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Seismic Sensor Configuration Design for a Geothermal Field to Monitor High-Resolution Seismicity

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ABSTRACT

Micro-seismicity has been reported to be induced by both developing or operating geothermal field. In the developing stage, to create underground cracks for water circulation within geothermal wells, hydraulic fracturing is frequently employed. High pressure water fluid will be injected into borehole to create fractures. In the producing stage, continuous extraction hot water and injection cool water fluid is a standard procedure. Condition monitoring of seismic activity of geothermal field is important to re-modulate, interrupt and restart of industrial activities. To monitoring micro-seismic activity, dense seismic stations on surface and sub-surface are usually deployed to track high-resolution seismicity spatial-temporal evolution. To optimize the design of a seismic network and increase the detection/location resolution of a small event. In this study, a multiple station earthquake method based on grid search technique has been developed. This algorithm has employed to evaluate the travel time residuals of earthquake within networks of special layouts. Based on the message of distribution size of travel time residual pattern, network performance of event location is calculated. We evaluated and compared the performance of different layouts (surface deployment and small seismic arrays) in terms of detection/location threshold and location errors to design optimize array. The proposed design procedure has been suggested to plan the seismic network of a geothermal field in Taiwan.

1. INTRODUCTION

With the development of both conventional and unconventional resources in the world, induced seismicity caused by industrial activities has been observed, documented, and studied (Grigoli and Wiemer, 2017). Currently, water injection into geothermal systems has become a nearly universal and often required strategy for extended and sustained production of geothermal resources. Seismic events near water injection sites can lead to costly operational suspensions or shut downs and serious public and regulatory concerns. Reports from the geothermal fields of the Geysers (California, US), Basel (Switzerland) and Pohang (South Korea) have been illustrated as examples of such situation (Martínez-Garzón et al. 2016; Häring et al., 2008; Kim et al., 2018). The induced earthquake and its increasing seismicity are usually considered as suspicion that some active faults might have been lubricated and events triggered by its nearby geothermal activities. Hence, the monitoring of induced seismicity has become an important objective as geothermal production operation.

Typical real-time seismic monitoring of tectonic earthquakes networks is usually provided such case in first step. However, geothermal activity induced earthquakes have signatures of local and shallow concentrated events. Regional seismic network usually can not provide enough resolution for requirement. To establish a baseline of local seismic activity, a seismic network or array of appropriate size and geometry to properly measure and locate seismic events is necessary. It can be a permanent or with a temporary network. By building a high-resolution record of both natural and induced seismic activity, it can quickly evaluate when felt events are within your areas of operation, helping you to control risks. However, the distribution of seismic station configuration may affect the performances of event detection and its accuracy. To optimize the design of a seismic network and increase the detection/location resolution of a small event, in this study, we evaluated and compared the performance of different layouts (surface deployment and small seismic arrays) in terms of detection/location threshold and location errors by numerical simulation.

2. METHOD

In the case of an earthquake, to determine exact location (hypocenter) and its occurrence time (origin time) are both most important tasks in practical seismology. The hypocenter and origin time are usually determined by seismic first arrival times (P-waves) and incidence directions recorded by multiple seismic stations. Standard earthquake catalogs (such as from the International Seismological Center, ISC or the National Earthquake Information Center (NEIC) of the USGS) report origin times and locations based primarily on arrival times of high-frequency first P-wave arrivals. Although this assumption does not always hold, especially for great earthquakes, however, it is acceptable for both natural and induced seismic activity with small magnitudes.

2.1 Multiple station earthquake location

In general, it is also possible to locate a seismic source using a single 3-component station (Shearer, 1999). With a single station, the direction to the seismic source (backazimuth) is calculated from the polarization of P-wave motion in the vertical plane. The distance can also be obtained from the difference in arrival time of two direct arrival phases, usually P and S (second wave). When at least 3 stations are available, a simple manual location can be made from drawing circles (the circle method) with the center at the station locations and the radii equal to the distances calculated from the S-P times (Shearer, 1999). These circles will cross in one point and considered as the epicenter. However, the location may be error due to the assumed velocity model.

In practice, earthquake location is determined using many seismic phase observations from seismic network stations and its calculation to be relied on computer. In the following, the most common ways of calculating hypocenter and origin time by computer will be described. The calculated arrival time t_i^c at station i can be written as

$$t_i^c = T(x_i, y_i, z_i, x_0, y_0, z_0) + t_0 \qquad (1)$$

where T is the travel time as a function of the location of the station (x_i, y_i, z_i) and the hypocenter. This equation has 4 unknowns, so in principle 4 arrival-time observations (P or S wave) from at least 3 stations are needed in order to determine the hypocenter and origin time. If we have n observations, there will be n equations of the above type and the system is overdetermined and has to be solved in such a way that the misfit or residual r_i at each station is minimized. r_i is defined as the difference between the observed and calculated travel times which is the same as the difference between the observed and calculated arrival times

$$r_i = t_i^o - t_i^c \qquad (2)$$

where t_i^o is the observed arrival time. The travel-time function T is a nonlinear function of the model parameters, it is not possible to solve Equation (1) with any analytical methods.

2.2 Event location based on grid search

In the following, the grid search method of solving this problem will be discussed. Since it is easy to calculate the travel times of all seismic phases to any point in a selected model by computer, a simple way is to perform a grid search over all possible locations and origin times and compute the arrival time at each station (Havskov et al., 2012). The hypocentral location and origin time would then be the point with the best agreement between the observed and calculated times. The most common approach is to use the least squares solution, which is to find the minimum of the sum of the squared residuals e from the n observations:

$$e = \sum_{i=0}^{n} (r_i)^2 \qquad (3)$$

The root mean squared residual RMS, is defined as $\sqrt{e/n}$. RMS is given as a guide to location precision and as an indication of the fit of the data. The least squares approach is the most common measure of misfit since it leads to simple forms of the equations in the minimization problems. Once the misfits have been calculated at all grid points, one could assign the point with the lowest RMS as the 'solution'.

In general, no strict definition of a seismic array exists. However, array data need to show high signal coherency across the whole array aperture as well as low coherency of noise between the individual stations. A seismic array differs from a seismic network mainly in the way the data are processed (Schweitzer et al. 2002), but the high signal coherency that is required for most seismic array methods puts constraints onto the usability of network data for array processing. In the case of seismic arrays, apparent velocity and backazimuth can directly be measured by observing the propagation of the seismic wavefront with array methods, independently from the local seismic velocities below the station (Rost and Thomas, 2009). In this study, usage of seismic arrays for seismic source location are also evaluated.

3. ANALYSIS AND RESULTS

3.1 Test for parameter sensitivity

In this study, any location can be selected as seismic station to theoretically compute its travel time from assumed source using the algorithm 'ttimes' The travel time computation program calculates travel-times for seismic phases using a 1-D spherical earth model (Kennett and Engdahl, 1991) and this travel time then was considered as station observation for further evaluation. Based on the grid search method described in above section and its error estimation method, the regional residuals image can be constructed as shown in Figure 1. In this example, the red triangle symbols are assumed as seismic stations with earthquake occurred at the center of the cross-shape station distribution. The observations are computed based on computer program 'ttimes'. All grid points within this map have been considered as a possible event location and computed its travel times to all stations (red triangles). The residual of each grid was computed based on equation (3) and estimated its RMS following. As shown in Figure 1, the minimum error is located at the center of map (true location) and residual errors symmetric distributed.

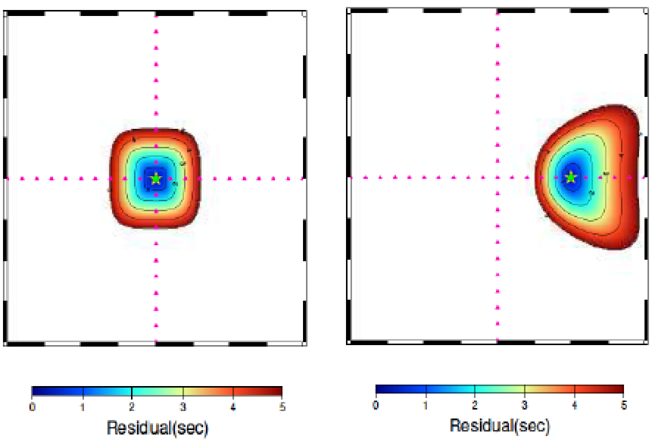

Figure 1: The distribution of travel time residual maps for earthquake located two sites within network. Seismic sensors are distributed as cross-shape (Red triangles) for test. The residuals are shown as image plotted based on color bar below.

To test the residuals distribution with respect to seismic network pattern, we selected a network with three stations (Figure 2). Four events are selected as the yellow symbol in each panel, the residual distribution as shown in each panel also. Although the grid search results have matched the true locations of earthquake, however, the residual distribution are changed with respect to its locations. The residuals is related to well constrain with stations and larger residuals far from stations (Figure 2).

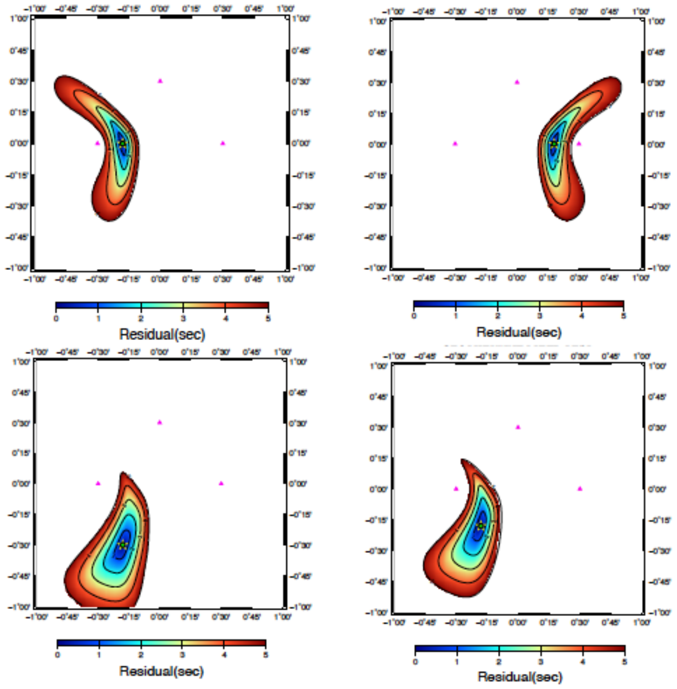

Figure 2: Test for ravel time residual distribution with respect to station location. Yellow star represents the event location.

To test the residuals distribution with respect to seismic network size, we selected two networks with the exact station distribution, small network size with 10 km x10 km in horizonal plan and the large one with100km x 100km (Figure 3). The station spacing of large network is 10 time of the small one. Both models shared the same velocity structure, For an shallow event with depth 4.3 km, the residual pattern after the grid search is shown in Figure 3. The pattern in horizonal is similar although scale up in station spacing, however it is significant variation in depth distribution.

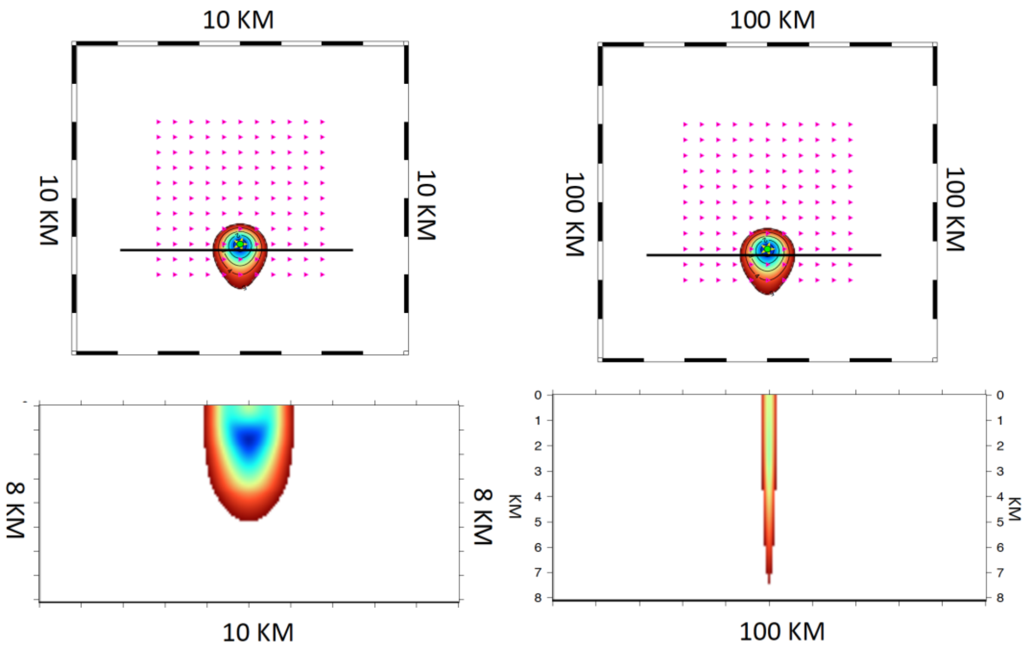

Figure 3: Test for model size and source depth (4.3 km) with same velocity structure. Left: Small scale model (10 km x 10 km). Right: Regional scale crustal model (100 km x 100 km).

To locate earthquake, simplified seismic velocity model is usually employed. However, event location and its residuals affected by variation of velocity model always is unclear. In this study, we proposed a numerical case to check this issue. Figure 4 presented grid search results of true velocity model (1D) and its velocity perturbation in its value and depths. It is shown that the 1D velocity model is not a significant parameter to affect its residual pattern and exact location.

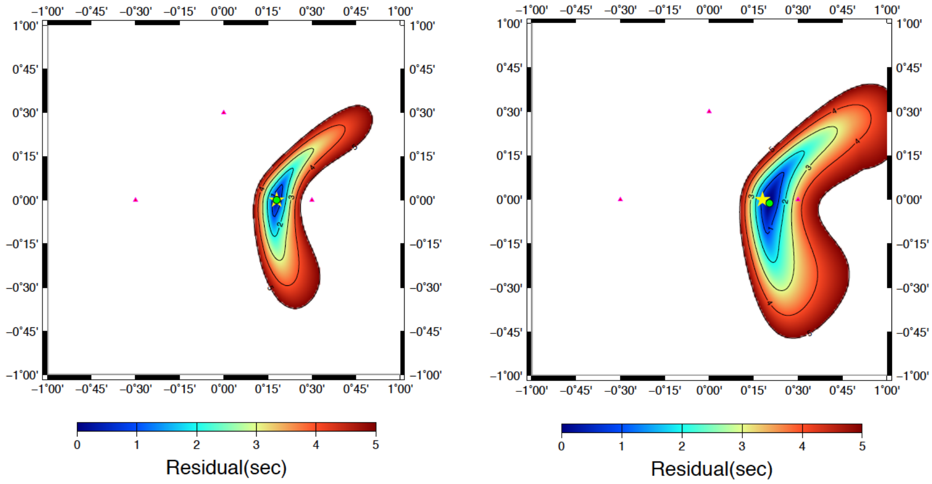

Figure 4: Grid search to test the effect of seismic velocity model perturbation. Left: location with true velocity mode. Right: result from a velocity perturbed model.

3.2 Test for seismic network layout on a geothermal field

Based on the tested sensitivity parameters described above, we designed five array layouts to test its travel time residual patterns. The best array resolution should provide the most concentrated residual pattern under the same number of stations. In this study, to test the performance of a seismic network with special configuration, we have selected constant number of seismic stations for each case. The station number is fixed as 41 stations for all test station layouts. Furthermore, we considered surface deployment for each seismic network and no downhole stations included. Five seismic networks (arrays) are designed for test (Figure 5). It is (1). Cross network, (2) L-shape network, (3). Square network, (4). Group network and (5). Equal distribution network. Five layouts are designed to fit possible topographic and traffic conditions usually faced during the seismic array deployment. Of course, the simple geometric pattern of our layouts may be used as elements for further combination.

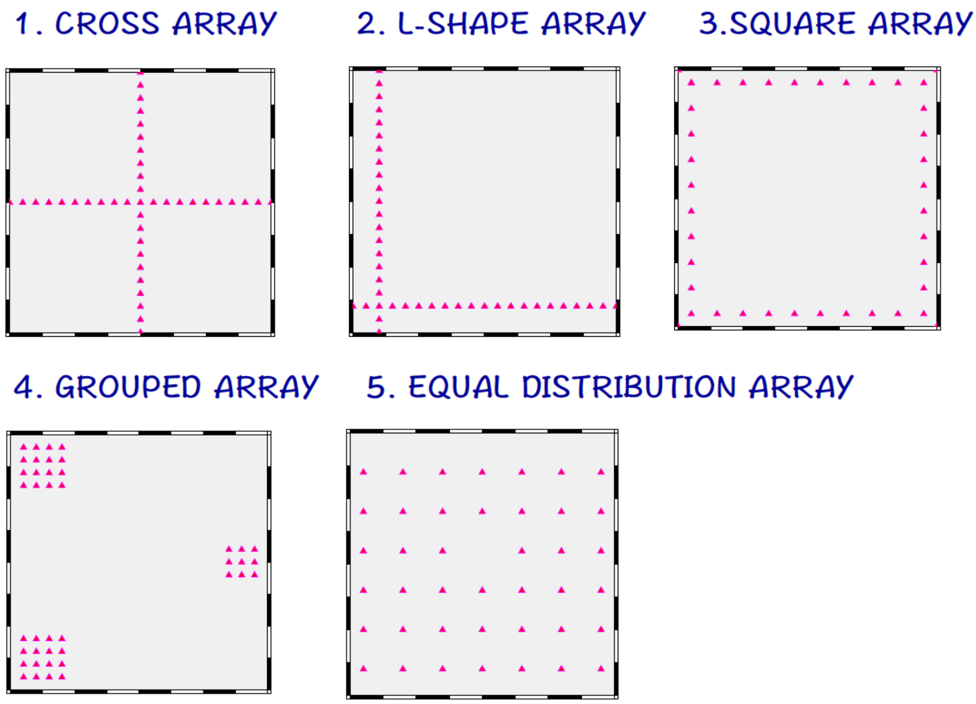

Figure 5: Five seismic network configurations for performance testing.

Figure 6 provides an example for the simulated travel time residual patterns of events located at different sites within the cross array. The travel time residual is the concentrated at the array center, the pattern is symmetry when the event near the station line. However, the travel time residual will increase as event far away any stations. Due to the symmetric properties of cross array, the pattern is symmetry up and down, left and right.

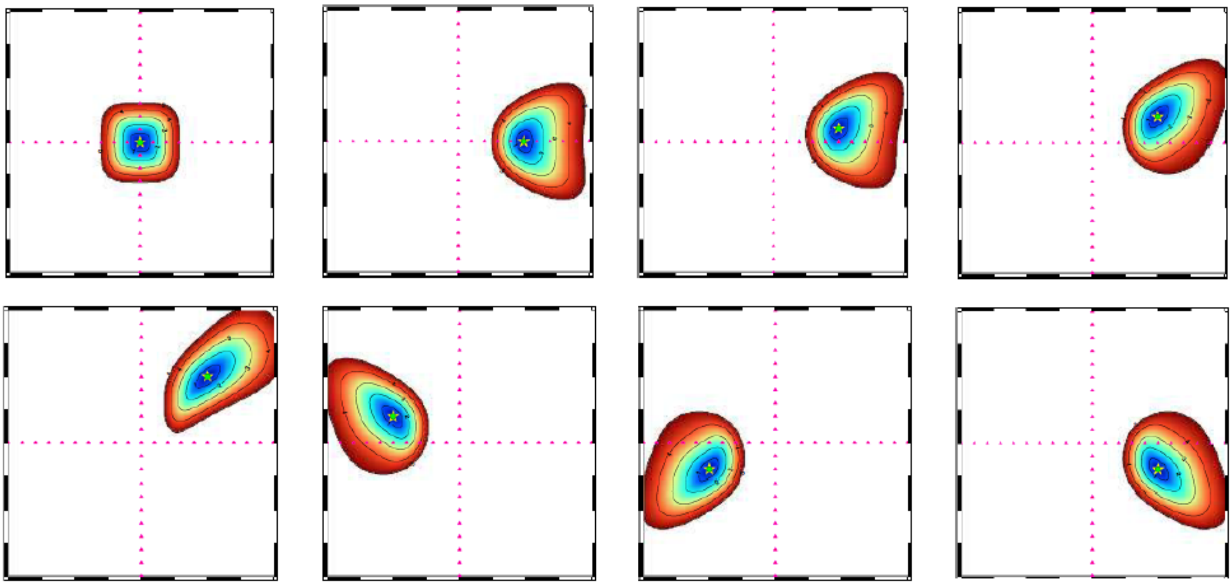

Figure 6: Test for ravel time residual distribution of the cross network.

Based on the grid search technique, all other 4 array configurations have been numerically simulated and list in Figure 7. The L-shape array has a similar simulated travel time residual patterns of cross network. However, the residuals are larger far from array center. Square array provided a consistent travel time residual patterns inside the network. Although the square has good general performance within array, however, no station inside this array, the travel time residual patterns cannot significantly reduce inside array. The group array shows a diverse pattern of residual with array. It has good performance in the center of array and residual patterns are not symmetry in its boarder. The equal distribution array has a good and uniform performance inside the array and this values are larger near its boarder.

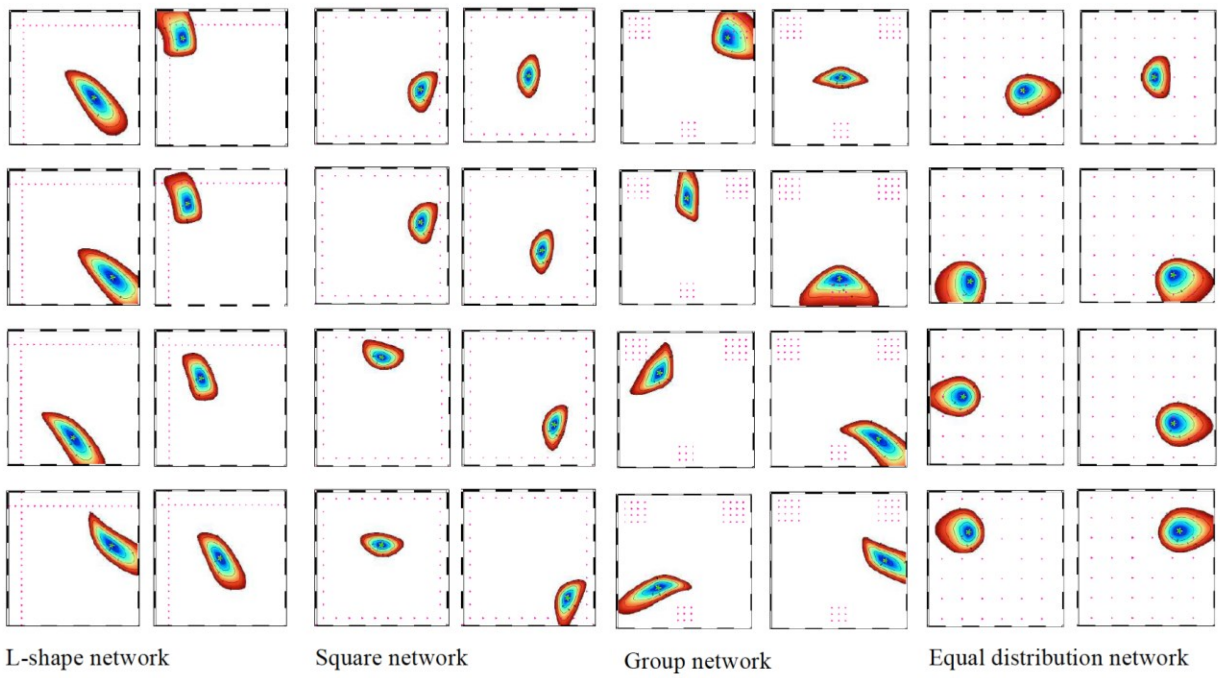

Figure 7: Test for ravel time residual distribution of the other four networks of Figure 5.

The forward grid searching for travel time residual pattern of any seismic array can be generated using the method proposed in this study and employed to discuss the performance of station within array by different configuration. However, the array performance cannot be evaluated because the trivial description of the simulated travel time residual pattern of each event location. To evaluate event location performance of selected array, we compute the numerical summation and defined an equal residual area from any array station and sum all residual area using events equal distributed within this array. Figure 8 is an example of the determined residual image from the equal distribution array (Figure 5). This approach provided an evaluation of seismic array about its event location accuracy within this array. We use grid search technique and any array configuration can be consistence to evaluate and get consistent evaluation. It shows that the event within the center of array has been located in good performance. Although the event near the array boarder can be located to its exact location as shown in Figure 7, however, the potential location error is larger than the array center if some observation error included.

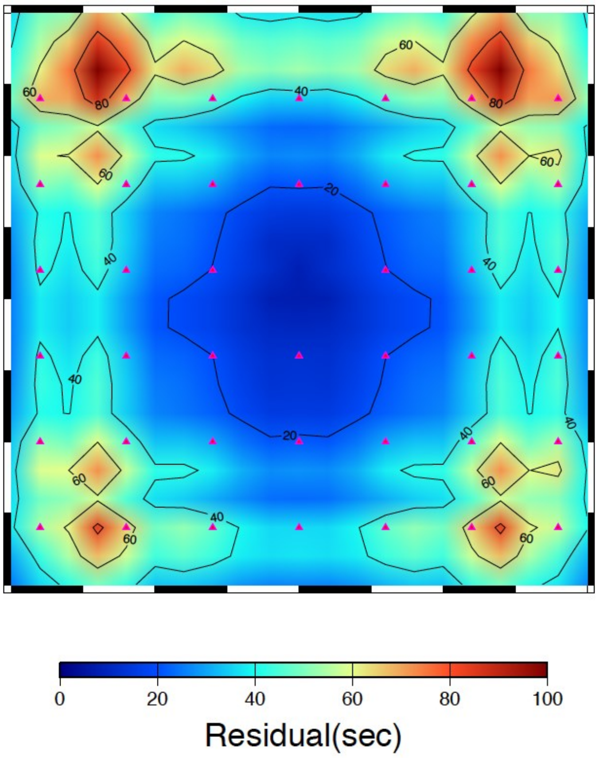

Figure 8: Computed travel time residuals of events within the equal distribution network (see Figure 5).

4. DISCUSSIONS AND CONCLUSION

In this study, a multiple station earthquake method based on grid search technique has been developed. This algorithm has employed to evaluate the travel time residuals of earthquake within networks of special layouts. Based on the message of distribution size of travel time residual pattern, network performance of event location is estimated. To optimize the design of a seismic network and increase the detection/location resolution of a small event, we have evaluated and checked the performance seismic networks. We evaluated and compared the performance of different layouts (surface deployment and small seismic arrays) in terms of detection/location threshold and location errors. In this study, based on grid search technique, five typical seismic network layouts have been proposed to test its array performance to locate earthquakes. In conclusion, the equal distribution network has the best event detection ability for events inside network. However, there are several factors may affect the accuracies of event location, for example, the regional seismic velocity model which is shown in Figure 4. Furthermore, the installation of deep borehole stations may provide extra constrain to locate earthquake. However, shallow borehole station has contributed to reduce background noise and do not provide constrain to event depth.

Micro-seismicity has been reported to be induced by both developing or operating geothermal field. Condition monitoring of seismic activity of geothermal field is important to re-modulate, interrupt and restart of industrial activities. To monitoring micro-seismic activity, dense seismic stations on surface and sub-surface are usually deployed to track high-resolution seismicity spatial-temporal evolution. Through the method proposed in this study, event location performance of any seismic array can be numerically simulated and systematically evaluated. The proposed design procedure has been suggested to plan the seismic network of a geothermal field in Taiwan.

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