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Reservoir Seismology: Essentials of Reservoir Modelling ın Small-Scale Geothermal Area

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Abstract

Reservoir modellings are important to define seismic hazard assessment associated with production process and to better understand the future location of re-injection/production wells in small-scale geothermal areas. The reservoir seismology is an innovative technique to enlighten a multi-dimensional model of a geothermal reservoir using the Passive Seismology Tomography (PST) method. The PST includes Ambient Noise Tomography (ANT) and Local Earthquake Tomography (LET) methods. Each method requires some principal attention to bring the high-resolution image of underground models down to near-sub surface structures. Fluid movements towards the reservoir in geothermal areas cause an artificially induced earthquake. The flow direction along the fractures can be detected by monitoring the micro-earthquakes caused by micro-fractures due to the pressure difference that will occur during the re-injection process of the cold water formed after the production process. Since the oldest and the most important geothermal areas are located in the Aegean region of Turkey, we have introduced the significance of the PST technique and its application to geothermal fields and described it with the used method with data characteristic, data processing and tomography inversion scheme as a whole to characterize the geothermal reservoir.

1. Introduction

Modelling of seismic velocity data using reservoir seismology study crucially improves the feature of sub-structures and processes in the earth crust. In small-scale (e.g. geothermal) areas, this type of modellings is essential, indeed, to determine seismic hazard assessment related with production phases, and to better understand the future location of re-injection/production wells. It also provides important insights down to greater depths that are not resolved by other geophysical methods and/or not accessible by geological field studies. Reservoir seismology is an innovative technique to enlighten multi-dimensional model of a target reservoir (e.g., geothermal, hydrocarbon, natural gas storage, etc) by using Passive Seismology Tomography (PST) method. The PST covers Ambient Noise Tomography (ANT) and Local Earthquake Tomography (LET) techniques. Each technique requires some principal attention to bring the high-resolution image of underground structures down to near-sub surface structures (until 5-7 km). Since the oldest and the most productive geothermal fields are located in the Aegean region of Turkey, we present the importance of the PST technique and its application to geothermal areas in the frame of this research.

2. Data and method

We express the used technique with data characteristics, data processing and tomography inversion scheme to characterize targeted underground features of a study area.

As one of the used techniques, the LET method has often been preferred for tectonic, geothermal and volcanic studies in recent years. Selection of the code that will be followed during data analysis, strongly depends its user-friendly ergonomic structure, open accessibility, allowance of optional synthetic test designs and compatibility with Windows and/or Linux operating systems. These features will certainly provide huge advantages to users if the correct software is selected. Users should take into account the importance of arrival times and station coordinates. The positions of events need to be computed specifically for (or surrounding of) the study area using an initial 1-Dimensional (1-D) crustal structure. The quality of the initial locations should be improved by using re-generative and simultaneous inversion of the crustal structure [1,2]. As it is clear for the LET, reliable images of the subsurface of the target area are closely related to consistent set of arrival times, proper definition of uncertainties (RMS, number of earthquakes and station, azimuthal distribution of ray path, etc.) and extensive use of synthetic tests for defining the correct parameterization of the model and assessing its resolution [1,2,3]. At least 300 local earthquakes recorded by at least 9 stations can be enough to understand the seismic velocity structure of the project area. Geological settings and other efforts (e.g., seismic reflection, magneto-telluric, micro-gravity, etc.) are also particularly important to address in increasing and enhancing the resolution and robustness of the reservoir modelling of a geothermal area [3]. Another used technique is the ANT. In recent years, number of small or local-scale studies related with this technique has also significantly grown due to its great applicability in fields like fluid injection monitoring and geothermal reservoir modelling, hydrocarbon exploration, geological engineering studies, imaging of caldera of volcanos and fault mapping in determining seismic hazard. The ANT uses ambient seismic noise that is typically dominated by oceanic microseisms and shows peaks around frequencies of 0.05-0.1 Hz and 0.1-0.2 Hz. Microseisms propagate predominantly as surface waves (Rayleigh & Love)[4]. Therefore, the simultaneously cross-correlated seismic noise and calculated Empirical Green's Functions (GF) are dominated by the surface wave components. They certainly lead to reveal underground image of target areas by tomographic inversions. The main advantage of this technique is the usability of noise sources and does not require earthquake data in a target region that shows low seismicity rate. On the other hand, the lateral resolutions of the ANT greatly depend on the interstation distances. This may bring disadvantage for small-scale regions if station numbers and consequently ray paths are not sufficient. To overcome this difficulty, we suggest a station installation geometry at least 15 km diameter for geothermal license areas to resolve down to 3 km depths at least [4]. As a result, taking the advantage of earthquake data analyzed by the LET technique will unquestionably increase the multi-dimensional spatial resolution and underground imaging efforts obtained from the ANT technique.

Data processing is the most important stage in reservoir seismology (and ANT) as with all other geophysical methods. According to time and frequency domain analysis, the 3-month continuous data may need to be divided by 10-minute (600 s) windows with 25% (150 s) of the windows overlapping in time length, removing the mean & trends and decimating to 10 sps. It should be also considered that each window should be filtered with a Butterworth filter with corner frequencies depending on the interested depths. 0.1-1.0 Hz may resolve the target reservoir starting from ~500-meter depth. Illuminating shallower depths may require lower frequency ranges (e.g., 0.01-1.0 Hz or much lower). The next important step will be the data normalization in time and frequency domains. Redundant recordings such as mainshocks, aftershocks, inconsistent peaks and anthropogenic activities should be erased in the time domain. Spectral whitening needs to be applied in the frequency domain and the high-energetic (positive or negative lag) of the signals should be folded [5, 6, 7]. After processing the best cross-correlation functions, they can be stacked to extract GFs with signal-to-noise ratios (SNR). The SNR should be considered with the RMS of the noise window. Then, a multi-filter technique should to applied to obtain the group velocities of the GF. It should be also noted that an optimal resolution in the time and the frequency domains can be only achieved using a suitable Gaussian operator coefficient, which considers the interstation distances. A value of 1.5 will be reliable for the interstation distances less than 20 km, and a value of 3.0 can be thought for much greater distances. Group velocity dispersions are calculated under the interstation distance (Δ) and wave-length (λ) conditions.

The tomography inversion scheme estimates the 2-D group velocity maps of the fundamental mode Rayleigh waves. As outlined for the LET, users should also consider an iterative inversion package to minimize the difference between the observed and the calculated travel times. Checkerboard synthetic test requires both LET and ANT techniques to evaluate the reliability of the resolved model. It mainly depends on the path coverage at specific periods and the azimuthal distribution of paths. Checkerboard box sizes for the input model should be considered according to the size of the studied area. It can be selected as 1x1 km (0.01x0.01°) for a target area 10x10 km, roughly. And, the inversion cell size can be fixed to 0.5x0.5 km (0.005x0.005°). But analyzing the whole dataset needs to be checked by users first, and then the optimal cell size used in the inversion should be decided after extensive synthetic tests. Because this optimal cell size will absolutely serve to illuminate a robust and stable tomographic images [8]. After that, surface-wave travel-time tomography can be performed for a small-scale geothermal area using 0.5x0.5 km grid size to produce 2-D group (Rayleigh) wave velocity maps. As mentioned in the previous paragraph, each group velocity was proportional to a given depth range for which the average value was proportional to one-two (or one-third) of the dominant wavelength, approximately ($\Delta \geq 2\lambda$ or $\Delta \geq 3\lambda$). However, the calculated sensitivity kernel of the group velocities provides convincing information about the depth resolution as a function of the period lengths. If the information reveals 1 s, 3s, 7s periods, it can be associated with the depths of 0.5 km, 1.5 km, and 4.0/5.0 km, respectively (Figure 1).

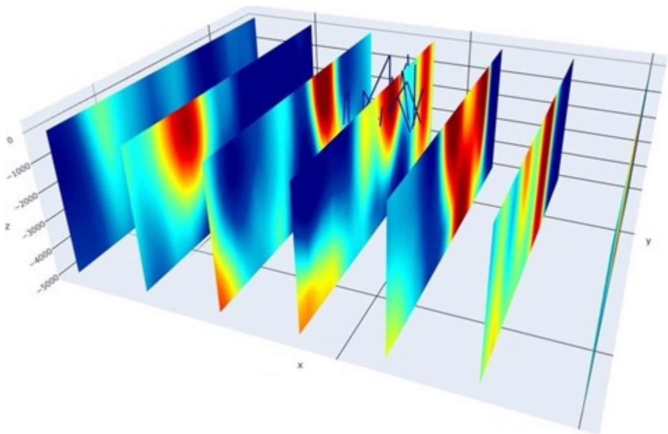

Figure 1. The 2-D visualization of different Vs (m/s) model slices on planar x, y, z coordinates as the latitude, longitude (°), and depth (m) axes for a targeted geothermal area down to ~5.0 km depths. Colors vary from red to blue by indicating low and high velocities [9]

Almost all inversion packages ignore altitudes which are quite important for decision-makers for future planned operations in selecting re-injection/production wells. A recent effort has just started to overcome this complexity in the frame of a new multi-dimensional modelling interface/code [9].

3. Conclusions

In this research, we have shown the essentials of reservoir modelling in small-scale geothermal areas in the frame of reservoir seismology (and ambient noise tomography) studies. In order to perform multi-dimensional modellings and characterize the geothermal reservoir of a study area, this type of studies should consider the data characteristic, data processing and tomography inversion scheme.

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Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. 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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