Checkerboard resolution test for natural earthquake tomography of volcanic islands in Tokyo

Kentaro OMORI[1] and Yoshiya ODA[1]

[1]Dept.of Civil and Environmental. Eng., Tokyo Metropolitan University

In natural earthquake tomography targeting a single volcano, temporary seismic observation is carried out in order to improve resolution in general. However, since the number of observation points and observation period are limited, it is important to grasp the presumable resolution in advance. Therefore, we conducted to examine how much resolution we can estimate the underground velocity structure by performing temporary seismic observation with how many observation points and observation period (the number of earthquakes), when carrying out natural seismic tomography on Hachijojima, Kozushima and Niijima of volcanic islands in Tokyo by using numerical experiments, a checkerboard resolution test (CRT). CRT is one of the reasonable tests to show the resolution of the natural earthquake tomography and to evaluate the influence of parameters with good resolution (a pair of grid point spacing, observation points and number of earthquakes) on the resolution. As the results of parametric study using CRT, we have found that in every island I have researched, when setting a pair of some grid point spacing, some number of observation points and some number of earthquakes, they were possible to image with a resolution of some degree. Considering that temporary seismic observation will be carried out in volcanic islands, Tokyo, in the future, the data obtained in this study will be very important for establishing the observation plan.

1. INTRODUCTION

Currently, there are 111 active volcanoes in Japan, and about 50 of them are subject to continuous observation. It is easy to imagine that human and physical damage caused by volcanic eruption once will be enormous. Volcanic eruption is a phenomenon in which magma generated in deep underground erupts to the surface, and research on eruption prediction is being advanced from various methods at present. One of them is a seismological approach. Seismological approaches include estimating the behavior of magma caused by volcanic eruptions from changes in amplitude and dominant frequency, using seismic waveforms of volcanic tremor and volcanic earthquakes (Ukawa et al., 1993)1), and using natural earthquakes or artificial earthquakes (0da, 2008) 2). The latter is a method to grasp the underground velocity structure of the volcano using them. Knowing it not only increase the possibility of estimating the presence or absence of magma and its position, but also predict the volcanic activity which are very important to improve the accuracy of determining the hypocenter of volcanic earthquakes. So traveltime tomography (natural earthquake tomography) is widely used as a method of grasping the velocity structure of the inside of the volcano from the initial run of the natural earthquakes.

In natural earthquake tomography, temporary seismic observation may be carried out in order to improve resolution, but since the number of observation points and the observation periods are limited, it is important to grasp the resolution that can be estimated beforehand. Therefore, in this study, we were aimed to know how much resolution the underground velocity structure can be estimated by performing temporary seismic observation with how many observation points and observation periods by numerical experiment on Hachijojima, Kozushima and Niijima of volcanic islands in Tokyo.

Due to the limit of the space, we will discuss about Hachijojima island in this paper.

2. METHOD

Natural earthquake tomography is a method of estimating the underground velocity structure by observing a natural earthquake with a receiver installed on the ground surface and inverse analysis of its initial running time. For the inverse analysis, we used SIMULPS 12 (Evans et al. 1994)3), a three dimensional travel time tomography program, which simultaneously obtains the source location and the underground velocity structure. In addition, in this study, we have performed a checkerboard resolution test (CRT) using a parametric study in which the number of observation points and the number of earthquakes were changed in order to evaluate the resolution of the analysis results. In general, CRT is used to determine the optimum grid point intervals, but in this study, it was used to evaluate the influence of the number of observation points and the observation period with good resolution on the resolution.

Then, the results of CRT, which conventionally was judged only visually, was formulated as shown in equation (1) and quantitatively judged.

$$\bar{\mu}(\%) = \frac{1}{N}\sum_{\mathrm{i}=1}^{\mathrm{N}}\frac{\mathrm{x_i}}{5}\times 100 \qquad (1)$$

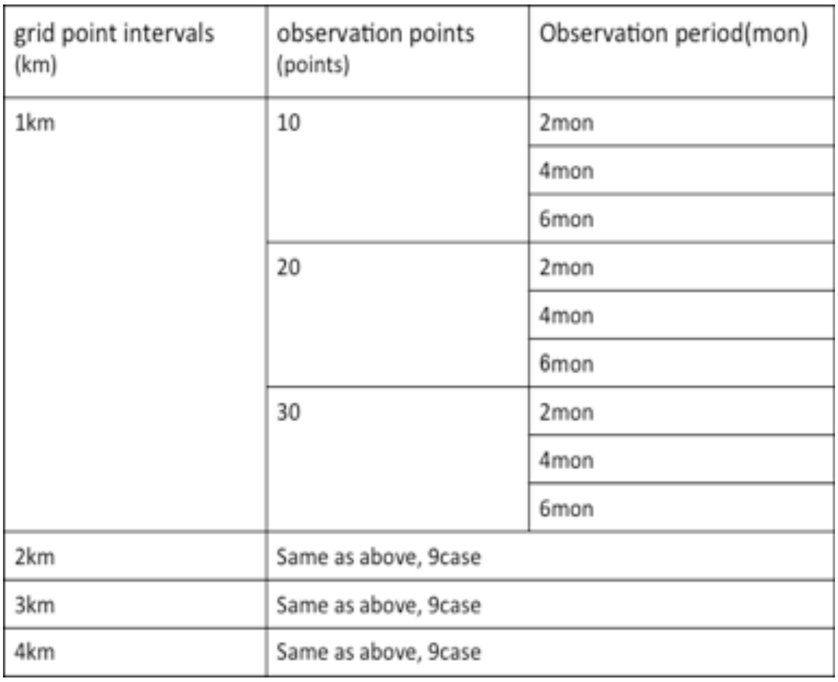
Where 'N' represents the number of grid point that I decided. Of course, this number varies depending on the grid point intervals. X_i represents the recovery rate of CRT (Max.5). $\bar{\mu}$ represents the average of the recovery rate of CRT. In this study, since the grid points adjacent to each other are given ± 5% velocity heterogeneity, the denominator of the recovery rate is 5.

3. DATA

For numerical experiments, we have used earthquakes data that occurred from May 1, 2017 to October 31, 2017, which were referenced tothe Japan Meteorological Agency Unified Hypocenter Catalogues. Parameters used for the analysis are grid point intervals (1 km, 2 km, 3 km, 4 km), observation period (2 months, 4 months, 6 months), observation points (10 points, 20 points, 30 points), thus we have made 36 cases of analysis on each island by varying each. In this study, we assumed that the temporary seismic observation was carried out, so we used the observation period instead of the number of earthquakes as a parameter. The parameters used in this study are shown in **Table 1**. And for the analysis, we have used JMA 2001 (Ueno et al., 2002)$^{4)}$ as the initial velocity model. The initial velocity model used in this study are shown in **Table 2**.

In conducting the analysis, we set arbitrarily the point which is about the center of each island as the origin, In Hachijojima island, There were few seismic activities around its origin, so we used earthquake data occured within 30 km radius, and observation points were randomly placed on the island. **Figure 1** and **Figure 2** represent the locations of the observation points and hypocenters. The analysis area was set at -30km to +30km in the horizontal direction and -2 km to 30 km in the depth direction centering on the east longitude 139˚45.3', north latitude 33˚ 8.33' of the origin.

Table 1 The parameters used in this study



grid point intervals (km)	observation points (points)	Observation period(mon)
1km	10	2mon
		4mon
		6mon
	20	2mon
		4mon
		6mon
	30	2mon
		4mon
		6mon
2km	Same as above, 9case	
3km	Same as above, 9case	
4km	Same as above, 9case	

Table 2 Initial velocity model

Depth(km)	Vp(km/s)	Vp/Vs
0.0	2.84	1.73
2.0	3.16	1.73
4.0	3.38	1.73
6.0	3.45	1.73
8.0	3.49	1.73
10.0	3.53	1.73
12.0	3.57	1.73
14.0	3.61	1.73
16.0	3.66	1.73

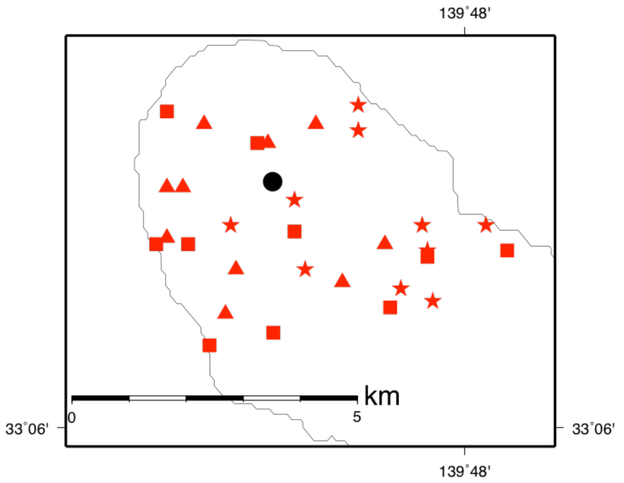


Figure 1 Observation point distribution map of Hachijojima. Black point: origin red triangle: observation point 1 to 10, red square: observation point 11 to 20, red star: observation point 21 to 30.

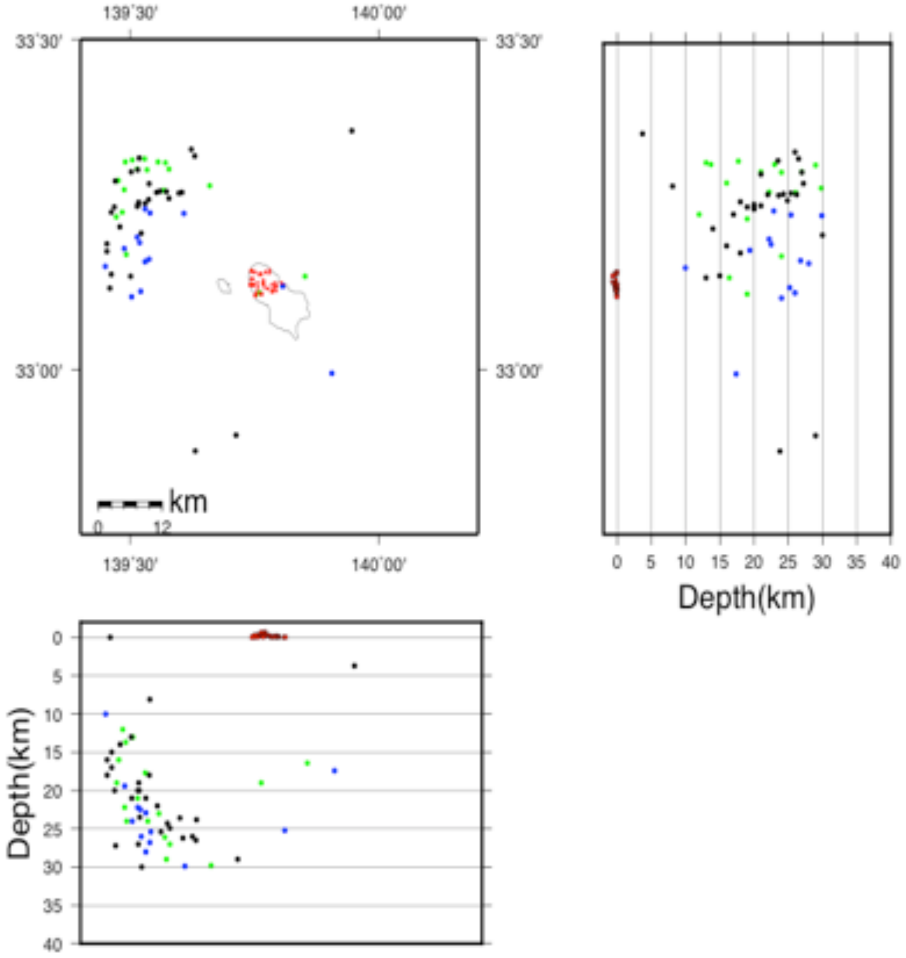


Figure 2 Observation point of Hachijojima and hypocenter distribution map. Red dot: Observation point 1 to 30, Green circle: Earthquake hypocenter from September 1 to October 30, 2017, Black circle: Earthquake hypocenter from July 1 to August 31, 2017, Blue circle: Earthquake May 1 to June 30, 2017.

4. RESULTS AND DISCUSION

The distribution of hypocenters around Hachijojima is concentrated around off the northwest of the island and the seismicity were remarkably low in the other areas. For that reason, the accuracy and the resolution were trlatively low in the area where the raypath density was low in every case (**Figure 3**). In the northwest area of the island, a certain degree of resolution compared with other areas was able to obtain, but in many cases the resolution was low because of those reason.

Tables 3, **Tables 4**, and **Tables 5** show the CRT recovery rates at depths of 2 km, 4 km, and 6 km respectively.It was confirmed that the recovery rate is close to 50% up to 4 km depth at any grid spacing using more than 20 stations and 6 months observation. However at depths of 6 km or more, any set of parameters had low resolution, and none exhibited a recovery rate of nearly 50%. Regarding the grid spacing, if the grid spacing is set to 2 km or more in Hachijojima which is small island, the island is represented by one or two grid points. Therefore, to interpret beneath the volcano, setting the grid spacing to 1 km or less would be preferable. In this study, we argued that we can image with some resolution up to the depth of 4 km, but it would be preferable to increase the number of observations and the number of earthquakes in order to grasp the presence and position of melt such as magma located in the deep part of the volcano. Finally, I show the results of the CRT (**Figure 3**). This is the result of the CRT of the pair of parameters of grid interval 1 km, observation point 30 points, observation period 6 months, which could be expressed with a certain degree of resolution up to a depth of 4 km.

Tables 3 Recovery rate of CRT with depth of 2 km

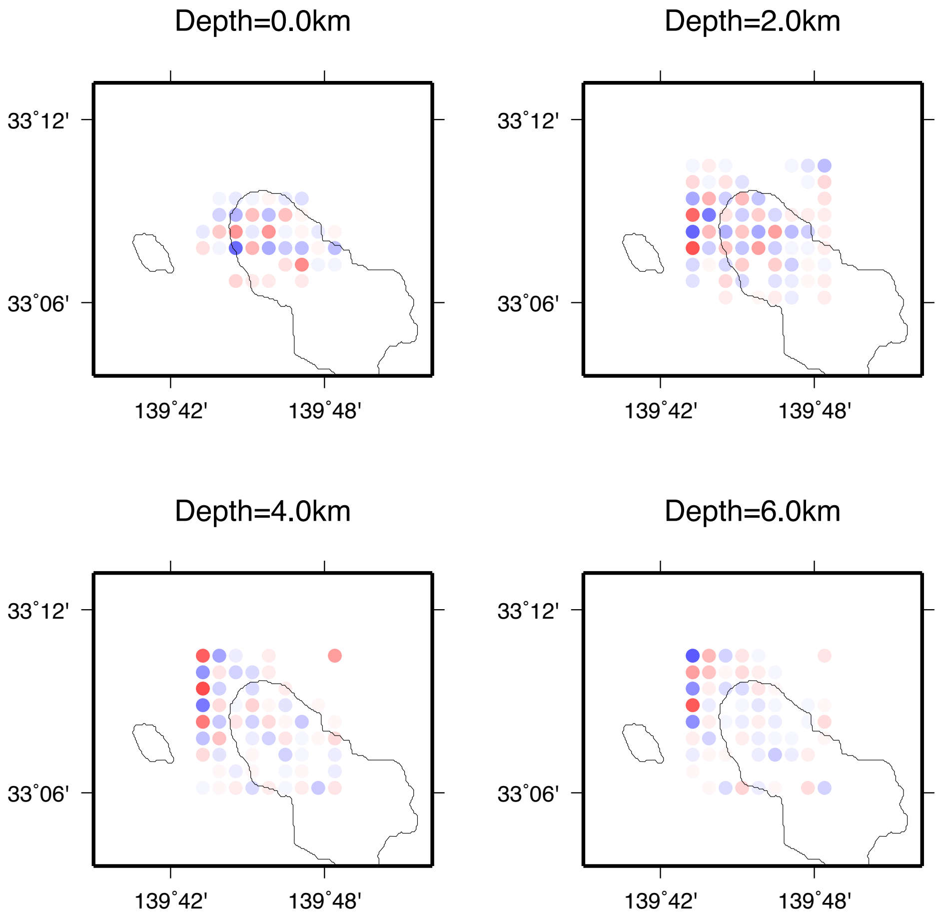
	Grid point intervals1km	Grid point intervals2km	Grid point intervals3km	Grid point intervals4km
Observation points10 Observation piriod2mon	−10.5%	−3.2%	5.1%	−3.0%
Observation points10 Observation piriod4mon	4.8%	6.8%	20.2%	9.4%
Observation points10 Observation piriod6mon	5.9%	6.9%	21.4%	9.4%
Observation points20 Observation piriod2mon	−4.1%	1.2%	3.8%	−0.1%
Observation points20 Observation piriod4mon	18.3%	20.3%	35.1%	32.5%
Observation points20 Observation piriod6mon	46.0%	49.1%	49.4%	44.2%
Observation points30 Observation piriod2mon	4.2%	2.2%	6.6%	7.1%
Observation points30 Observation piriod4mon	35.8%	36.1%	48.1%	42.8%
Observation points30 Observation piriod6mon	50.1%	49.2%	72.2%	48.1%

Tables 4 Recovery rate of CRT with depth of 4 km

	Grid point intervals1km	Grid point intervals2km	Grid point intervals3km	Grid point intervals4km
Observation points10 Observation piriod2mon	−7.0%	0.5%	−5.2%	0.9%
Observation points10 Observation piriod4mon	1.2%	2.6%	−0.8%	1.1%
Observation points10 Observation piriod6mon	1.5%	6.3%	−0.1%	9.5%
Observation points20 Observation piriod2mon	−0.7%	0.1%	0.2%	1.0%
Observation points20 Observation piriod4mon	2.2%	4.5%	3.6%	−0.3%
Observation points20 Observation piriod6mon	40.0%	41.1%	50.1%	40.1%
Observation points30 Observation piriod2mon	1.4%	−4.4%	5.4%	−1.1%
Observation points30 Observation piriod4mon	28.4%	5.2%	5.8%	3.2%
Observation points30 Observation piriod6mon	48.0%	40.5%	55.0%	40.1%

Tables 5 Recovery rate of CRT with depth of 6 km

	Grid point intervals1km	Grid point intervals2km	Grid point intervals3km	Grid point intervals4km
Observation points10 Observation piriod2mon	0.5%	0.8%	1.1%	−1.5%
Observation points10 Observation piriod4mon	3.2%	0.9%	6.3%	0.8%
Observation points10 Observation piriod6mon	7.6%	12.1%	7.1%	2.7%
Observation points20 Observation piriod2mon	0.1%	10.7%	0.1%	−3.0%
Observation points20 Observation piriod4mon	12.3%	18.4%	1.4%	−3.5%
Observation points20 Observation piriod6mon	38.1%	32.1%	2.2%	5.1%
Observation points30 Observation piriod2mon	−0.5%	4.8%	−0.1%	−4.9%
Observation points30 Observation piriod4mon	20.1%	8.1%	0.4%	−2.8%
Observation points30 Observation piriod6mon	39.1%	29.1%	40.2%	1.2%



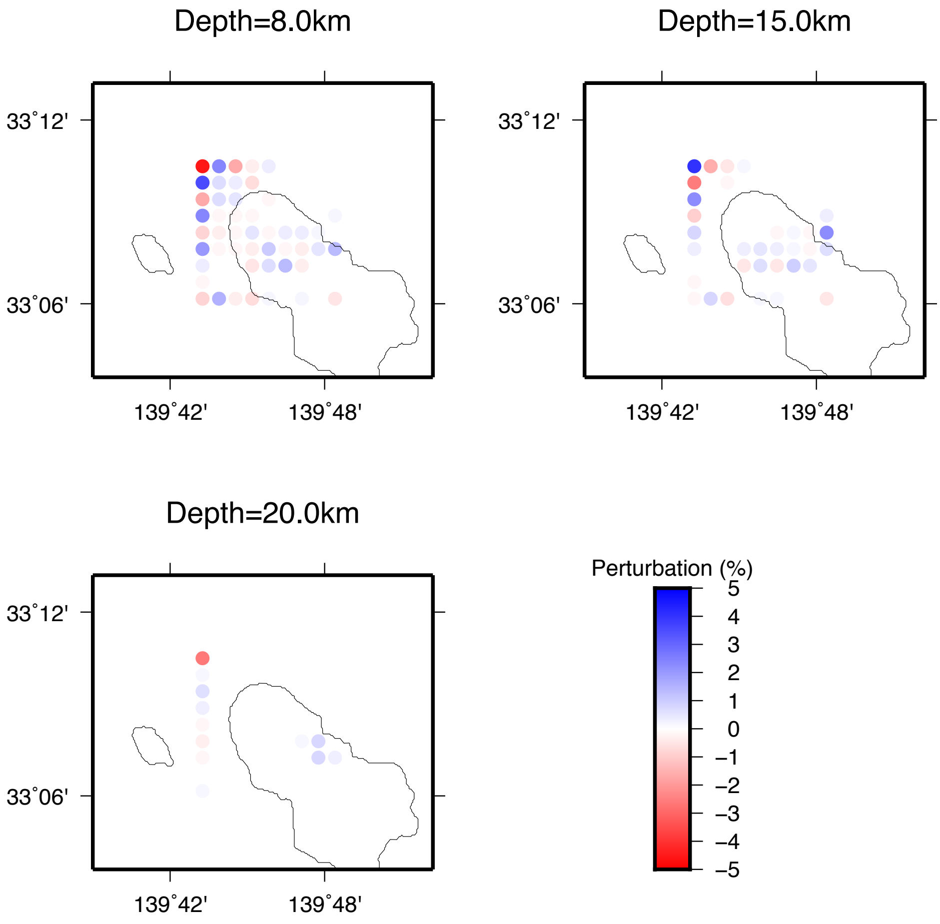


Figure 3 results of the CRT (grid interval 1 km, observation point 30 points, observation period 6 months)

5. CONCLUSION

In this study, we studied the resolution of Hachijojima Nishiyama, Kozujima and Niijima belonging to the volcanic islands of Tokyo using natural earthquake tomography. As a result of numerical experiments, we grasped that Hachijojima Nishiyama can image with some resolution up to 4 km deep. However, it was impossible to image with high resolution at depths below 6 km overall. It is because, in the volcanic islands targeted in this study, the number of earthquakes that occurred just below the islands were small and raypath density was low. Since the occurrence of a natural earthquake is unknown, it can not be said unconditionally, but when performing temporary seismic observation, in order to image the underground structure with higher resolution, it would be necessary to consider observation for more than 6 months I set this study.

REFERENCES

1) Ukawa, M. and Obara, K., 1993, Low Frequency Earthquakes around Moho beneath the Volcanic Front in the Kanto District, Central Japan, *Volcano*, **38**, no. 6, 187-197.
2) Oda, Y., 2008., Seismic Velocity Structure beneath Hakone Volcano, *Res. Rep. Kanagawa prefect. Mus. Nat. Hist.* **13**, 171-186
3) Evans, J.R., Eberhart-Phillips, D. and Thuber, C.H., 1994, User's manual for Simulps12 for imaging Vp and Vp/Vs :A derivative of the "Thuber" tomographic inversion Simul3 for local earthquakes and explosions, *USGS- OFR* -, 94-431.
4) Ueno, H., Hatakeyama, S., Aketagawa, T., Funasaki, J. and Hamada, N., 2002, Improvement of hypocenter determination procedures in the Japan Meteorological Agency, *Quarterly Journal of Seismology* 65, 123-134.