Procedure for determining geothermal viability

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ABSTRACT

The initial research to determine a procedure for evaluating the viability of a site for geothermal energy installation is outlined. The current routine looks to perform a joint p and s-wave velocity inversion utilizing refraction and surface wave data. There is the potential to include resistivity data to further constrain the inversion as part of the joint inversion scheme, whereby the difference between inverted porosity values calculated from the velocities and the resistivity drive the inversion. Hydrothermal modeling will act to replicate the fluid flow and heat transport around the site, as ground water flow has the most influence on the temperature of near surface rock and soil. Well data and core data will be required for calibrating such models.

INTRODUCTION

Global warming is already well established as one of the key world catastrophes facing the current generation. Temperatures continue to rise despite human efforts to curtail the use of fossil fuels and reduce our carbon emissions. One way to reduce the demand for fossil fuels is to reduce the demand for electricity, often produced using fossil fuels, via the application of geothermal energy on a residential scale. Geothermal energy can be used as a source of domestic heating and cooling, and the method has been utilized since the mid-20th century. Currently, geothermal is experiencing a revival of sorts due to the threat of global warming and the need for alternate energy sources as part of a combined energy solution.

According to the U.S. Energy Information Administration (2014), there are more than 600,000 ground source heat pumps in the U.S. with approximately 60,000 new systems being built each year. The technology uses the residual heat of the near surface rocks and soil to either heat or cool air or water being circulated through pipes in the near surface (Fig. 1). Geothermal energy is thought to be able to provide up to 49% of residential energy consumption and cut the carbon emissions of buildings by up to 50% (geoexchange, 2017). Due to the temperature of the ground being relatively consistent throughout the year - between 7 and 21 degrees Celsius depending on location (energy.gov, 2017) - the heat pump has a continuous uptime. During the winter the ground temperature is warmer than the outside air temperature and so the system can heat the building, and the reverse happens in the summer such that the system is used to cool the house, which reduces the use of air conditioning.

The research into the efficiency of such systems is limited. Most research of this nature is targeted at the operating parameters and the pipe arrangement within the subsurface. The authors note a lack of publications investigating the soil properties and distribution of facies with regards to optimizing heat transfer. It is the aim of this research to fully investigate the optimization of such systems with regard to placement within certain rock/soil types; the goal being to design a site evaluation routine to take into the field. At this stage it is predicted that an assortment of survey techniques will be required to characterize the subsurface to a satisfactory accuracy.

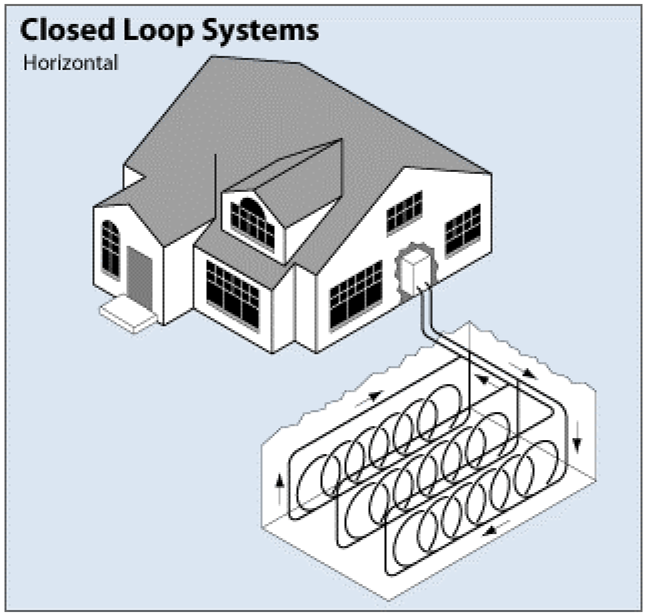

Fig. 1. Example of a horizontal layout for a closed loop geothermal heat pump (image taken from https://energy.gov/energysaver/geothermal-heat-pumps).

SOIL AND ROCK CHARACTERISATION

To best understand the flow of heat in the near subsurface it is important to be able to construct a reliable earth model. Using the technique of joint inversion, it will be possible to identify rock/soil types based on their mineralogy content, which in turn, will determine the thermal properties of the subsurface. This procedure will also determine the lateral continuity of these subsurface formations, which will be pertinent information during the design of fluid flow models. Although not known at this point, there is the possibility that we will be able to infer thermal properties directly from joint inversion. One of the objectives of this research is to determine which suite of geophysical methods are best suited to constrain the subsurface parameters with the aim of extracting thermal properties.

Velocity Inversion

The first step in the process will be to look at velocity variations in the near subsurface. The elastic parameters attained from such a work flow will form the basis of rock physics characterization to determine the minerology and facies distribution. Near surface methods of velocity inversion are well established in the literature and the survey techniques are very manageable on a ‘residential’ scale.

P,S-wave Joint Inversion

The s-wave velocity model can be attained from a surface wave inversion of Rayleigh waves. Xia et al (1999) outline the method as follows: Firstly, we must attain broadband ground roll data, then apply processing techniques to attain the Rayleigh wave dispersion curves from the data, and finally, use an inversion algorithm to generate a near-surface s-wave velocity profile. Given the need for broadband data, a vibroseis is often used as a source for such surveys (Xia et al, 1999). This also allows for the control of the frequencies used. The depth of the survey (z_{max}) is reliant on the lowest frequency recorded

$$z_{max} = v_1/2f_1 \tag{1}$$

where v_1 is the phase velocity of the frequency f_1 (Park et al, 1999). This will be important when designing the data acquisition parameters, depending on how deep the geothermal pipes must be buried. One of the issues with an s-wave inversion is that the solution is extremely non-unique (Piatti et al., 2013). Introducing the p-wave data from a refraction survey allows the problem to be more constrained. Traditional p-wave inversions from refraction data suffer from similar non-uniqueness issues as s-wave inversions from surface wave data. Piatti et al (2013) highlight particular issues with 'hidden layers' arising from gradual velocity increases in a layer overlying a sharp velocity contrast or low velocity layers between stiff layers. Hence, combining the two data sets also decreases the uncertainty in the p-wave inversion at the same time (Fig.2.). The intercept times of a seismic refraction survey are combined with the dispersion curve of surface waves to form our data set (Piatti el al., 2013). The use of two such methods will be beneficial during acquisition; the two surveys types have similar survey design and so it will be possible to collect both sets of data at the same time using a vibroseis as a source. This is an important point, we would like to minimize the costs of the overall procedure of characterizing a site for residential geothermal installation to be economically viable.

It is possible to constrain the velocity inversion further by assigning a range of acceptable Poisson's ratio values. Poisson's ratio, ν (Equation 2), ensures that the V_p/V_s ratio for a given layer describes a realistic rock or soil (Garofalo et al., 2013).

$$\nu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \tag{2}$$

The inversion algorithm most commonly used is a least squares method (Piatti et al, 2013, Garofalo et al, 2013 and, Park et al, 1999), where an objective function similar to the form of equation 3 is to be minimized.

$$O = \left[\left(\boldsymbol{d} - g(\boldsymbol{x})\right)^T C^{-1}\left(\boldsymbol{d} - g(\boldsymbol{x})\right)\right] \tag{3}$$

Where $\boldsymbol{d}$ is a vector of the observed data from the survey, **x** is a vector of the unknown parameters, C is the associated covariance matrix and, $g(\boldsymbol{x})$ are the results of forward modeling using the parameters **x**. The inversion algorithms iteratively solve for V_p, V_s, and the thickness of the layers, whilst holding density constant within a layer. As a result, some *a priori* information is required with regards to layer densities and how many layers we should expect. This is often decided upon using nearby well data.

Resistivity Data

The saturation conditions will impact both the resistivity and the velocity of the near surface, and will have significant impact on the thermal properties of the rock/soil surrounding the piping. Heat transport through groundwater flow will also be a factor, as heat advection via ground water flow is much more efficient than by conduction through a matrix. The initial objective of the resistivity data is to locate the water table, however, it may also be introduced into the joint inversion.

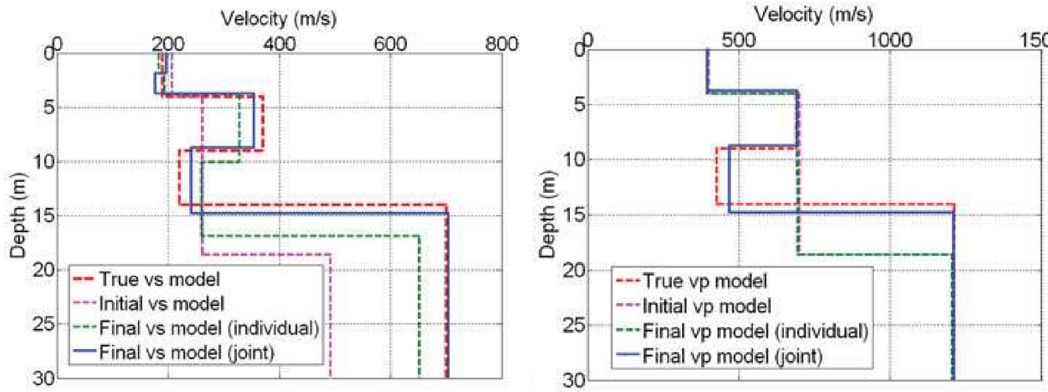

Fig. 2. Example plots comparing the true model, initial model, final model (Individual inversion) and final model (Joint inversion) velocity profiles (Image adapted from Piatti et al, 2013).

Focusing again on the seismic response, the p-wave velocity is determined by the bulk modulus of the material, which is affected by the fluid properties. Furthermore, the resistivity of the soil is going to be influenced by the fluid filling the pores. Garofalo et al (2013) explore this connection by introducing resistivity data to the joint inversion scheme mentioned previously, to retrieve porosity information for the subsurface. Knowing the porosity of the soil/rock will be essential in the heat flow modeling of the subsurface. The inversion is tied to structure i.e. the structure is assumed to be the same for each data set. A porosity, ϕ_s, is calculated from the inverted velocities according to equation 4 (Garofalo et al, 2013)

$$\phi_s = \frac{\rho_s - \sqrt{\rho_s^2 - \frac{4(\rho_s - \rho_f)K_f}{V_p^2 - 2\left(\frac{1-\nu}{1-2\nu}\right)V_s^2}}}{2(\rho_s - \rho_f)} \tag{4}$$

where ρ_s is the density of the soil/rock matrix, ρ_f is the density of the pore fluid and K_f is the bulk modulus of the pore fluid. The inverted resistivity for each layer provides another estimate of porosity, ϕ_r, according to Archie's law (Garofalo et al, 2013)

$$\phi_r = \sqrt[m]{a\frac{R_s}{R_f}} \tag{5}$$

where m is a cementation factor, a is a tortuosity factor, R_s is the resistivity of the layer and R_f is the resistivity of the pore fluid. The inversion algorithm tries to minimize the difference between these two estimates of porosity thus reducing the uncertainty in the earth model. The introduction of resistivity data not only provides useful information in the form of the location of the water table, it also adds a constraint to the inversion, increasing our confidence in the resulting earth model. Having a reliable earth model is going to be essential when attempting to model the heat flow around the pipes.

Rock Physics Templates

The earth model attained from the inversion provides the spatial distribution of the parameters of interest - p-wave velocity, s-wave velocity, resistance etc. - which can be used as part a rock physics analysis to identify areas of different lithologies, the aim of which, is to identify zones of differing thermal properties. Typical methods of rock physics templating use different rock models, depending on the rock type, to define effective elastic moduli for a given mineral composition, porosity, and fluid saturation (e.g. Hertz-Mindlin model for granular rocks, described by Mavko et al (2009)). Combinations of the inversion parameters can be used to calculate subsurface elastic moduli distributions. The data points from these models can be cross-plotted in elastic parameter space with the rock physics templates overlain to identify clusters of lithology. There is also the possibility that the combination of resistivity, EM, GPR or gravity data may provide additional information to constrain lithology. For example, a layer that is most likely high in clay content, based on the moduli data, could be supported by resistivity data indicating high conductivity. The moduli for such a workflow will have to be calculated using density measurements from core or well log analysis.

Heat Flow Modelling

The temperature distribution of the subsurface remains consistent throughout the year, the global average temperature gradient is $30°C/km$, increasing downwards (Florides and Kalogirou, 2007). The temperature at a specific location in the subsurface differs slightly from this average depending on the physical properties of the surrounding rock or soil and the structure. Rocks and soils that are high in quartz content have higher thermal conductivities than rocks and soils that are high in clay content (Florides and Kalogirou, 2007), meaning that they are more efficient at transmitting heat. It is proposed that thermal modelling is used initially to test different rock/soil types, with the aim of optimizing placement of the pipes. The methodology for modeling the thermal behavior surrounding a pipe will require solving the heat conduction equation via the finite difference method. Equation 6 shows a heat conduction equation in 2D cylindrical coordinates, which would potentially be the preferred coordinate system given the use of cylindrical pipes (Bi et al, 2002)

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(rk \frac{\partial T}{\partial r}\right) + H \quad (6)$$

where ρ is the soil density, C is the specific heat capacity, k is the heat transfer coefficient, T is the temperature, t is time, r is the radius from the central axis, z is the depth, and H is the heat reservoir. The current thinking is that the finite difference modelling could also be calibrated using the earth model results from the inversion. Finite difference modelling would then be used to find the most efficient placement for a pipe in the given earth model.

Ground Water Flow

The temperature of the first few meters of the subsurface are heavily influenced by the temperature of the atmosphere above. Below this first few meters the temperature remains constant throughout the year (Florides and Kalogirou, 2007). The main driver of temperature variations at this depth is going to be ground water flow. For example, if a site is located at a ground water discharge site, the flow of water to this location is going to bring with it heat from deeper in the earth, and such locations would be better heat sources. The reverse of this are ground water recharge sites, where the water is close to atmospheric temperature and likely colder than the subsurface temperatures. Such sites would be less efficient at providing heat.

Due to the importance of ground water flow to this process it is necessary to perform ground water testing at a potential site. Several wells will need to be drilled to observe hydraulic head values and determine the regional groundwater flow direction. Coring and logging at these well locations will also provide valuable data to calibrate the inversions and ground water flow modelling. The core may be analyzed to determine a basis for stratigraphy, the density of layers for the inversions, and the permeability of layers for the ground water flow modelling. The modelling itself is an extension of the heat flow modelling mentioned above. However, the equation must now include a transport term and the heat conduction through the fluid is also considered.

Future Work

The next steps in this research will be to begin with some initial heat flow modeling to examine the thermal behavior of different minerology soils and rocks. Alongside this will be some synthetic data joint inversions to prepare the workflow for real data. There also needs to be further literature review into other geophysical methods such as gravity surveys and EM methods to see whether there are advantages to including them in the workflow.

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