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Thermal conductivity characterization of three geological formations by the implementation of geophysical methods

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A B S T R A C T

In very low enthalpy geothermal installations it is essential to know the thermal conductivity parameter of the surrounding ground. The present study uses seismic prospecting as a basis for the knowledge of the mentioned thermal property. Using the technique of Multichannel Analysis of Surface Waves (*MASW*) and seismic refraction, it has been possible to correlate the velocity of the *P* and *S* waves with the thermal conductivity of three study areas. Continuous measurements of the thermal conductivity parameter were performed on samples from the areas where the seismic prospecting was made. The maximum and minimum thermal conductivity values were connected to the highest and lowest *P* and *S* wave's velocities. From this relation, an interpolation between the couple of values allows to obtain a linear equation used to predict the intermediate thermal conductivity values. As a result, graphs of thermal conductivity against *P* and *S* wave's velocities were created for each of the study areas. Additionally, 2D images of the spatial distribution of the thermal conductivity of the subsoil of each formation were performed. Thus, seismic prospecting allows, besides knowing the geology of the subsoil, the possibility of estimating the thermal conductivity of a certain ground. This parameter is indispensable for the subsequent process of calculation and dimensioning of a very low temperature borehole heat exchanger.

1. Introduction

The growing demand of very low enthalpy geothermal installations encourages paying special attention in the design of these systems. An incorrect dimensioning could cause important consequences in the short and long term operation. It is therefore fundamental to carry out an exhaustive analysis of the ground where the installation will be placed.

In this context, the thermal conductivity of the surrounding ground is especially important. This parameter influences the thermal exchange between the ground and the rest of components of the installation. Thus, the value of this property affects the drilling length required to cover some specific needs (Blázquez et al., 2016). The thermal conductivity is an important physical property for predicting heat flow and corresponding subsurface temperatures (Haenel et al., 1988; Rühaak et al., 2015; Rühaak, 2015). It describes how well the heat is conducted through a material.

Although it is still difficult to estimate the thermal conductivities of rocks at a large scale required for geothermal applications, different methods currently estimate it for full geological formations, sections or boreholes (Fuchs and Balling, 2016a; Fuchs and Balling, 2016b). In this context, tools as the optical scanning technique, allows providing measurements on cores samples directly (Popov et al., 2016). At present, there is tabulated information that assigns a value of thermal conductivity to each geological formation. It associates an approximate thermal conductivity value to a certain material without cost. However, its precision is quite low given that the thermal conductivity can still vary considerably, even for the same rock type (Cermak and Rybach, 1982). The opposite case would be the execution of a Thermal Response Test (*TRT*) in the corresponding ground. It provides an accurate thermal conductivity value despite the additional cost that this test involves. There are also numerous devices that measure the thermal conductivity of a material from samples analyzed in the laboratory. The controversy of these methods is that the whole rocky formation is not considered and the thermal conductivity results do not represent all the ground (Blázquez et al., 2017; Barry-Macaulay et al., 2013; Liou and Tien, 2016; Kukkonen and Lindberg, 1995; Lira-Cortés et al., 2008; Jorand et al., 2013; Krishnaiah et al., 2004).

For these reasons, it is important to look for alternatives to estimate the thermal conductivity of the whole geological formation that surrounds the borehole heat exchanger. The implementation of these techniques should not constitute an impediment from the economic point of view.

The integration of secondary data, like seismic velocities

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measurements could constitute an excellent option to balance the accuracy and the representation of the thermal conductivity results with the cost that its execution entails (Esteban et al., 2015; Pimienta et al., 2014). Before drilling the geothermal borehole/s, it is necessary to know the subsoil materials to choose the most suitable drilling method. Generally, seismic prospecting is commonly used for such purposes. The present research suggests the use of this technique with an additional aim: estimating the thermal conductivity parameter of the ground where is used. Thus, seismic prospecting would allow knowing the geological composition of a certain ground and in turn, its thermal conductivity by the correlation of this property with different seismic parameters.

The occurrence of a similar trend between thermal conductivity and compressional wave velocity has sufficiently been demonstrated in numerous previous studies (Balling et al., 1981; Fuchs et al., 2015; Gegenhuber and Schoen, 2012; Hartmann et al., 2008; Özkahraman et al., 2004a; Özkahraman et al., 2004b; Popov et al., 2003). This is why the principal objective of this research is to combine thermal conductivities from laboratory measurements and seismic velocities from in situ seismic prospecting. Thermal conductivity measurements are carried out on samples analyzed in the laboratory (rocks) or directly in their original place (loose materials). Seismic profiles are made throughout the study area where samples are collected to measure the thermal conductivity parameter. The principal purpose of this study is correlating both parameters: by the use of real seismic and thermal conductivity measurements and without model predictions. Thus, results will be completely representative of the area in question given the basis on real data. The final results provide a 2D thermal conductivity image of each area where the present methodology was implemented.

2. Materials and method

2.1. Theoretical basis

Geophysics includes a large number of techniques whose aim is the study of the Earth's crust materials. Throughout this work these techniques and the resulting parameters from them were analyzed to find a logical relation between them and the thermal conductivity. After an exhaustive analysis and study of state of the art, the seismic prospecting methods were selected as potential candidates to achieve the objective of this work.

Seismic prospecting techniques are based on the measurement of the arrival times of the *P* and *S* waves generated on the ground by a particular mechanical energy source. These waves are transmitted from a point to another where sensors (geophones) are connected to a seismograph recorder.

The way in which the seismic waves are transmitted through the ground presents a great similarity to the way in which the heat is transmitted by the mechanism of conduction. The propagation velocity of seismic waves in the ground is different depending on each material, as in the case of the heat conduction. In most cases, both parameters have a directly proportional relation ([Özkahraman et al., 2004a,Özkahraman et al., 2004b]Özkahraman et al., 2004a; Özkahraman et al., 2004b), although, for certain materials and conditions this positive trend is not always observed (Fuchs and Förster, 2014; Gegenhuber, 2011). In this research, the positive correlation between both parameters was previously verified by in situ measurements in the study areas subsequently defined.

Thus, for the same geological composition, the transmission velocity of the seismic waves is higher in hard and compact rocks and lower in the case of poorly consolidated rocks. In the same way, the thermal conductivity of a ground is higher if the compaction and consolidation of that material is also high.

For a given material, its state of maximum deterioration and decomposition corresponds to the minimum velocity at which *P* and *S* waves propagate through it. In contrast, the state of maximum consolidation and compaction of a formation corresponds to the highest velocity at which these waves are capable of being transmitted through it. Also, the thermal conductivity for that material will have the lowest value for its state of maximum decomposition and its highest value for its state of maximum consolidation.

Table 1
Study areas selected in the present research.

Area	Location	Rock type
1	*40°37′37.57"N 4°36′38.45"O*	Schists
2	*40°39′48.99"N 4°42′47.27"O*	Medium grain adamellite
3	*40°39′23.68"N 4°40′13.99"O*	Coarse-grained adamellite

Based on this fact, (and given the directly proportional relation between *P* and *S* waves' velocity and thermal conductivity) it is possible to establish a correlation between the propagation velocity of these waves in a given material and its thermal conductivity.

By carrying out seismic prospecting on a particular area and on the basis of its geology, some relevant information can be deduced:

- Distribution of materials in the subsoil.
- Detection of the most altered areas (maximum state of alteration) and those ones that present the maximum state of compaction. Each of these areas has an assigned velocity value of the *P* and *S* waves.

By taking samples of these zones and measuring the thermal conductivity of each one, we obtain the initial and final points of a relation between the seismic velocities and the thermal conductivity. From this pattern, it is possible to know by thermal seismic tests the thermal conductivity at any place (constituted by any of the materials tested in this article) where the geothermal installation will be placed.

2.2. Materials (Techniques)

Seismic prospecting and thermal conductivities used in this work were the following:

2.2.1. Seismic measurements

The exploration techniques used to achieve the objective of the present research are included in the seismic field:

2.2.1.1. Multichannel analysis of surface waves (MASW). It is a non-destructive seismic method that evaluates the thickness of the pavement as well as the linear elastic modules of the materials placed under this pavement (Park et al., 1999). This method analyzes the dispersion properties of the surface seismic waves, which horizontally propagate along the surface from the impact point to the receivers.

A set of receivers distributed along short (1–2 m) and long (50–100 m) distances simultaneously record the emissions from an impulsive or vibratory source. Statistical redundancy is provided to measure phase velocities. Multichannel data show a variable frequency format over time. From the analysis of these data it is possible the identification and rejection of non-fundamental Rayleigh waveforms and incoherent noise (Louie, 2001).

In the present work, MASW tests were carried out using a device of 10 (area 1) and 12 (area 2 and 3) geophones of 4.5 Hz placed every 5 m. The working methodology involved the execution of a series of shots by a 20 kg tenderiser. The equipment used in these tests was the commercially known as "Stratavisor Nx" belonging to "Geometrics". This device has 60 channels and an auto-calibration option.

After the execution of the in situ MASW tests, data were extracted and processed by the "Surface Wave Analysis Wizard" module of the software "Seisimager". This software allows obtaining the *S* wave by