat conduction process (with no heat sinks or sources) is considered. The equation for the transient heat flow is:

$$C_V \frac{\partial T}{\partial t} - \nabla \cdot (\lambda \nabla T) = 0 \tag{22}$$

In the equation above t represents time, T is the temperature field and C_V is the volumetric heat capacity [Jm^{-3} K^{-1}]. Geometry of the model and the FE mesh are presented in Fig. 2 (left). The model represents a portion of the homogenous soil at relatively large depth – so, it is assumed that on the external boundary of the model the temperature is constant and equal to 10°C. In the center of the model there is a circular (radius $R = 0.5$ m) pipeline modelled as a void whose boundary is thermally loaded according to the T–t path, as shown in Fig. 2 (right). The initial value

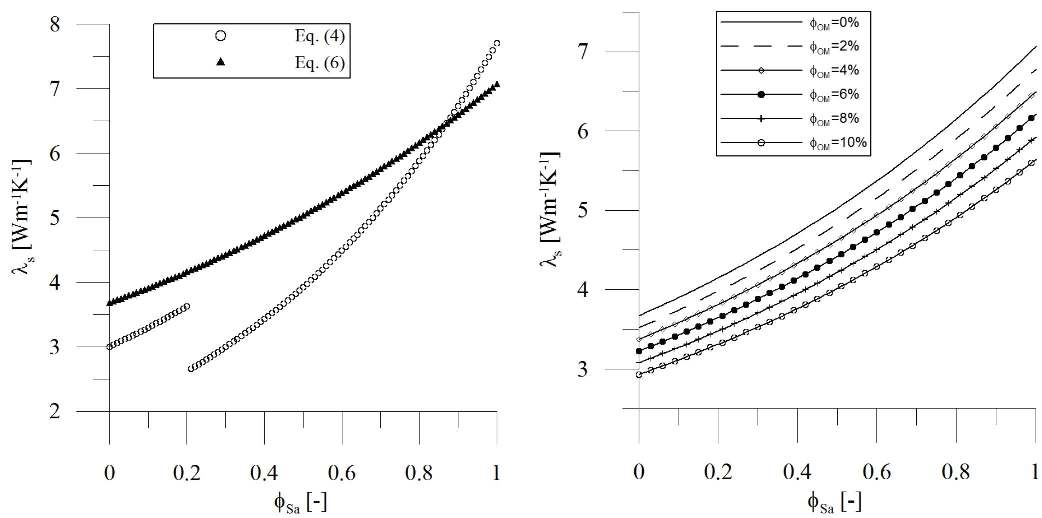

Fig. 1. Solid conductivity vs. content of sand with respect to:
(left) Eqs. (4) and (6) and no organic matter;
(right) Eq. (6) and different values of organic matter content (0–10%)

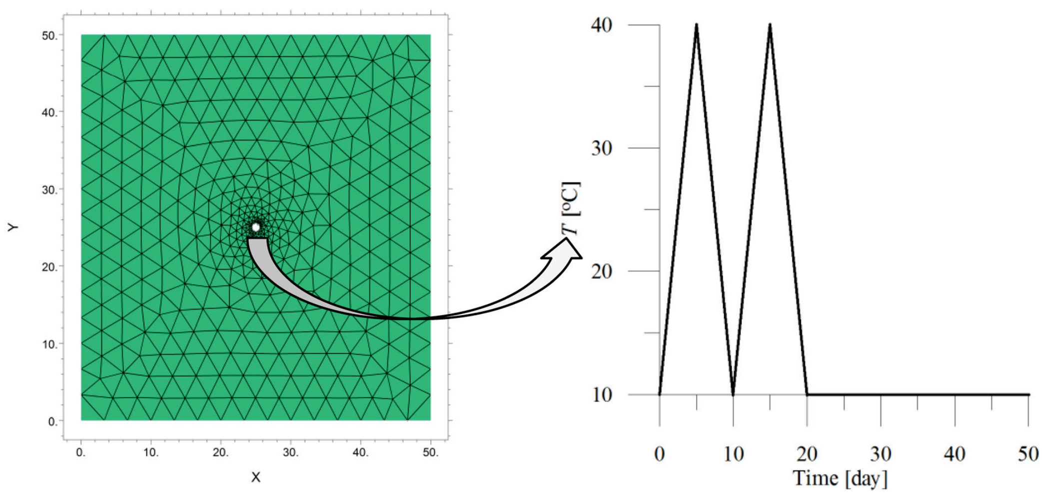

Fig. 2. Left: geometry and 2D mesh discretization of the model.
Right: varying in time boundary condition applied to the circular void

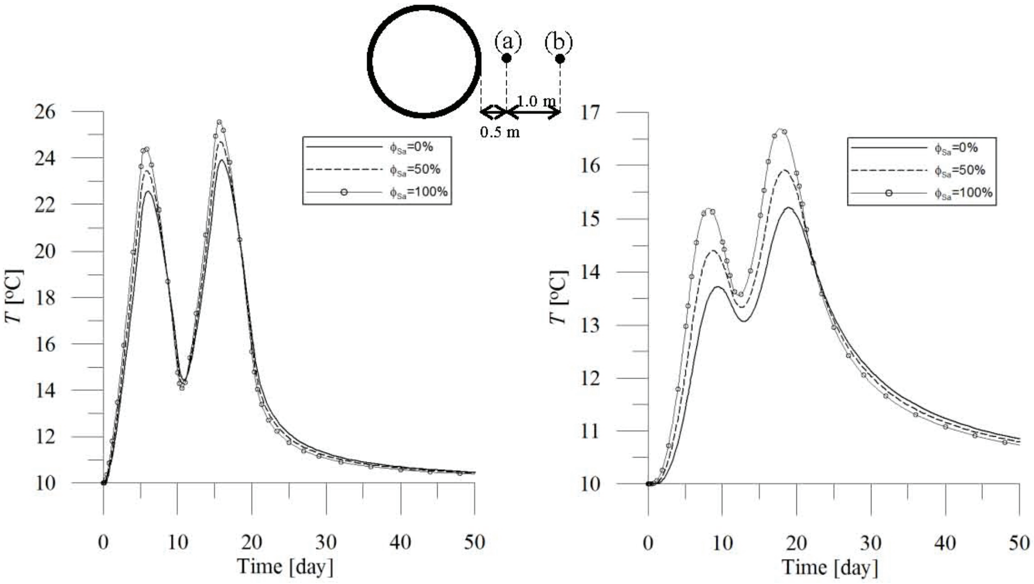

Fig. 3. Temperature distribution vs. time for different contents of sand.
Left: reference point (a), right: reference point (b)

of temperature in the soil is consistent with external boundary condition, $T(t = 0) = 10$ °C.

The simulations are carried out for three different values of sand content, i.e., 0, 50 and 100%. The solid conductivity is evaluated with the use of Eq. (6) – the case of no organic matter content is considered. It is assumed that the soil is partially saturated ($S_r = 0.5$) and its conductivity is estimated by Johansen approach (Eqs. (15) and (21)). Thermal conductivity at dry state is therefore evaluated by Eq. (17); dry density is ρ_d = 1900 kg/m^3. Conductivity of fully saturated soil is estimated with respect to Eq. (18). The values of remaining properties are: conductivity of water λ_w = 0.6 Wm^{-1}K^{-1}, porosity n = 0.1 and volumetric heat capacity C_v = 1.4*10^6 Jm^{-3} K^{-1}.

The results of numerical simulations are shown in Fig. 3 – left portion corresponds to the temperature distribution at point (a) whereas in the right panel the results for point (b) are shown. Localizations of these reference points (a and b) are shown in the top part of Fig. 3 (note that the problem under consideration is axially symmetrical, so at each point at distance 0.5 or 1.5 m from the void, the temperature distribution is the same). Observing the results we can notice the influence of sand content on temperature distribution in the vicinity of the thermally loaded void. The higher the content of sand the higher the peak values of temperature. Moreover, the differences between temperature distributions are more evident for the case of point (b) – it is reasonable, since the closer the "heat source", the influence on temperature distribution should vanish.

4.2. THE EFFECT OF SATURATION DEGREE

As mentioned earlier, beyond the conductivity of solid phase, another fundamental factor influencing the overall conductivity of soil is water content, usually defined in terms of degree of saturation. Again, the same problem as in Fig. 2 is considered; this time, however, the temperature distributions at points (a) and (b) are evaluated for three different values of S_r, i.e. 0, 50 and 100%. The solid conductivity is evaluated assuming that ϕ_{Sa} = 50% and ϕ_{OM} = 0%. The results of numerical calculations are shown in Fig. 4. As previously, left panel of the graph corresponds to point (a), whereas right portion of Fig. 4 presents results for point (b).

The results reveal significant influence of water content on the temperature distribution in the vicinity of the thermally loaded boundary. Similarly to the previous example, the more evident influence of this factor is in the case of point (b). Moreover, for both points, (a) and (b), one can notice the more significant difference between temperature values obtained for $S_r = 0$ and $S_r = 0.5$, than between $S_r = 0.5$ and $S_r = 1.0$. This is due to fact that the rate of increase of soil conductivity is much larger within S_r interval from 0 to 0.5 than from 0.5 to 1.0. This characteristic, for the considered soil, is graphically presented in Fig. 5 – overall conductivity is evaluated with the use of Eqs. (15) and (21).

Numerical results presented above are carried with assumption that the distribution of degree of saturation

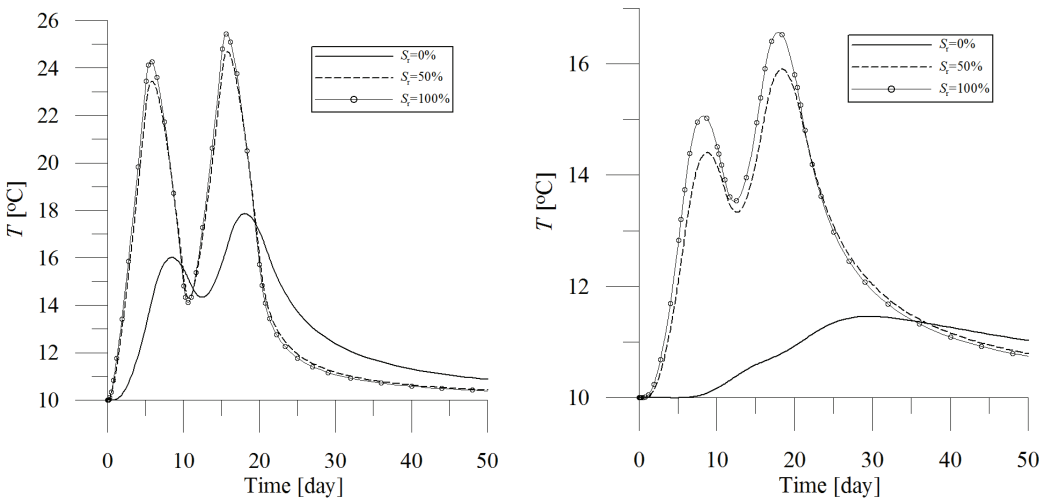

Fig. 4. Temperature distribution vs. time, at different degrees of saturation.
Left: reference point (a), right: reference point (b)

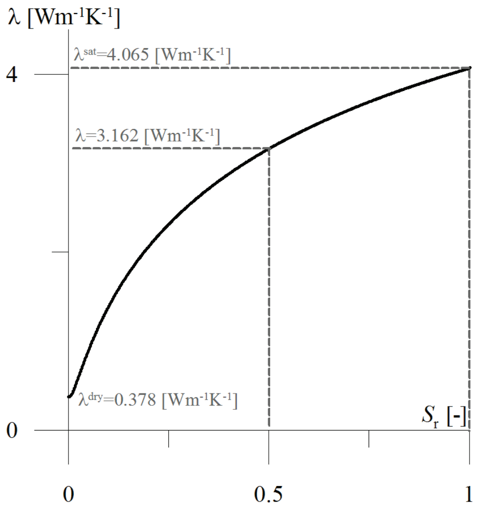

Fig. 5. Overall soil conductivity vs. degree of saturation – Eqs. (15) and (21)

is homogenous within the soil. Such an assumption is obviously far from real conditions where two distinct zones are usually distinguished, i.e., phreatic and vadose zone. One can simply imagine that the existence of these two zones can significantly influence the temperature distribution, particularly if the thermally loaded structure is in the neighborhood of the transition zone from full to residual saturation. In order to visualize this effect, another numerical simulation is performed – weak coupled problem (in the sense defined in Hameyer et al., 1999) of heat and water flow is considered. Hence, the previously analyzed heat flow problem is supplemented with the transient state form of water flow equation:

$$n\frac{\partial S_r}{\partial t} - \nabla\cdot(k\cdot\hat{k}\cdot\nabla(h+y)) = 0 \qquad (23)$$

where k is Darcy's permeability coefficient, h is the hydraulic head, y is the local altitude and $\hat{k} = S_r^3$ is the permeability reduction factor. Utilizing Richard's (1931) hypothesis on the continuity of gas phase in vadose zone, a saturation degree, S_r, above the water table is evaluated with respect to van Genuchten (1980) model (assuming zero value of residual saturation):

$$S_r(h) = \left[\sqrt{(1+(1-\mathrm{H}(h))\cdot(\alpha\cdot|h|)^2}\right]^{-1} \qquad (24)$$

In the equation above H(h) is the Heaviside's function and α is the parameter of the model (it is a measure of thickness of transition from full to residual saturation and its value depends on the soil texture).

The coupled problem under consideration is therefore characterized by the system of equations, (22) and (23). Geometry of the model is the same as for previously investigated examples (Fig. 2); the same goes for soil thermal and physical properties as well as boundary conditions and initial values for the heat flow. The boundary conditions, for the water flow, are as follows: on the top and bottom edge of the domain (presented in Fig. 2) no flow is assumed and on the side edges (left and right) the imposed pressures are compatible with water table level, namely y = 20 m. The initial value of h is consistent with the boundary conditions applied to left and right edge of the domain (water table at y = 20 m). The water flow is induced by changing the water table level at the right side of the domain. This change is performed with respect to the water table–time path presented in the left portion of Fig. 6. The value of Darcy's permeability

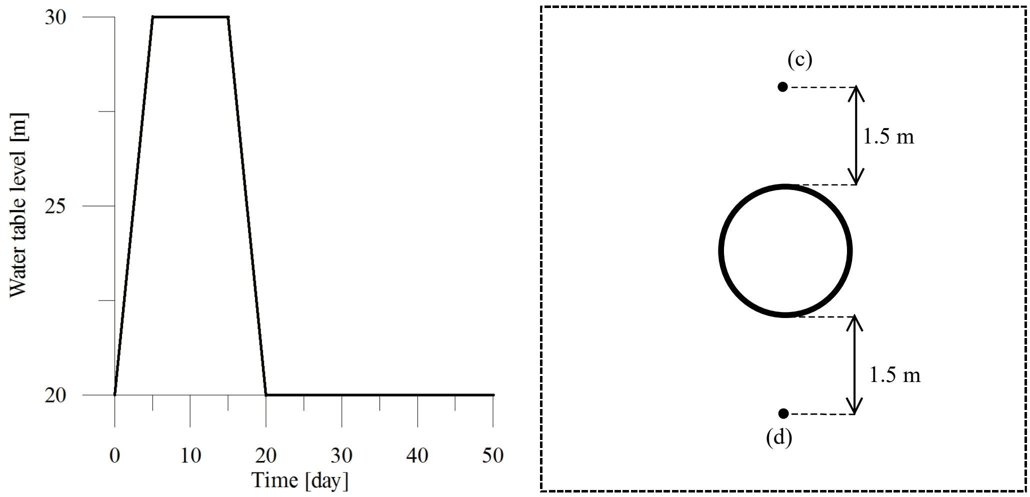

Fig. 6. Left: water table level vs. time (varying in time boundary condition applied to the right side of the domain). Right: localization of reference points (c) and (d)

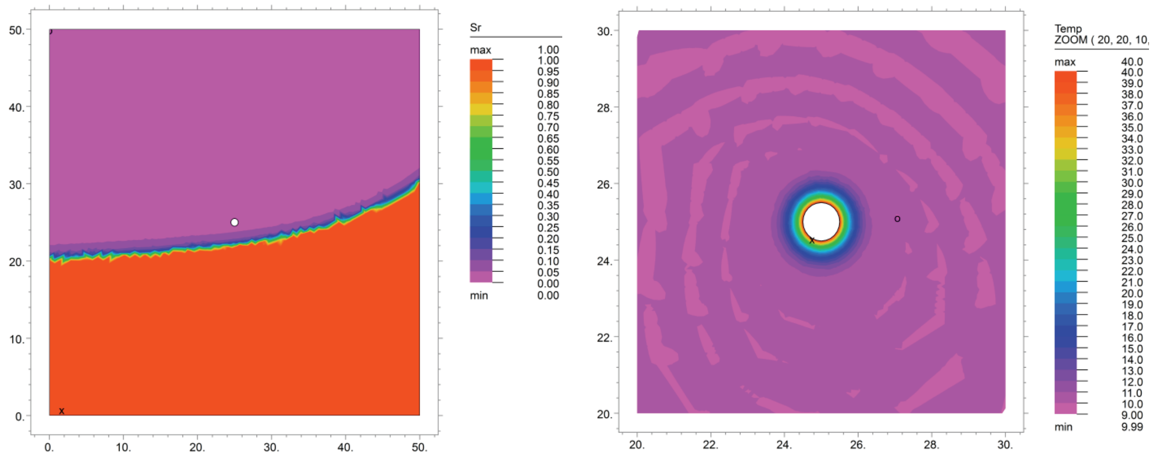

Fig. 7. Distribution of saturation degree S_r [–] (left panel) and temperature T [°C] (right panel) after 5 days

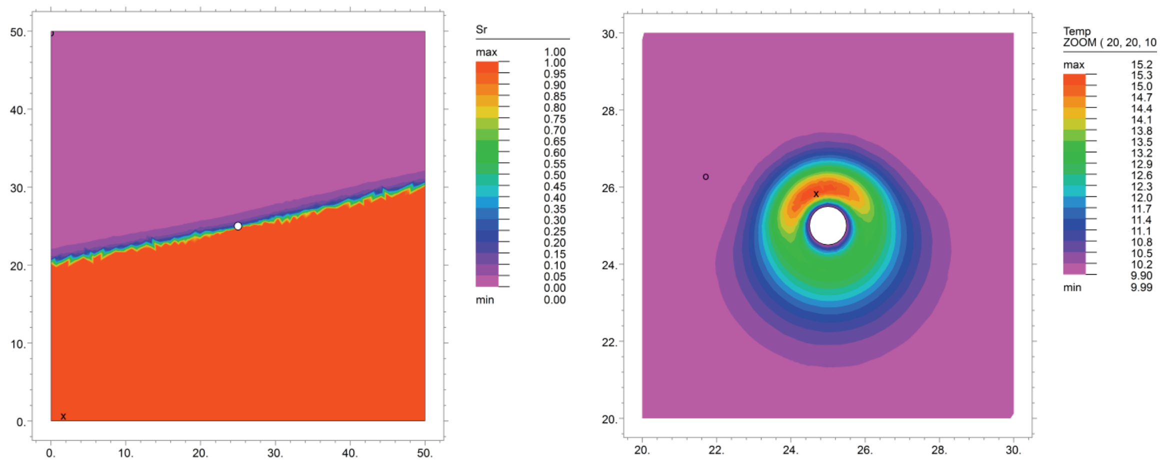

Fig. 8. Distribution of saturation degree S_r [–] (left panel) and temperature T [°C] (right panel) after 10 days

coefficient is k = 5.0*10^{-6} m/s and the parameter for van Genuchten model is α = 10 m^{-1}. At each time step, the system of Eqs. (22) and (23) is solved, and then according to the current degree of saturation, the overall soil conductivity is updated with respect to Eqs. (15) and (21). The localization of reference points (c and d), in which the temperature changes are observed, is presented in right panel of Fig. 6.

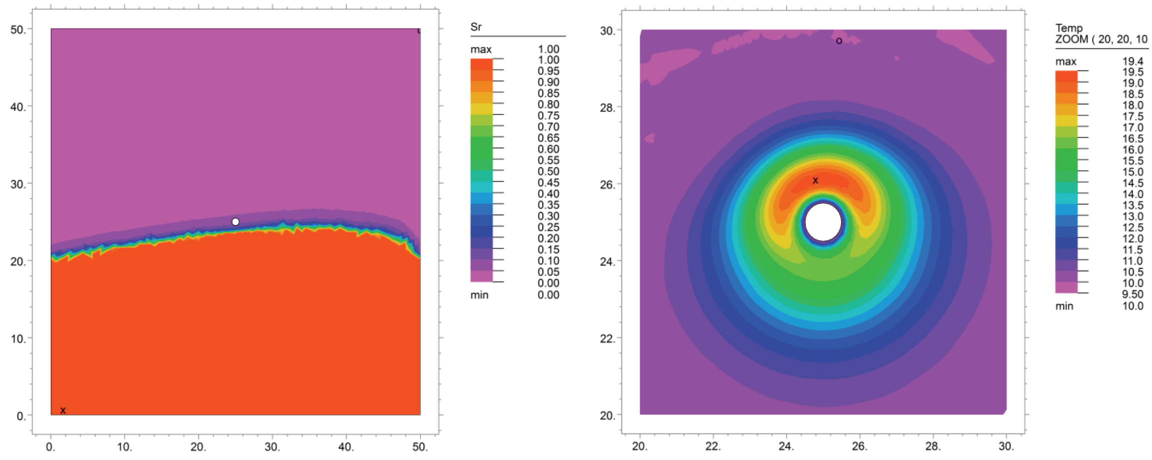

Fig. 9. Distribution of saturation degree S_r [–] (left panel) and temperature T [°C] (right panel) after 20 days

In Figs. 7–9 the contour plots of the saturation degree (left panel) and the temperature (right panel) at different time steps (5, 10 and 20 days, respectively) are shown. Since the saturation degree influences current soil thermal conductivity the temperature distribution is no more (compared to the previously investigated examples) axially symmetrical. Detailed results for the reference points, (c) and (d), are presented in Figs. 10 and 11.

In particular, in the left portion of Fig. 10 the change of saturation degree in time is presented. The results for point (c), which is located 1.5 m above the pipeline, is represented by the continuous line; dashed line corresponds to the results obtained for point (d), the one located 1.5 m below the pipeline. Maximum value of S_r, for point (c), is obtained after 16 days; it is around 0.07; it implies the maximum value of local thermal conductivity coefficient 1.11 $Wm^{-1}K^{-1}$. In point (d), the full saturation occurs in the time interval, 6–21 days. Within this time period the thermal conductivity obtains its maximum value, namely 4.07 $Wm^{-1}K^{-1}$.

The changes of temperature in time are shown in the left panel of Fig. 11. We observe quite significant influence of saturation degree fluctuations on the distributions of temperature at considered points (c) and (d). The peak values of temperature occur at different times. Furthermore, in the time interval, 0–20 days, the temperature is higher at point (d), while after 20 days the opposite situation is observed.

In the right portion of Fig. 11 the absolute difference of temperature at points (c) and (d), $|\Delta T|$ [°C], is plotted against time. The maximum difference between temperatures is around 2 °C. Furthermore, significant variations of $|\Delta T|$ in time are observed. These variations are due to both thermal loading of the void

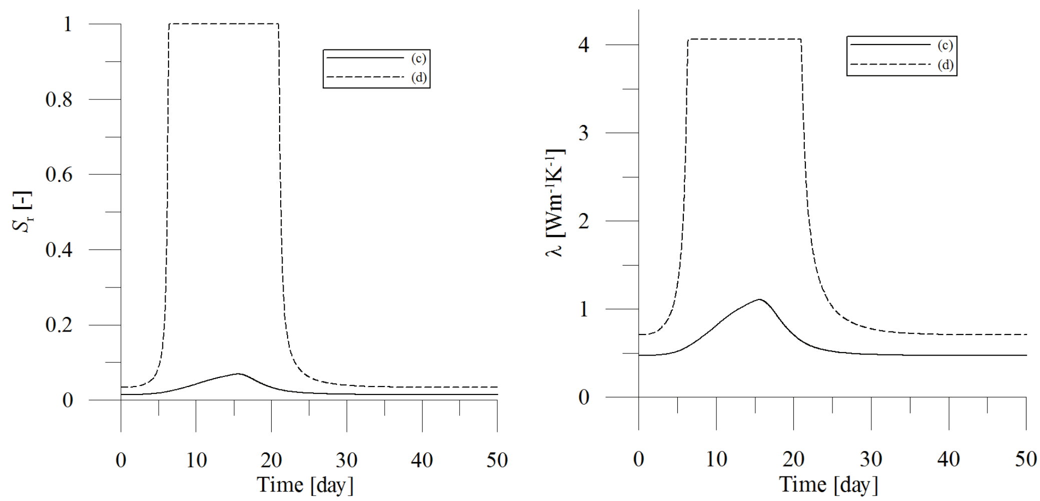

Fig. 10. Changes of saturation degree (left panel) and thermal conductivity (right panel) in time at reference points (c) and (d)

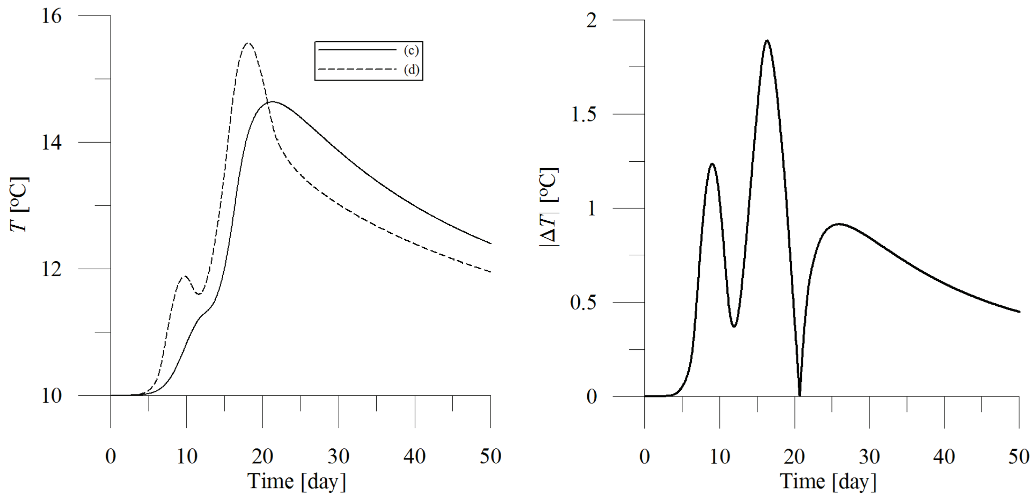

Fig. 11. Left: Temperature vs. time at reference points (c) and (d).
Right: the absoulte difference of temperatures at points (c) and (d) vs. time

as well as saturation degree changes caused by the water flow, which is induced by the gradient of hydraulic head.

5. CONCLUSIONS

It is commonly known that the greatest influence on the soil conductivity is due to the mineral composition of solid phase as well as the degree of saturation. Recent models estimating the conductivity of solids take into account the contents of quartz and organic matter; it is due to fact that these components are characterized by highest and lowest conductivity, respectively, among all constituents forming soil skeleton. As indicated earlier, the content of quartz is very often assumed to be equal to the content of sand. The degree of saturation directly influences the overall soil conductivity – thermal conductivities of dry and saturated soil can differ even by one order of magnitude. From the point of view of engineering applications, it is important not only how these factors affect the value of overall soil conductivity, but primarily, how they influence the distribution of temperature in the soil. For that purpose numerical simulations of thermally loaded pipeline embedded in a homogeneous soil were carried out. The following conclusions can be drawn from the present study:

i. Sand as well as organic matter contents in the soil solids significantly influence the conductivity of solid phase. Equation (4), i.e., the geometric mean model, does not take into account the organic matter and it exhibits sudden loss of conductivity at 20% of sand content. It was shown in the work of Różański and Stefaniuk (2016b) that Eq. (6) gives better agreement with measured values, compared to the results evaluated with the use of Eq. (4).
ii. Numerical simulations showed that, depending on the content of sand, the difference between temperatures, registered in the vicinity of thermally loaded pipeline, can reach around 10% – comparing the cases of no sand and 100% of sand content. The calculations were performed with assumption that there is no organic matter in the solid phase.
iii. Calculations for the soil treated as a homogeneous medium with prescribed value of saturation degree showed a significant effect of water content. At extreme cases, i.e., dry and fully saturated soil, the difference in temperature values can reach even 40%. This effect disappears fairly quickly with the increase in the degree of saturation. It is triggered by the high rate of increase of soil conductivity within S_r interval from 0 to 0.5 (Fig. 5).
iv. A weak–coupled problem showed significant effect of localization of the pipeline (or any thermally loaded structure) in the area of vadose zone on the temperature distribution. Water flow implies local changes of thermal conductivity coefficient. It strongly influences temperature distribution in reference points located 1.5 m below or above the pipeline – the relative difference reached 15%. Therefore, fluctuations of the water table in time are also recognized as important factor influencing distribution of temperature in the vicinity of thermally loaded structure.

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