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Relating thermal conductivity of soil skeleton with soil texture by the concept of "local thermal conductivity fluctuation"

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ABSTRACT

The thermal conductivity of the soil skeleton λ_s is an essential parameter from the point of view of the correct assessment of soil overall/effective conductivity. This work introduces the concept of "local thermal conductivity fluctuation" which characterizes the microscale variation of conductivity within the solid phase. It is proposed to link the "local fluctuation" of thermal conductivity λ with the soil texture − the information that is available at the scale of engineering applications. It was possible to relate the skeleton thermal conductivity with the grain size distribution of the soil. Finally, based on a large series of numerical simulations, the paper provides four triangle diagrams (at different organic matter contents: 0%, 2%, 4% and 6%) relating the value of λ_s with volume fraction of individual soil separates. This result is extremely important from the practical point of view. One can quickly evaluate λ_s value provided that information on the grain size distribution and organic matter content is available.

1. Introduction

It is commonly known that an accurate estimate of skeleton thermal conductivity (λ_s) has a marked effect on the evaluation of overall soil conductivity within the full range of water saturation (e.g. Cosenza et al., 2003; Różański and Stefaniuk, 2016a, b). In other words, incorrectly estimating the value of λ_s implies a significant error in overall soil thermal conductivity prediction. All existing models, both empirical (e.g. Kersten, 1949; Johansen, 1975; Donazzi et al., 1979; Côté and Konrad, 2005; Lu et al., 2007; 2014; Chen, 2008) and theoretical ones (e.g. Mickley, 1951; Gemant, 1952; Webb, 1956; de Vries, 1963; Gori, 1983; Tong et al., 2009; Haigh, 2012; Corasaniti and Gori, 2017; He et al., 2017; Chu et al., 2019; Jia et al., 2020) usually treat the soil skeleton as a homogeneous medium characterized by a unique value of conductivity, thus they do not take into account the heterogonous nature of solid phase, which is revealed at microscale. On one hand, it is an appropriate approach since at the scale of engineering applications (macroscale), the soil skeleton can be treated as a homogeneous material. On the other hand, presuming its conductivity for engineering applications, one should consider the influence of microheterogeneity (with respect to both geometry and thermal conductivity variation within the skeleton) on the macroscopic response of the material.

In previous efforts conducted by researchers (Łydżba et al., 2014, 2017; Różański and Stefaniuk, 2016a; Stefaniuk et al., 2016), some attempts were made in order to formulate new approach for evaluation of λ_s value in the framework of micromechanics, taking into account the random and heterogeneous nature of soil skeleton at microscale. In the current paper, those results are systemized and used to introduce the concept of "local thermal conductivity fluctuation". This is then associated with the information on the soil that is available in practice (at the scale of engineering applications), i.e. the soil texture. As a result, it is possible to assess the variability of the thermal conductivity coefficient within the skeleton at the micro level, only on the basis of information from the macro level, i.e. soil texture. The concept of "local thermal conductivity fluctuation" can be then utilized in any model, either empirical or theoretical, for overall soil conductivity assessment. In this paper, this concept is applied to the computational micromechanics approach proposed by Łydżba et al. (2017) and a series of numerical simulations is performed. As a result, thermal conductivity of the skeleton is calculated for different soil textures and organic matter contents (0%–6%). This enabled the creation of triangular plots showing the value of λ_s in relation to the soil

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texture. This result is extremely important from the point of view of engineering applications – it allows one to quickly estimate the value of λ_s provided that the information on grain size distribution and organic matter content is available.

In what follows, the importance of skeleton thermal conductivity as well as difficulties in its estimation is discussed. This leads to the formulation of the problem analyzed in this work. Fig. 1 shows the overall thermal conductivity plotted against the degree of saturation S_r, which illustrates how important the proper estimation of λ_s is. In particular, Fig. 1a–c presents λ-S_r relation for coarse-textured soils (sand), and the remaining plots (Fig. 1d–f) represent the results for fine-grained soils (clays). The dots in the graph represent measured values from Lu et al. (2007). For each case (Fig. 1a–f), the overall thermal conductivity is predicted using the model proposed by Lu et al. (2007) at different values of λ_s, i.e. calculated by Gemant (1952)'s and Johansen (1975)'s approaches. The former predicts the value of λ_s based on the percentage of clay (Cl) in the soil solids:

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

whereas the latter uses the information on the content of quartz minerals (q) and its conductivity λ_q:

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

For computational purposes, Johansen (1975) assumed that the conductivity of quartz is $\lambda_q = 7.7$ W/(m K) and that of other soil

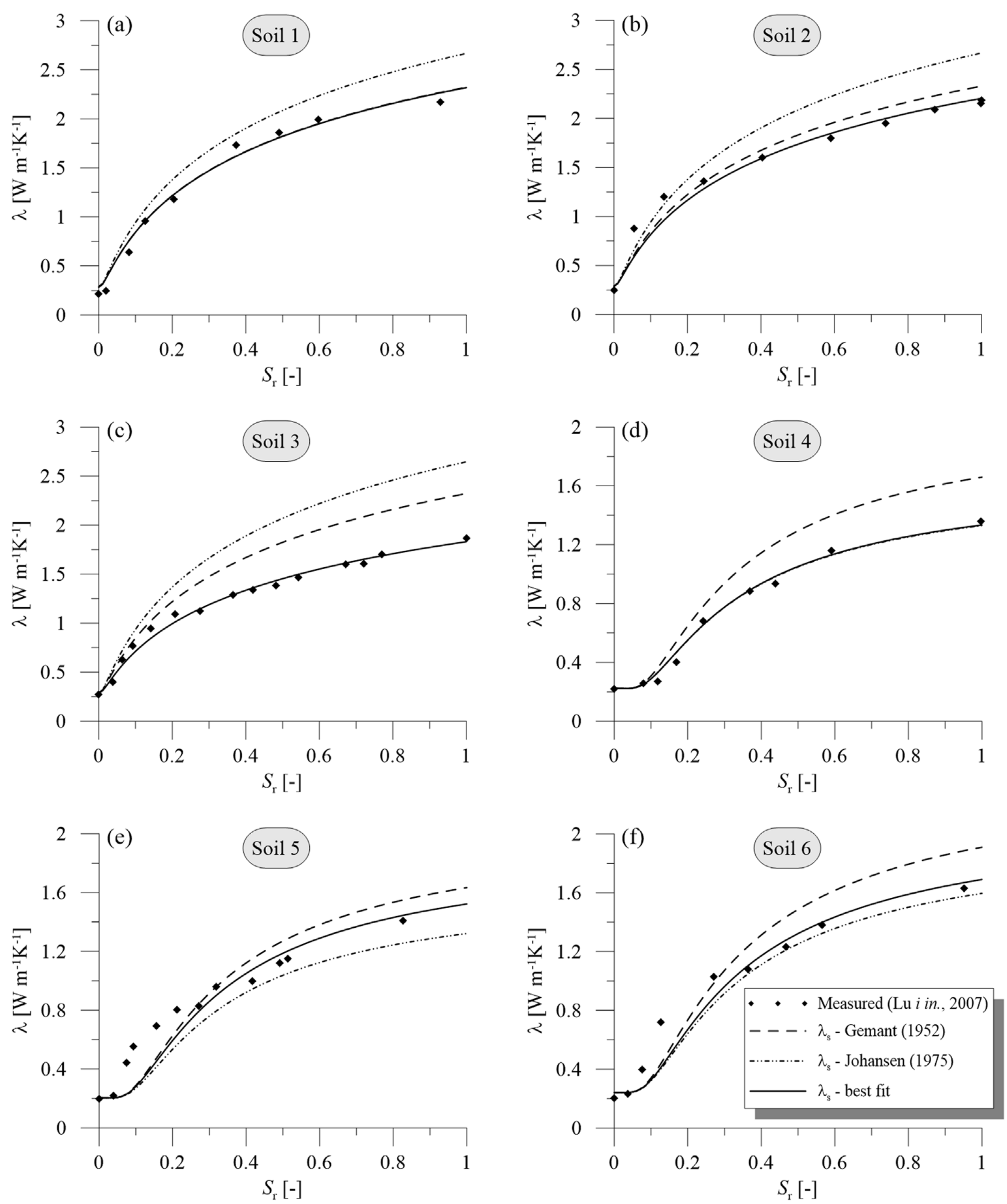

Fig. 1. Thermal conductivity against degree of saturation S_r for three different values of skeleton thermal conductivity (measurement results from Lu et al., 2007).

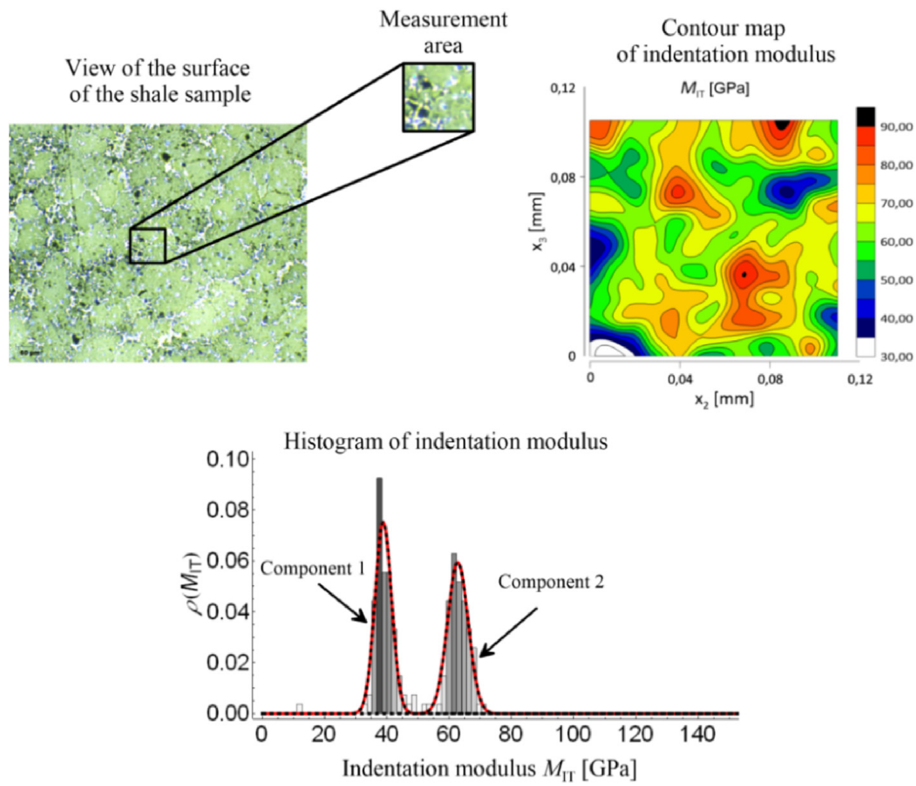

Fig. 2. Results of nanoindentation tests for shale sample. ρ is the probability density.

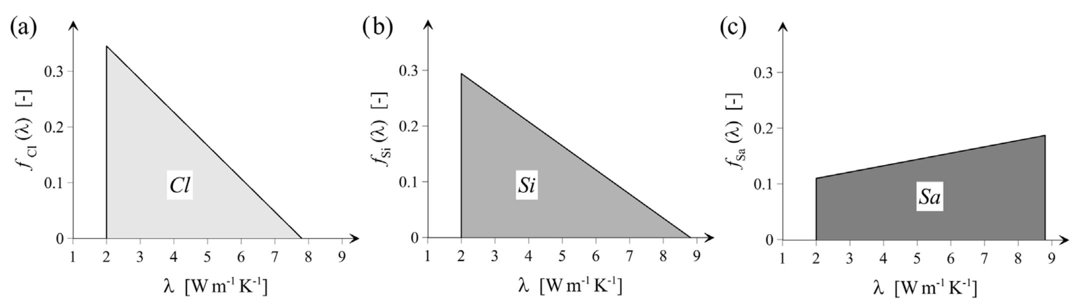

Fig. 3. Probability density functions obtained as a solution of homogenization inverse problem: (a) Clay separate, (b) silt separate, and (c) sand separate (Stefaniuk et al., 2016).

forming minerals is $\lambda_o = 2$ W/(m K) for $q > 0.2$ and $\lambda_o = 3$ W/(m K) for $q \leq 0.2$.

Additionally, for the purposes of these analyses and in order to better understand the significance of this parameter (skeleton conductivity), for each of the six considered soils (Fig. 1), the λ_s value was also determined (using the least squares method) that provides the best fit of Lu et al. (2007)'s model to the measured values. This result is presented in Fig. 1 by a solid line. It can be seen that assumed value of λ_s strongly influences λ-S_r relation within entire range of saturation degree. Therefore, the proper estimation of λ at given degree of saturation is strongly affected by appropriate prediction of λ_s. What is even more important, the models used to determine the value of skeleton conductivity very often give significantly different results, e.g. in the case of soil No. 5, $\lambda_s = 5.48$ W/(m K) and $\lambda_s = 3.43$ W/(m K), according to the Gemant's and Johansen's models, respectively. At the same time, the best fit value is $\lambda_s = 4.69$ W/(m K). Taking into account soil No. 3 (sand), it can also be observed that λ_s values are not only far from each other, but most of all from the value ensuring the best fit to measurements: $\lambda_s = 5.64$ W/(m K) and $\lambda_s = 7$ W/(m K), according to the Gemant's and Johansen's approaches, respectively, and the best fit value is equal to $\lambda_s = 3.81$ W/(m K). However, in some cases, these approaches can also provide satisfactory results. Note that for soils Nos. 1 and 4, Gemant's and Johansen's approaches lead to well predictions (in Fig. 1a and d, the solid and dashed/dash-dotted lines almost overlap).

The above analyses, limited to the Gemant's and Johansen's methods, confirm what is commonly known, namely, none of the approaches used in practice to determine the thermal conductivity of a soil skeleton can be described as universal/versatile, i.e. one method that estimates the value of λ_s well, regardless of the type of soil (Różański and Stefaniuk, 2016a). Some of the approaches only work well for selected soil types, while for others, they give incorrect estimates (He et al., 2020). This is because, first, each method uses different soil information to estimate the thermal conductivity of the soil skeleton, and second, the soil information used in each approach appears to be insufficient to provide a good λ_s prediction, regardless of soil type.

On the other hand, a good prediction of solid conductivity can be calculated based on the mineralogical information with the geometric mean model (Woodside and Messmer, 1961):

$$\lambda_s = \prod_j \lambda_{mj}^{\varphi_j} \tag{3}$$

where λ_{mj} is the thermal conductivity of j-th mineral and φ_j is its volume fraction. However, the main problem of such an approach is that information about "full" mineral composition is very rarely available in practice. This is due to the fact that soil mineralogy is not easily available and requires the use of special instruments such as X-ray fluorescence (XRF) and X-ray diffraction (XRD) (Schönenberger et al., 2012; Nikoosokhan et al., 2016). Another demerit of geometric mean model (Eq. (3)) lies in the uncertainty in thermal conductivities of individual minerals — even the same minerals can have their own unique internal structure resulting in the scatter of thermal conductivity. This is also in the context of internal anisotropy with respect to conductivity (Jorand et al., 2013). Clauser and Huenges (1995) reported possible scatter of the thermal conductivity of quartz as 6–11 W/(m K). Therefore, even for deterministic mineral thermal conductivity, it still needs careful interpretation based only on mineralogical information to determine the thermal conductivity of soil/rock matrix (Fuchs and Förster, 2010).

Another inconvenience with relation to evaluation of λ_s value is that soil solid thermal conductivity cannot be measured directly. It is impossible to directly measure λ_s because soil is a porous material and it is not possible to compact the grains to create a perfectly continuous solid body without porous space. A possible solution may be based either on advanced experimental techniques allowing measurement of the properties of small parts of the material (like nanoindentation or micropillar compression for evaluation of elastic properties) or on the solution for inverse problems. For example, Chu et al. (2018) proposed to use harmonic approach between series and parallel thermal resistance models to inversely calculate the conductivity of the solid matrix of selected geomaterials. Łydżba et al. (2021) proposed a new methodology for evaluation of thermal (or electrical) conductivity of the skeleton of a porous material with known porosity from the measurements of the effective conductivities of this material saturated with several conductive liquids. The latter approach is based on the concept of "equivalent microstructure" (Łydżba et al., 2018).

2. The concept of local thermal conductivity fluctuation

Let us begin our further considerations by reminding us that, depending on the scale of observation, practically every material may be characterized by a more or less distinct heterogeneity of its internal structure. As a consequence, it may cause, at individual

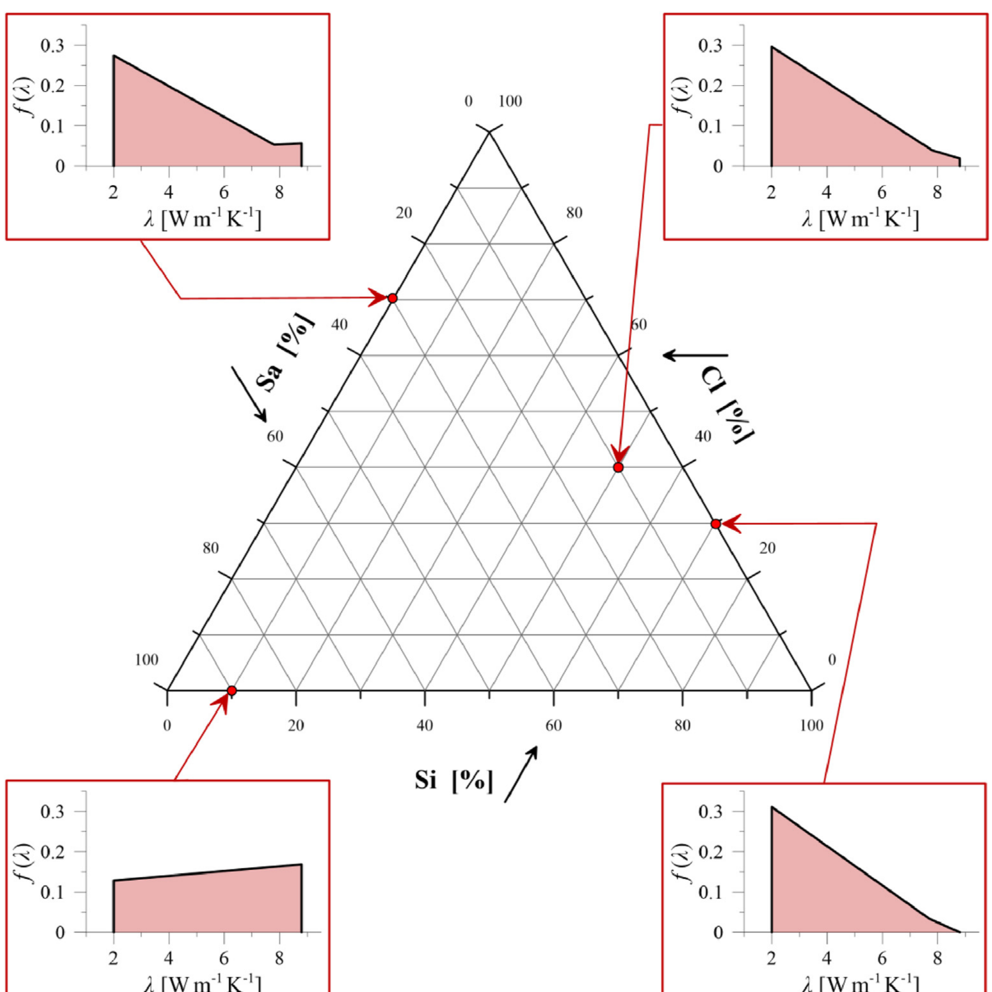

Fig. 4. Local thermal conductivity fluctuation of the soil associated with its texture via the soil texture triangle.

levels of observation, certain fluctuations in mechanical parameters directly associated with the morphology of the microstructure, and thus with the spatial arrangement of individual components of the medium. This can be observed using advanced experimental techniques allowing measurement of the properties of small parts of the material in different scales, e.g. nanoindentation tests (Bobko and Ulm, 2008). Fig. 2 presents exemplary results (contour plot and histogram of indentation modulus) of nanoindentation tests conducted for rock material, namely shale.

It can be noticed that on the microscale, the studied rock material is characterized by significant fluctuations in the indentation modulus. Let us also pay attention to the fact that the histogram of the indentation modulus shows a bimodal character, which clearly suggests that two separate components can be distinguished in the examined microstructure. Moreover, it should be noted that even within the individual components, i.e. 1 or 2, there is a distinct scatter in the value of the indentation modulus. Hereafter, such fluctuation of the value of mechanical parameter on a microscale, as illustrated here, will be referred to as “local variability” or, equivalently, “local fluctuation".

Obviously, the considerations presented above concern the case of local variability of mechanical parameters determined in the nanoindentation test. However, due to the complex mineralogical composition of the soil as well as the wide range of thermal conductivity of minerals forming the skeleton (even within individual minerals, there is a certain fluctuation, e.g. Côté and Konrad, 2005), it is justified to assume that on the microscale, the soil skeleton is a strongly heterogeneous medium. In other words, the thermal conductivity of soil skeleton reveals local fluctuations, i.e. it changes “from point to point” within the microstructure.

As a consequence of the above analysis, it seems natural to treat thermal conductivity at this level of observation (microscale) as a random variable characterized by a certain probability density function (PDF). However, a primary task is combining this microstructure information with that available at the scale of engineering applications. In other words, the problem should be formulated in such a way as to avoid such difficulties as, for example, in the application of Eq. (3) – usually there is no complete information about the mineral composition of the soil. Therefore, it was proposed by Różański and Stefaniuk (2016a) as well as Łydżba et al. (2017) to link the local fluctuation of thermal conductivity at microscale with thermal conductivities of individual soil separates: clay, silt and sand. Stefaniuk et al. (2016), based on the set of thermal conductivity measurements for different types of saturated soils, solved the inverse problem and identified optimal PDFs (Fig. 3). The solution was obtained within the framework of computational micromechanics and assumption of the checkerboard-like microstructure (for more information about this type of microstructure, the reader is referred to Torquato (2002)) as well as a triangular distribution of random variable λ (bounded by $\lambda_{min} = 2$ W/(m K) and $\lambda_{max} = 8.8$ W/(m K)) for each individual soil separate.

Analytical formulae for PDFs (as shown in Fig. 3) for individual soil separates are given by the following equations (Stefaniuk et al., 2016):

$$f_{Cl}(\lambda) = \begin{cases} -5.945 \times 10^{-2}\lambda + 4.637 \times 10^{-1} & (\lambda \in [2,\ 7.8]) \\ 0 & (\text{otherwise}) \end{cases} \tag{4}$$

$$f_{Si}(\lambda) = \begin{cases} -4.325 \times 10^{-2}\lambda + 3.806 \times 10^{-1} & (\lambda \in [2,\ 8.8]) \\ 0 & (\text{otherwise}) \end{cases} \tag{5}$$

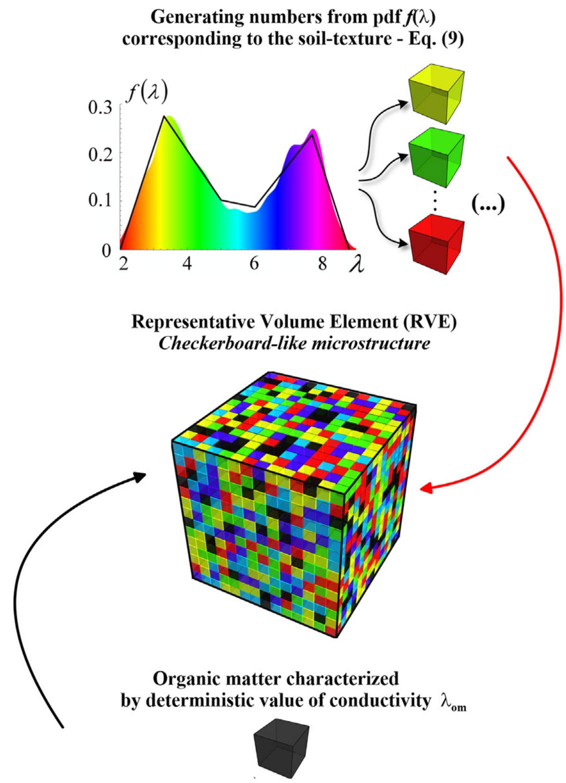

Fig. 5. A schematic view of the process used for generation of RVE domain.

$$f_{Sa}(\lambda) = \begin{cases} 1.136 \times 10^{-2}\lambda + 8.727 \times 10^{-2} & (\lambda \in [2,\ 8.8]) \\ 0 & (\text{otherwise}) \end{cases} \tag{6}$$

3. Local thermal conductivity fluctuation vs. soil texture

Due to the variety of thermal conductivity values of individual minerals forming characteristic soil separates, it is generally assumed that the following inequality holds true (Tian et al., 2016):

$$\overline{\lambda_{Cl}} < \overline{\lambda_{Si}} < \overline{\lambda_{Sa}} \tag{7}$$

where $\overline{\lambda_{Cl}}$, $\overline{\lambda_{Si}}$ and $\overline{\lambda_{Sa}}$ are the averaged values of the thermal conductivities of the minerals forming the soil skeleton with respect to the individual separates (clay, silt and sand, respectively). Since the probability densities shown in Fig. 3 are given in the analytical form (Eqs. (4)–(6)), it is quite easy to determine the expected values of the thermal conductivities for individual separates and verify whether the condition given in Eq. (7) is fulfilled.

Utilizing the relation below, the following expected values of thermal conductivities were evaluated: $\overline{\lambda_{Cl}} = 3.93$ W/(m K), $\overline{\lambda_{Si}} = 4.27$ W/(m K), and $\overline{\lambda_{Sa}} = 5.75$ W/(m K).

$$\overline{\lambda_j} = \int_{-\infty}^{+\infty} \lambda f_j(\lambda) \mathrm{d}\lambda \tag{8}$$

In Eq. (8), j is the index representing individual soil separate. Note that obtained results are in a very well agreement with the hierarchy given by Eq. (7). It is very important in the context that identified distributions (Fig. 3 and Eqs. (4)–(6)) were obtained on

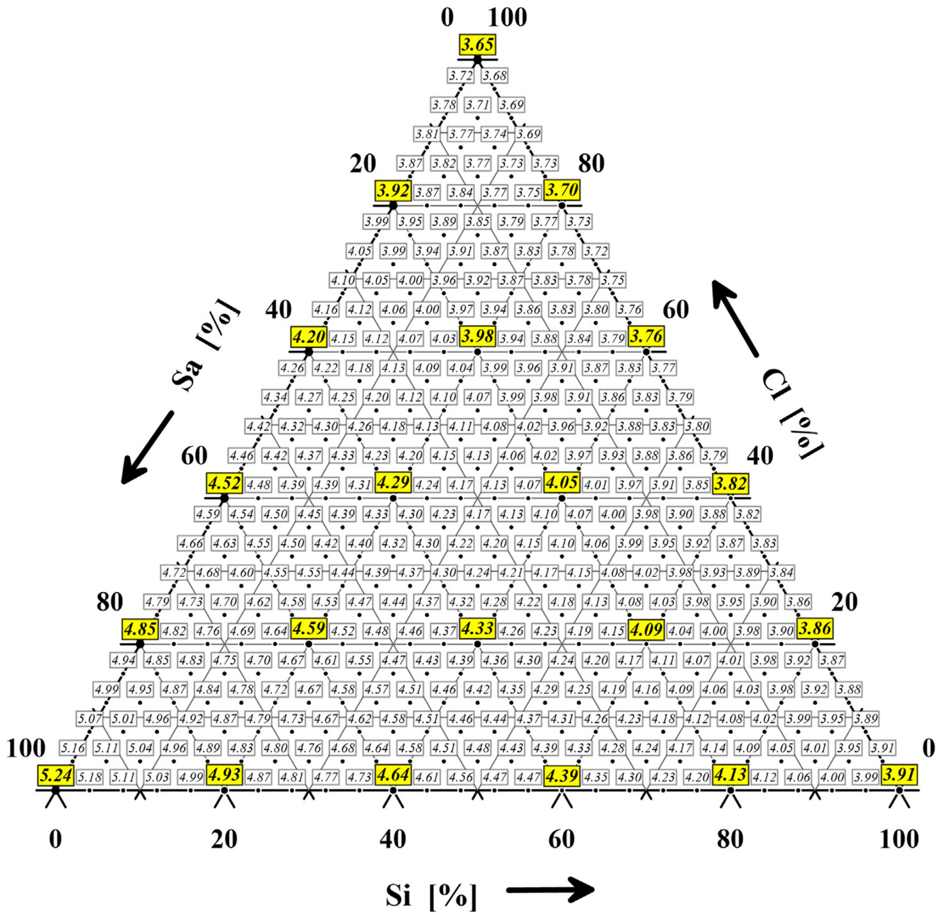

Fig. 6. Thermal conductivity of the soil skeleton λ_s (W/(m K)) as a function of the soil texture: Case 1 – no organic matter content.

the basis of the micromechanical inverse problem solution, without assuming this hierarchy (Eq. (7)) initially.

Purushothama and Judge (1977) reported that the ranges of thermal conductivities for individual separates based on measurements for different types of soils are 3.2–9 W/(m K) ($\overline{\lambda_{Sa}} = 6.1$ W/(m K)) for sand, 2.4–5.9 W/(m K) ($\overline{\lambda_{Si}} = 4.15$ W/(m K)) for silt, and 2.8–4.8 W/(m K) ($\overline{\lambda_{Cl}} = 3.8$ W/(m K)) for clay. What is even more remarkable, the values of expectations calculated above (Eq. (8)) fit very well with the data reported by Purushothama and Judge (1977).

Taking into account above, it has been shown that results obtained on the basis of the identified local fluctuations of thermal conductivity (Fig. (3) and Eqs. (4)–(6)) are consistent with the knowledge available in the literature. Therefore, it is postulated now that the PDF of λ, describing the local thermal conductivity fluctuation of the soil, can be associated with its texture by the following formula:

$$f(\lambda) = \phi_{Sa} f_{Sa}(\lambda) + \phi_{Si} f_{Si}(\lambda) + \phi_{Cl} f_{Cl}(\lambda) \tag{9}$$

where ϕ_{Sa}, ϕ_{Si} and ϕ_{Cl} are the volume fractions of individual soil separates, i.e. sand, silt and clay, respectively, and they obviously hold the following condition:

$$\phi_{Sa} + \phi_{Si} + \phi_{Cl} = 1 \tag{10}$$

Usually in practice, the soil type is associated with the soil texture triangle. Note that in the same manner, any of the soil type, characterized by arbitrary texture (given by the values of ϕ_{Sa}, ϕ_{Si} and ϕ_{Cl}), can be provided with its own local thermal conductivity fluctuation governed by Eq. (9). The visualization of this concept is shown in Fig. 4 which presents exemplary PDFs of four different soil textures represented by the triangle diagram.

4. Thermal conductivity of the skeleton vs. soil texture: results of numerical computations

As shown earlier, the local thermal conductivity fluctuation, being the information on the medium at the microscale, can be associated with the scale of engineering applications – with the information on the soil texture. This implies that as long as a given model allows the random nature of the thermal conductivity to be involved in the calculations, this information can be used to determine the thermal conductivity of the soil skeleton. Such a possibility is provided, for example, by computational micromechanics approach presented in earlier works of Różański and Stefaniuk (2016a) and Łydżba et al. (2017).

In this approach, the geometry of the representative volume element (RVE) of the solid skeleton is a cubic sample composed of independent (in the statistical sense) voxels associated with the thermal conductivities which are randomly obtained from the appropriate soil texture PDF (Eq. (9)). This creates, in some sense, a three-dimensional (3D) random field of λ with the correlation length (or scale of fluctuation) converging towards zero (Fig. 5) (Vanmarcke, 1977; Torquato, 2002). The domain can be supplemented, if necessary, with voxels corresponding to the organic matter whose thermal conductivity, λ_{om}, is a deterministic (non-random) value (according to Bristow (2002), $\lambda_{om} = 0.25$ W/(m K)).

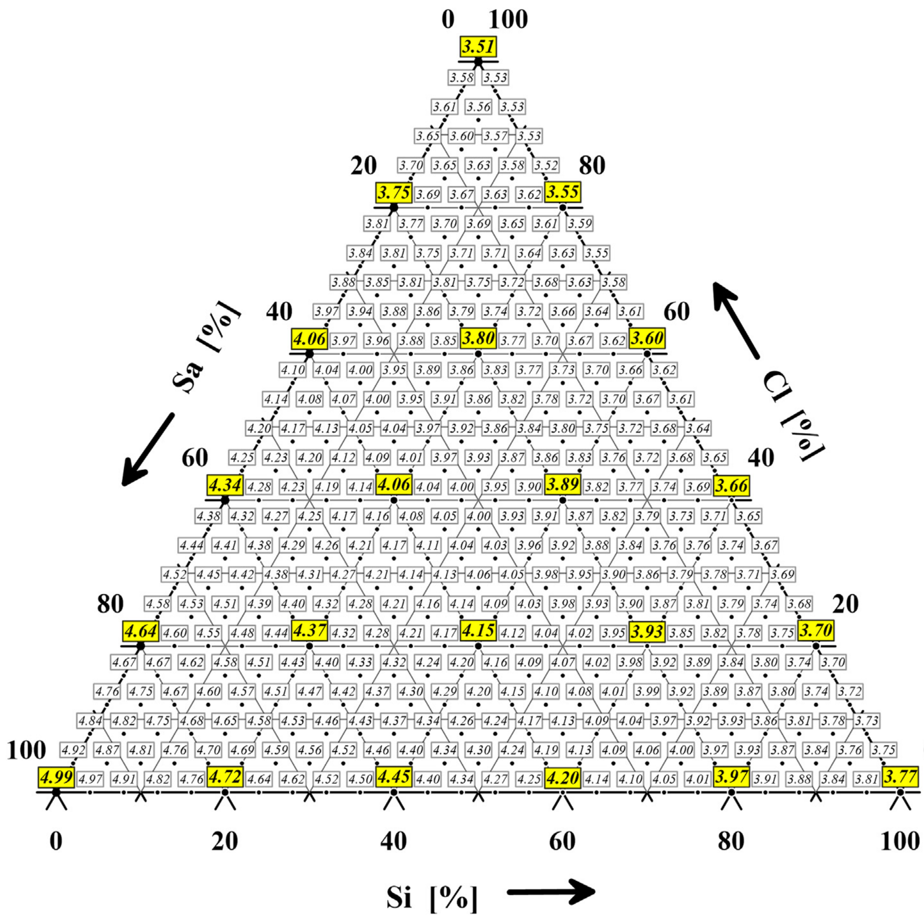

Fig. 7. Thermal conductivity of the soil skeleton λ_s (W/(m K)) as a function of the soil texture: Case 2 – organic matter content of 2%.

Evaluation of effective thermal conductivity of soil skeleton, for a given soil texture, requires the solution of a certain boundary value problem with the use of numerical techniques. Due to the large number of results presented later in this section, as well as the limited amount of space in the paper, the details of the problem formulation in terms of micromechanics, as well as its solution with the use of numerical methods, are omitted here. For details of this methodology, the reader is referred to e.g. Łydżba et al. (2017) where the fundamentals of this methodology are provided.

In the current work, the sequence of a large number of boundary value problems of micromechanics was solved in order to determine the thermal conductivity of the soil skeleton as a function of soil texture. During the calculations, the content of each soil separate (sand, silt and clay) was changed with a step of 0.04 (4%). The results of simulations are presented in triangular diagrams, thus the thermal conductivity of the skeleton is associated with the soil texture. Fig. 6 presents the values of λ_s against soil texture for the case of no organic matter content. The possible values range from 3.65 W/(m K) (corresponding to 100% of clay) to 5.24 W/(m K) (corresponding to 100% of sand). The intermediate result, for 100% of silt separate, is 3.91 W/(m K).

A separate sequence of calculations was carried out for the case of organic matter presence in the soil skeleton. Three cases of organic matter content, i.e. 2%, 4% and 6%, were considered. The results are presented in the following triangle diagrams (Figs. 7–9).

Due to the fact that organic matter is characterized by a relatively low value of thermal conductivity (0.25 W/(m K)), one should expect a decrease in the λ_s value with an increase in the content of organic matter. For example, 6% of organic matter causes a relative decrease in the thermal conductivity of the soil skeleton by an average of 13% by comparing the results in Figs. 6 and 9, from 5.24 W/(m K), 3.91 W/(m K) and 3.65 W/(m K) to 4.54 W/(m K), 3.43 W/(m K) and 3.2 W/(m K), respectively.

The triangle diagrams relating skeleton thermal conductivity to the soil texture (Figs. 6–9) are extremely important from the practical point of view. The value of λ_s can be obtained very quickly provided that the information on the particle size distribution (soil texture) and organic matter content is available. However, this information is a fundamental one and is usually available.

5. Discussion

Due to the complex mineralogical composition of the soil as well as the wide range of thermal conductivities of minerals forming solid phase of soils, it is obvious that on the microscale the skeleton is a strongly heterogeneous medium. In other words, the thermal conductivity of soil skeleton reveals local fluctuations, i.e. it changes "from point to point" within the microstructure. Furthermore, even within individual minerals there is a certain fluctuation of thermal conductivity. As a result, thermal conductivity at this level of observation (microscale) can be treated as a random variable characterized by a certain PDF. Recently, a challenging task was to relate information on local variability of λ to the one that is available in engineering practice (e.g. soil texture), so that it is possible to apply micro-level

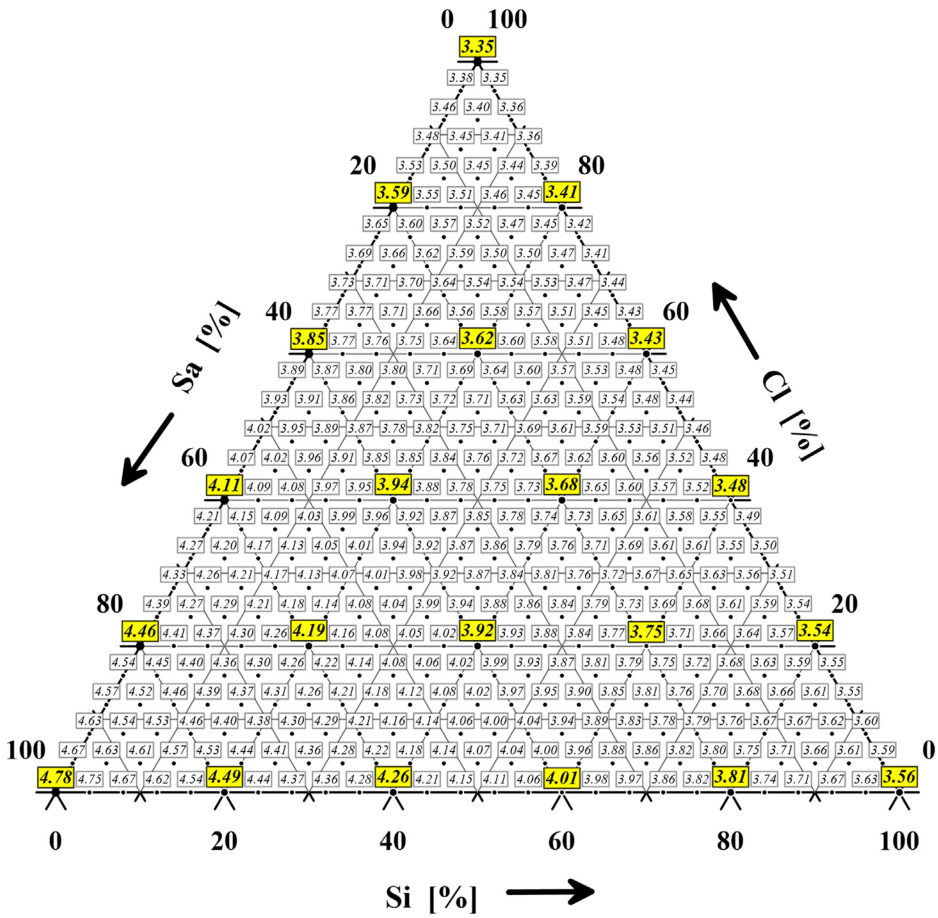

Fig. 8. Thermal conductivity of the soil skeleton λ_s (W/(m K)) as a function of the soil texture: Case 3 – organic matter content of 4%.

knowledge to models used to estimate the thermal conductivity of the skeleton/soil. Initial attempts to apply such an approach to theoretical models based on computational micromechanics were proposed in previous works related to this subject.

In Różański and Stefaniuk (2016a), it was the first time when the local fluctuation of λ was introduced and used for evaluation of λ_s in the framework of computational micromechanics. Satisfactory efficiency and performance of this approach were validated against measured values of thermal conductivities of soils characterized by wide range of different textures. Moreover, in Łydżba et al. (2017), this technique was applied to the two-scale homogenization method for evaluation of thermal conductivities of 32 fully saturated soils with various textures. It has been shown again that local fluctuation based approach gives satisfactory results with respect to evaluation of λ for saturated soils. And this parameter is a key to further evaluation of λ-S_r relation using for example Kersten number (Johansen, 1975). The performance of the model in evaluation of λ_s was also reported by He et al. (2020) – for considered soils, the root mean square error was evaluated as 0.22 W/(m °C).

Nevertheless, it should be emphasized that the model proposed by Różański and Stefaniuk (2016a) had two major disadvantages. First, the clay and silt separates were described by a single PDF. In other words, it was then assumed that the variability of λ at the micro-level for these two separates is exactly the same. Secondly, the course of these functions (triangular distribution) was assumed a priori, i.e. only on the basis of literature data on the range of thermal conductivity values of individual minerals. Therefore, in Stefaniuk et al. (2016), an attempt was made to solve the following inverse problem: given the results of measurements of the thermal conductivities of 32 soils with various textures, identify the optimal PDFs for the three separates (clay, silt and sand). As a result, each of the soil separates was characterized by a separate PDF, and additionally, the range of λ values and the shape of these functions resulting from the solution of the inverse problem (see Fig. 3). This approach has been shown to be highly effective for soils of various particle size distributions.

The results of current paper are significant in at least two major respects. First, all the results are now systemized and used to introduce the concept of “local thermal conductivity fluctuation”. Secondly, the presented results can be directly used in engineering practice – there is no need (as before) to use advanced computational micromechanics techniques.

With regard to the former, it was proposed to couple the “local fluctuation” of λ with the soil texture. Thus the information from microscale is now directly related to that available in engineering practice. This concept, graphically presented in Fig. 4, can be then utilized in any model for overall soil conductivity evaluation provided that such a model enables the application of random variability of λ. Regarding the second aspect, a large series of numerical simulations was performed in order to evaluate skeleton conductivity for different soil textures and organic matter contents. As a result, four triangle diagrams (at different organic matter contents of 0%, 2%, 4% and 6%) relating the value of λ_s with volume fraction of individual soil separates were proposed. This result is extremely important from the practical point of view. One can quickly evaluate λ_s value provided that

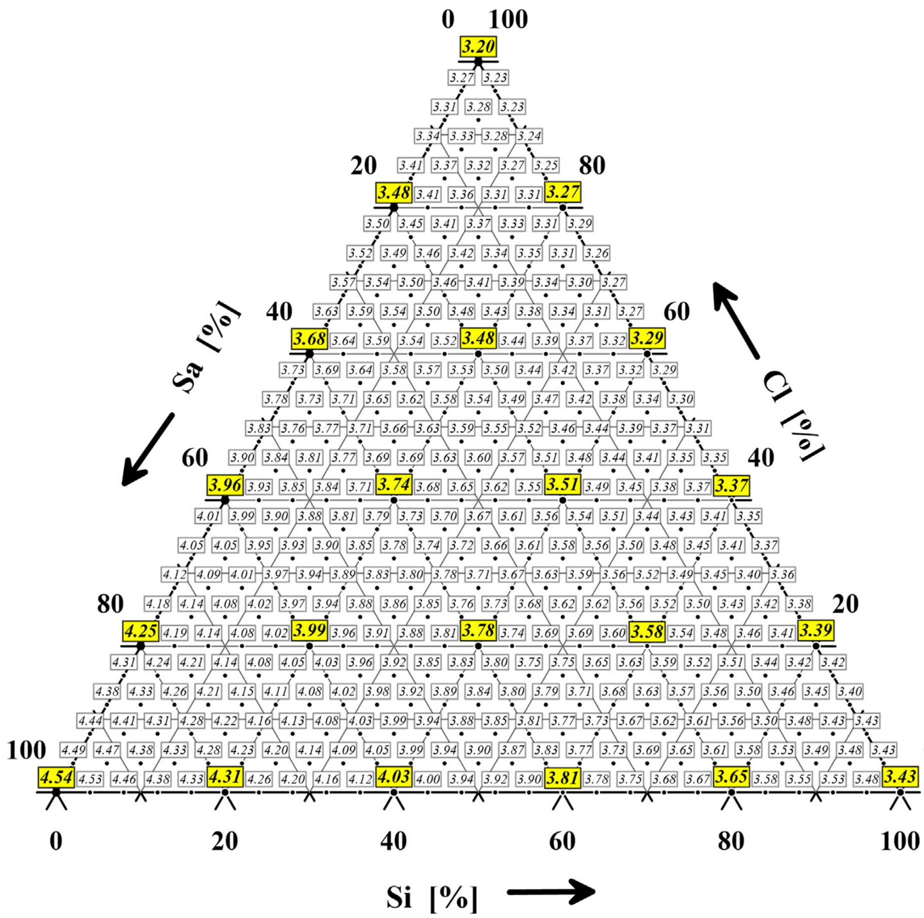

Fig. 9. Thermal conductivity of the soil skeleton λ_s (W/(m K)) as a function of the soil texture: Case 4 – organic matter content of 6%.

information on the grain size distribution and organic matter content is available. Thus, the major drawback of requiring the use of advanced computational techniques to evaluate the λ_s value has been overcome.

6. Conclusions

Overall, this study strengthens the idea that local fluctuation of thermal conductivity at microscale can be associated with soil texture, thus the information available in engineering practice. The findings of this investigation complement those of earlier studies widely discussed in Section 5. The most interesting result, to be used in engineering practice, is the diagrams representing thermal conductivity of soil skeleton (so the parameter that cannot be measured directly) against percentage fractions of three main soil separates. In this context, the results obtained in this study may have a number of important implications for future practice.

It should also be emphasized that these analyses may be somewhat limited by the following factors. Note that generally in practice, fractions of soil separates are measured in weight, but the model describing local variability of λ is based on volume fractions (Eq. (9)). In all considerations, it is assumed that these metrics are equivalent, and this can be a source of some uncertainties. To overcome this problem, evaluation of particle size distribution can be performed using laser particle size analyzer which provides distribution in the form of "cumulative volume percentage less than a certain size vs. grain size" (e.g. Wang et al., 2019). The second problem is that very often in engineering practice, the assessment of the content of organic matter is not performed. However, the possibility of obtaining the λ_s value depending on the organic matter content (Figs. 6–9) should be considered as an advantage of the approach proposed in the current paper. If such information is not available, the λ_s estimate should be made assuming no organic matter content (Fig. 6) and then treated as the upper bound for skeleton thermal conductivity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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