MACRO-SCALE UNDERGROUND GEOMECHANICAL AND THERMAL MAPPING FOR VERY SHALLOW GEOTHERMAL APPLICATIONS

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The authors request that this paper be considered for a special issue in the Journal *Mathematical Geosciences*

Extended abstract

The exploitation of Shallow Geothermal Energy (SGE), mainly using Borehole Heat Exchangers (BHE), down to a depth of 100 – 200 m, has become popular for heating and cooling purposes [1]. The widespread application of BHE to exploit SGE could help European countries fulfill their commitments in terms of energy saving, renewable energy quota and carbon dioxide emissions reduction [2]. Nonetheless, the current state of the technology uptake in the EU varies across Member States, and significant barriers limiting the investments still exist [3]. Increasing the use of SGE systems in Europe could be achieved by: 1) moderating the investment costs (drilling, grouting, tubing, pipes), 2) reducing the system complexity and safety issues (drilling depth, site-working conditions) and 3) enhancing the quota of SGE recovery [4].

Starting from the available official geological [5] and climate data [6] of the EU Member States, we launched a macro-scale geographical investigation of thermal and mechanical properties, and we provided a method of mapping realization, based on geostatistical techniques. The aim was to define useful elements to evaluate the market potential for very shallow geothermal systems.

The geostatistical approach recognizes the variability of spatial behavior of the different mapping parameters (geological, geomechanical and geothermal) and incorporates them, using appropriate models to identify the structural relationships in the area of each country (the area of the target). Using geostatistical methods is helpful since adding the uncertainty maps for each parameter.

Shallow underground layers are thermally dependent on both seasonal climatic variations and hydrogeological properties; as a result, the quota of SGE recovery even with the most efficient BHE is strongly influenced by natural variables. Moreover, geotechnical and geomechanical properties influence the drilling technique selection.

Heat transfer in unconsolidated subsoil and rock mass, and the related temperature distribution assessment in shallow depths (T_g), is a function of the ambient temperature wave, the thermal properties of the ground layers and the geothermal gradient [7]. Equation (1) summarizes the well-known distribution of temperatures in the subsoil [8]:

$$T_g(d,t) = T_m - A \cdot \exp\left[-d \cdot \sqrt{\left(\frac{\pi}{\mathrm{T} \cdot \alpha}\right)}\right] \cdot \cos\left[\frac{2 \cdot \pi}{\mathrm{T}} \cdot \left(t - t_{T_0} - \frac{d}{2} \cdot \sqrt{\left(\frac{\mathrm{T}}{\pi \cdot \alpha}\right)}\right)\right] + \vec{\nabla} T \cdot d \qquad (1)$$

where T_m is the annual average temperature (°C), A is the wave amplitude (°C), T is the wave period (days), d is depth (m), t is time (days), t_{T0} is the time at minimum temperature (days), α is the equivalent thermal diffusivity on the depth of investigation (m^2/days) and ∇T is the geothermal gradient (°C/m), depending on geothermal heat flow h (W/m^2) and equivalent thermal conductivity on the depth of investigation λ (W/(m·K)).

For most of final user needs (both heating and cooling), optimum underground thermal conditions where extracting geothermal energy usually coincide with a layer called “neutral zone” (NZ). The temperature of this layer neither follows seasonality (it is constant over time), nor the influence of the geothermal gradient is significant (Figure 1).

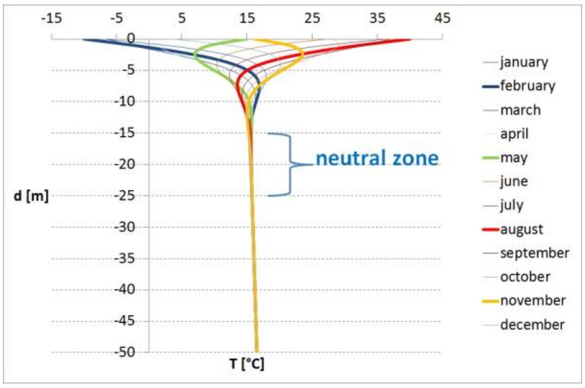

Figure 1. Standard evolution of underground temperature with the “neutral zone” highlighted

In fact, NZ defines the optimal depth at which to install BHEs. NZ is particularly important in combined heating and cooling projects in order to exploit the maximum ground potential for both uses.

Different factors influence the top and bottom of the neutral zone. If the thermal influence of the urban environment is not taken into account, the following deviations of NZ can occur at the top (Table 1) and at the bottom (Table 2):

Table 1: Deviation of top level of the “neutral zone” due to the percentage variation of different natural parameters influencing heat exchange in the subsoil

	Natural parameter deviation		
	0%	50%	100%
Natural parameters	**Variation of the top**		
Average temperature	0,00%	0,00%	0,00%
Climatic wave amplitude	0,00%	5,06%	10,13%
Ground layer thermal diffusivity*	0,00%	22,78%	41,77%
Ground layer thermal conductivity	0,00%	0,00%	0,00%
Geothermal heat flow	0,00%	0,00%	0,00%

Table 2: Deviation of bottom level of “neutral zone” due to the percentage variation of different natural parameters influencing heat exchange in the subsoil

	Natural parameter deviation		
	0%	50%	100%
Natural parameters	**Variation of the bottom**		
Average temperature	0,00%	0,00%	0,00%
Climatic wave amplitude	0,00%	1,63%	3,25%
Ground layer thermal diffusivity*	0,00%	7,32%	13,41%
Ground layer thermal conductivity	0,00%	33,74%	67,89%
Geothermal heat flow	0,00%	-22,36%	-33,74%

*In this analysis, thermal diffusivity and thermal conductivity are quantities considered independent. Because of the possibility of interdependence between these two parameters, the deviations of top and bottom levels of NZ could be affected. The interdependence is evaluated case by case, by investigating the underground composition.

As the amount of exploited energy is strongly influenced by the depth and thickness of neutral zone, this inevitably affects drilling and installation costs. In shallow unconsolidated subsoil, dry auger techniques may be the best solutions in terms of costs containment and drilling speed, while air flush roto-percussion and water flush rotary drilling are the most common solutions for deeper depths. The need to utilize drilling fluids inevitable raises installation costs, and also lowers yard cleanliness and workers safety.

As regards the resistance of shallow underground to be drilled by auger machines, the most used criterion is the Mohr theory of failure, shown in Equation (2), which identifies shear stress limits (MPa) for different rock geomechanical properties [9].

$$\tau = c + [\sigma_v + p(d)] \cdot \tan\varphi \qquad (2)$$

where c is the cohesion (MPa), σ_v is the compressive strength (MPa), p is the hydrostatic pressure (MPa), d is the depth (m) and φ is the friction angle.

Equation (1) and equation (2) contain all the parameters to be estimated by the geostatistical techniques, and to be included in the mapping, according to the available information gathered.

The workflow of the general methodology is illustrated in Figure 2.

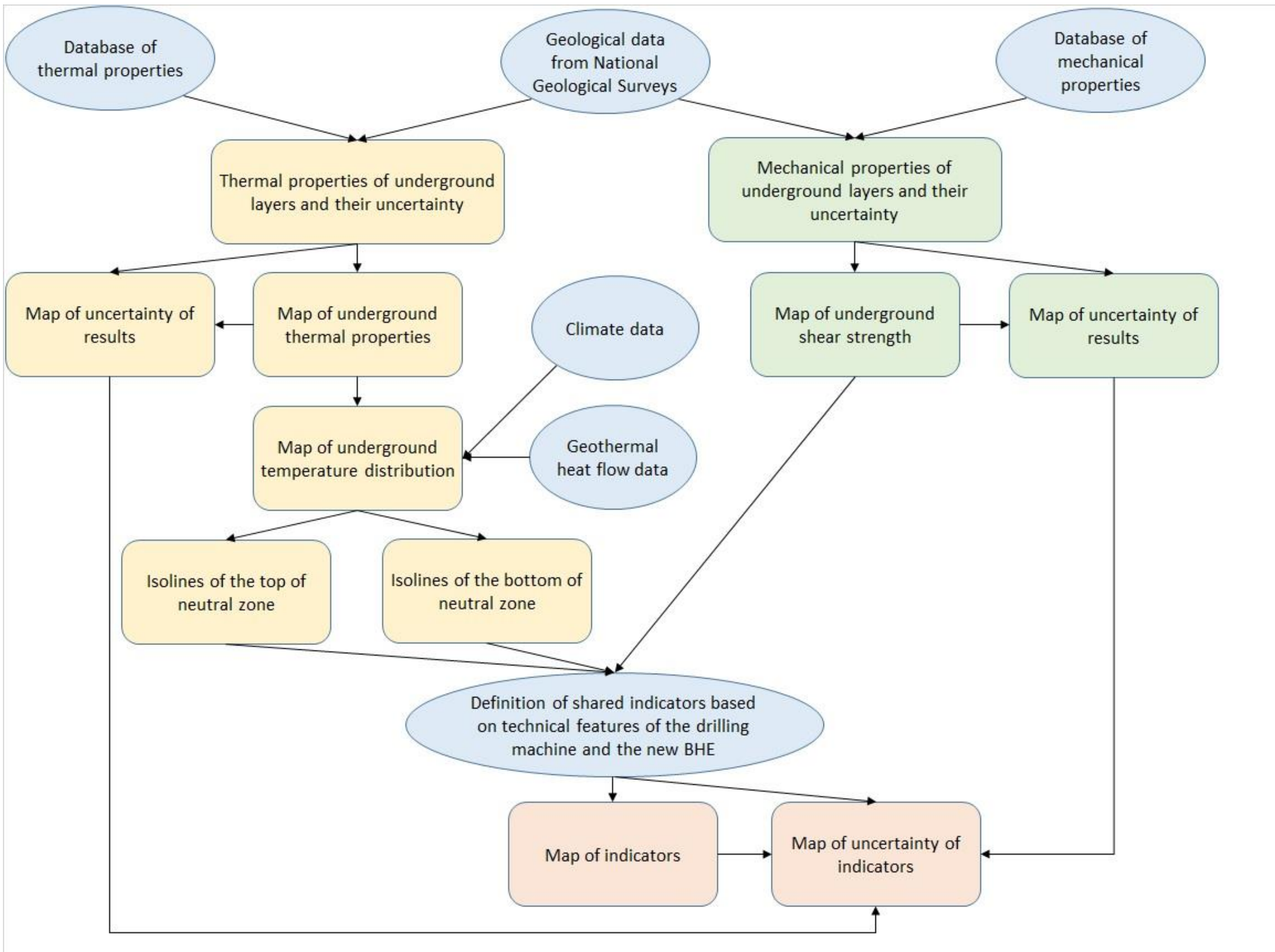

Figure 2. Workflow of the methodology for the spatial interrelation between thermal and mechanical properties of underground, to assess useful indicators for market analysis.

According to available geological and geomechanical data and geothermal properties of different rock types, we performed the geo-referencing of appropriate indicators for very shallow geothermal energy exploitation. Furthermore, we considered the uncertainty of mapped parameters, compared to their actual data from in situ and lab tests.

We extracted the input data useful for mapping from indicators in some databases (DB), synthetized in Table 3.

Table 3: Databases used to get indicators

Source of information	**Gathered data**
Geological surveys from European Countries	Geological information of shallow layers for European countries
Tables from technical norms and scientific literature in the topics of geotechnics and rock mechanics	Geotechnical and geomechanical properties of lithotypes, rocks and unconsolidated material
Tables from technical norms and scientific literature in the topics of geothermal energy	Thermal properties of lithotypes, rocks and unconsolidated material
Weather historical information	Climate data
Geological surveys, geothermal associations and national mining and petroleum departments	Geothermal heat flow data

We georeferenced the data gathered in the DBs and we were able then, firstly, to create initial independent maps of indicators, and then to approach the geo-processing of data (Figure 3) to recreate in a three dimensional form the temperature and shear stress distributions presented in equations (1) and (2). According to the statistical and spatial structure analysis of data in the scale of the work (the area of each country), the spatial behavior of some variables showed a non stationarity behavior trend, which thus caused us to use the universal kriging method (UK), while other variables showed stationarity, thus caused us to use ordinary kriging (OK). The difference between the two methods is the dichotomy of stationarity. It is common to assume that the variable is stationary when its distribution is invariant under translation: homogeneous, statistically the mean and the covariance are constant. However, when there is a trend the mean value of the variable cannot be assumed to be constant [10].

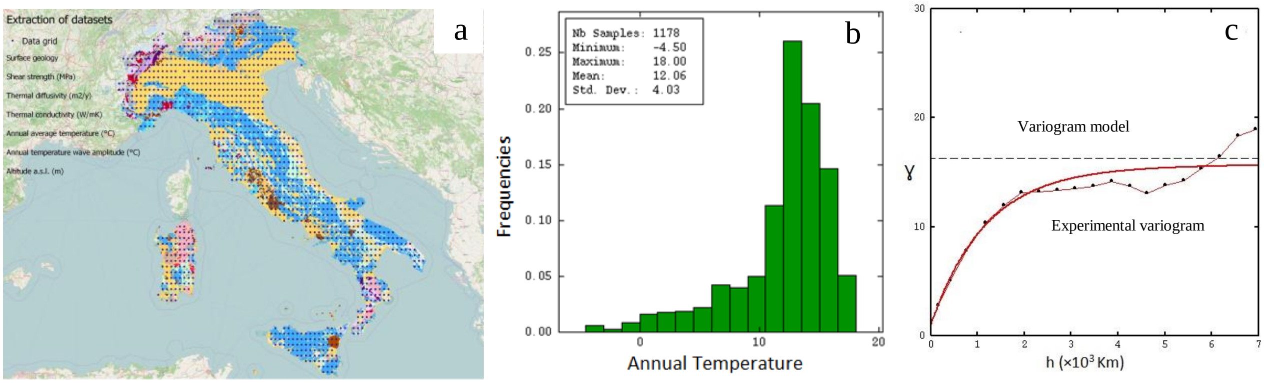

Figure 3. Example of grid creation (a) and geo-processing of data: histogram (b) and comparison between experimental variogram and its model (c)

The proper methods used for mapping data are chosen according to the spatial behavior of each variable considered for mapping. In the UK method, the random function is considered as the sum of a deterministic drift *m(x)* and a zero mean stationary or intrinsic random residual *Y(x)*:

$$Z(x) = m(x) + Y(x) \tag{3}$$

This method is used to estimate parameters (such as the amplitude of temperature wave) when the data exhibit a spatial drift [11]. However, for other parameters (for example the thermal conductivity) the geostatistical interpolation technique of OK qualified depending on the spatial structure model. The general approach is to consider a class of unbiased estimators for mapping the appropriate variables, some of those are shown in Figure 4:

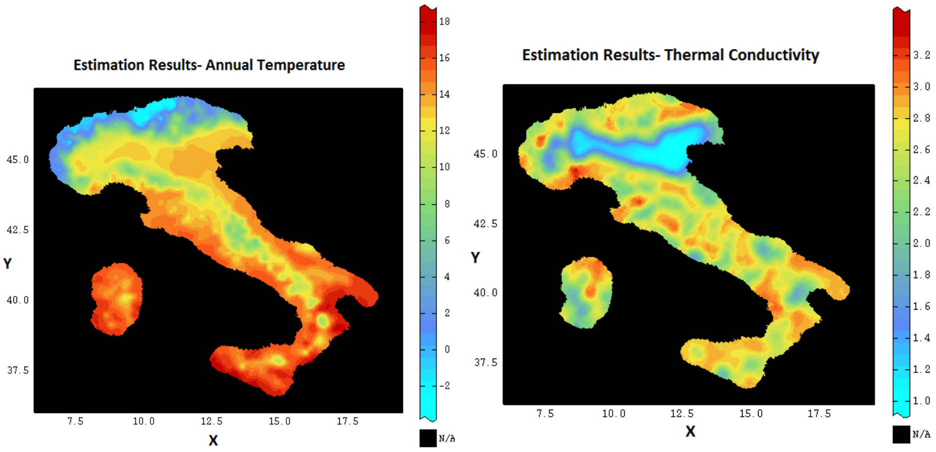

Figure 4. Kriging maps obtained from (Left) the annual temperature data and (Right) the equivalent thermal conductivity data.

From the activities carried out, we could define some preliminary indications useful for market assessment:

- auger technology is strongly influenced by geotechnical and geomechanical properties of underground and can be easily used where unconsolidated material is predominant. Although the percentage of potential territory varies from country to country, and is particularly limited in southern European countries, it should be noticed that the highest heating and cooling needs concentrate in urban areas, usually established in valleys, with predominance of unconsolidated material;
- exploitable energy increases with higher values of thermal conductivity of underground, although there is a sort of direct proportionality with shear strength so that in terms of actual market potential of the technology, the two properties opposite them each other;
- defining the depth and thickness of the neutral zone is of great importance for shallow geothermal solutions. To extract the maximum amount of energy, the BHEs should reach the neutral zone and the drilling cost to reach this depth must be taken into account in each geothermal project.

Acknowledgements

This work was possible thanks to the research project H2020 GEOTeCH. GEOTeCH is co-funded by the European Community Horizon 2020 Program for European Research and Technological Development (2014-2020) and has received research funding from the European Union (www.geotech-project.eu)

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