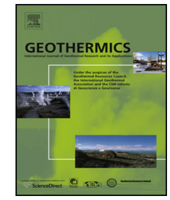
Geothermics 57 (2015) 145–156

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics



Stratigraphy modeling and thermal conductivity computation in areas characterized by Quaternary sediments

Giordano Teza[a,*], Antonio Galgaro[a,b], Elisa Destro[b], Eloisa Di Sipio[b]

[a] *Dipartimento di Geoscienze, Università di Padova, Via Gradenigo, 6, I-35131 Padova, Italy*
[b] *Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse (CNR-IGG), U.O.S. Padova, Via Gradenigo, 6, I-35131 Padova, Italy*

ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form 16 April 2015
Accepted 23 June 2015
Available online 9 July 2015

Keywords:
Geoexchange
Borehole heat exchanger
Thermal ground characterization
Stratigraphy
Thermal conductivity
Spatial statistics

ABSTRACT

A feasibility plan for the exploitation of low enthalpy geothermal resources at regional scale requires a map of the ground thermal conductivity. Available information often comes from heterogeneous well log data related to boreholes drilled for various purposes (e.g. irrigation) and whose spatial distribution is sub-optimal. Therefore, a suitable interpolation technique is necessary. An approach based on local evaluation of the mode of distribution of the subsoil geological species is proposed here. It provides a stratigraphy model, the equivalent ground thermal conductivity and the corresponding statistical/geometrical significance in the nodes of a regular grid. Besides a validation with synthetic data of the MATLAB/GNU Octave implementation of the method (GRIDWELL toolbox), the results of its application to the data from Apulia's plain areas are shown here.

1. Introduction

Nowadays, the increasing cost of energy sources like oil and coal and the corresponding environmental impact suggest an extensive use of geothermal energy for heating and/or cooling of buildings. In particular, closed loop geothermal systems, often used in conjunction with ground-coupled heat pumps (GCHPs), have relatively high installation costs which are paid off by low operation and maintenance costs, leading to their use in a wide range of areas (see e.g. Banks, 2012). A GCHP consists in the following: one or more borehole heat exchangers (BHEs), with ∼100 m typical depth, which ensure coupling with the ground; some circulation pumps, which circulate the carrier fluid; and a heat pump, which uses a compression–expansion cycle to boost the temperature of the heat to a level that can be practically used for heating or cooling purposes. The carrier fluid (pure water or a mixture of water and propylene glycol or ethylene glycol) exchanges heat both with the ground, through the BHE, and with the heat pump.

In order to allow an evaluation of the degree of suitability of an area for low enthalpy geothermal energy exploitation purposes, and therefore to allow a good exploitation of the geothermal resources, a general thermo-stratigraphical assessment of the subsurface that should host BHEs is useful (Blum et al., 2011). Local insight provided by ground response test (GRT) and thermal modeling are needed for correct planning in the case of large BHE fields. In this way, a map of the areal distribution of thermal conductivity (TC) can be obtained. Such a map is an informative tool useful both for evaluating the feasibility of geo-exchange systems and land development planning by the competent public authorities. A detailed stratigraphical characterization of the ground is unnecessary for the design of a small GCHP system, where a successful design mainly depends on the correct evaluation of heating and cooling building demand. Nevertheless, it should be emphasized that the invariant component of the chain building-heat pump-subsoil consists in the thermo-physical properties of the subsurface to which a sound thermo-technical design should be adapted. Moreover, if large GCHP systems are planned in areas where groundwater flows exist, these flows should be adequately modeled (Sutton et al., 2003). For all these reasons, in some areas extensive campaigns of thermo-physical characterization of the ground are carried out by means of several techniques, from well logging analyses to active and/or passive geophysical techniques (see e.g. Soengkono et al., 2013).

A large amount of information related to the ground is often available. In rare cases, data have been taken specifically for geothermal energy deployment purposes. This is the standard if a large BHE field is planned or for the installation of the first geothermal system, both of which are typically preceded by a thermal response test (see e.g. Sharqawy et al., 2009), sometimes accompanied by numerical modeling (Signorelli et al., 2007). In the majority

* Corresponding author.
E-mail address: giordano.teza@unipd.it (G. Teza).

http://dx.doi.org/10.1016/j.geothermics.2015.06.016
0375-6505/

of cases, information about the soil is collected from geophysical explorations and/or boreholes drilled for other purposes, e.g. irrigation, use of hydrocarbon resources, planning and/or design of large civil engineering structures, waste management, analysis of presence and distribution of possible pollutants in industrial or rural zones, or even scientific research purposes. The quality of the data is heterogeneous, the depth can vary from few tens to several hundred meters, and a certain degree of subjectivity in geological assessment descriptions can exist. A possible solution to the problem was shown by Cultrera et al. (2012), where heterogeneous well log data and passive seismic data were used to develop a new stratigraphic model of the Venice area by means of a mode-based statistical analysis.

In this paper, a mode-based statistical approach to stratigraphy modeling for low enthalpy geothermal energy exploitation purposes is proposed. Equivalent well logs (EWLs) are obtained in the nodes of a regular grid defined in the studied area. The results are, for each grid node: the lithological sequence of the modeled EWL, the effective TC related to such an EWL, an estimation of the corresponding error and an evaluation of its geometrical/statistical significance. The MATLAB/GNU Octave implementation of the proposed method (GRIDWELL toolbox) was applied in the plain areas of a 19,000 km^2 region (Apulia, Southern Italy), leading to results that can be directly used for planning purposes.

2. The method and its MATLAB/Octave implementation

The proposed method is based on these operations: (1) possible import of data from a digital terrain model; (2) generation of a regular grid; (3) recognition of the subarea to which each available real well log (RWL) belongs; (4) mode-based EWL modeling for each subarea on the basis of the corresponding RWLs; (5) possible interpolation of water table data; (6) computation of the effective TC for each EWL; (7) visualization of the results and/or their export to a geographical information system (GIS). Although a well log generally is defined as a detailed record of the geologic formations penetrated by a borehole, in this paper the term RWL indicates all kinds of data on the subsoil stratigraphy, regardless of the data source (out-and-out well log, simple report on water well drilling, or also other sources).

The GRIDWELL toolbox, which is available as Supplementary Material to this paper, is a collection of MATLAB/GNU Octave (MO) functions (GNU Octave is the open source clone of MATLAB). If GRIDWELL runs under MATLAB, the user can either use the command line or graphical interfaces like combo boxes and input dialog boxes. If it runs under GNU Octave, the command lines, without graphical interfaces, must be used instead. In order to warrant a whole compatibility of GRIDWELL with the currently available GIS packages, the input and output data are EXCEL .xls or .xlsx files (it should be noted that the old format .xls has strong limitations in the maximum number of manageable rows with respect to the most recent format, i.e. .xlsx). The input data generally are well logs whose spatial distribution is suboptimal, i.e. whose typical distance is too high. Nevertheless, in some cases pre-processed data related to a digital terrain model (DTM) could be used. The toolbox can be utilized in both cases. The detailed flowchart is shown in Fig. 1. All the operations implemented in GRIDWELL are now described in detail. Further information can be found in the GRIDWELL User's guide.

2.1. Use of a digital terrain model (optional)

Sometimes the user could have a digital terrain model (DTM) that represents the geometry of the study area, exported from a GIS package. The function gw_extradtm allows the data extraction from a DTM and the generation of files must be managed by GRIDWELL functions. It operates a planarization of the model, with ground level at depth 0. This means that if DTM elevation is z_{DTM} and the top level of a layer is z_{TL}, the corresponding values (i.e. depths) of the plane-parallel stratigraphy are 0 and $z_{DTM} - z_{TL}$, respectively. The grid used in GRIDWELL calculations can be equal to or different from the DTM one, according to the user's choice. Moreover, relatively small differences between DTM and soil can be managed by means of gw_extradtm function, as shown in the GRIDWELL User's Guide.

2.2. Grid generation

The subdivision of the studied area into square subareas by means of a regular grid is a straightforward operation. If the RWL having the extreme South-West position has coordinates $\mathbf{x}_{\min} = [x_{\min}, y_{\min}]^T$, where $x_{\min}$ and $y_{\min}$ are its East and North coordinate, respectively, and s is the chosen grid side (horizontal step), the EWLs are modeled in the points $\mathbf{x}^G_{hk} = [x^G_{hk}, y^G_{hk}]^T$, where

$$\mathbf{x}^G_{hk} = [x_{\min} + (h+1)s/2, y_{\min} + (k+1)s/2]^T,$$
$$h = 1, 2, \ldots, N_x - 1, \quad k = 1, 2, \ldots, N_y - 1 \tag{1}$$

and N_x, N_y depending on the studied area size. The corresponding GRIDWELL function is gw_wellgrid.

The user can choose between two options for stratigraphy modeling: (a) using data from the RWLs belonging to the corresponding subarea for each EWL; (b) using data from the RWLs belonging to both the corresponding subarea and the eight nearest neighbor subareas for each EWL (Fig. 2). Other options are unavailable because extrapolation on high distances is not recommended as it could lead to meaningless results in soil property evaluation. In case (a), an EWL cannot be modeled if the corresponding subarea is empty. In case (b), an EWL cannot be modeled if the corresponding subarea and the nearest neighbors are empty. Therefore, the EWLs are consecutively row-wise numbered with an integer number $m = 1, 2, \ldots, N$, where N is the number of effectively modeled EWLs.

The input data, which have previously been exported from a GIS environment or have been managed by means of the gw_extradtm function, are the identifiers, positions and depths of the RWLs. The output variables are cell arrays, which can be saved in a MATLAB .mat file.

2.3. Equivalent well log modeling

Step (3), i.e. the search of the RWLs belonging to each subarea, and step (4), i.e. the mode-based statistical approach to model an EWL for each subarea center, are implemented together in the gw_wellmod function.

Before the data processing, the user must define the maximum depth of the EWL to be modeled, H, and the vertical step Δz. They are defined from the ground level $z = 0$. Here, positive z values are related to the subsoil. For the mth EWL, let n_m be the number of depth intervals for which at least one RWL is available. Depth intervals from z_{k-1} to z_k where $z_k = z_{k-1} + \Delta z = k\,\Delta z$, $k = 1, 2, \ldots, n_m$, are therefore considered.

The mode is the most frequent value in a distribution (strictly speaking, the point at which the probability mass function has its maximum value). If the mode of the lithology distribution for the kth depth step for the mth EWL is evaluated, it corresponds to the most frequent lithology and therefore can be assumed to be the lithology for that step. In order to evaluate the mode, each lithology is labeled by means of an identifier, e.g. a string or a number. Although the lithology is defined by some quantitative parameters (e.g. mean density, granulometry, mechanical properties), the corresponding label has qualitative character only. This is not a