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Effect of Velocity Model on Hypocenter Determination by Small Networks

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Abstract: This study investigates the effects of the velocity model on the hypocenter determination using data from a quarry explosion. Travel times were observed within about 7 km around the quarry. The shot position was determined for three different velocity models; the model derived from travel time data and two arbitrary models. The results are summarized as follows. (1) Errors in determined shot position are small irrespective of velocity models if the observation points surround the shot. (2) In cases of biased distribution of observation points, an improper model causes unstable solutions. (3) A knowledge of the average velocity structure can make a considerable contribution to determining the shot position so long as the origin time is not concerned.

Deviation of the determined shot position from the true location was compared with the errors estimated by three different methods.

1. Introduction

In recent years, the accuracy of hypocenter determination by small networks has been studied through numerical experiments (Peters and Crosson, 1972; Lilwall and Francis, 1978; Uhrhammer, 1980; Duschenes *et al.*, 1983; Pavlis and Hokanson, 1985; Pavlis, 1986). In these studies errors in the velocity model are not considered or assumed to be small compared with velocity uncertainties inherent in the real earth. It may be difficult to choose a 'reasonable' extent of the modeling error in numerical experiments, because the modeling error varies greatly from region to region.

In order to investigate the effect of modeling errors on hypocenter location in the actual cases, studies by using the observation data from artificial earthquakes are useful. Asano (1954) determined locations of explosions by a small (100 m × 100 m) network and examined the hypocentral errors. Using the data from large seismic explosions, Asano (1959) and Horiuchi *et al.* (1981) investigated accuracy of hypocenter determination by the networks of the Japan Meteorological Agency and the Tohoku University, respectively. However, studies of this kind are few.

In this study, we examine the influence of the velocity model on hypocenter determination by using travel times from a quarry explosion.

2. Data

The locations of shot and observation points are shown in Fig. 1. We observed seismic waves using 2-Hz geophones and portable FM cassette recorders at three to five points for one shot. Recorded signals were sampled at 250 Hz and first arrivals were read on the graphic display. Reading errors were mostly within +/−0.02 sec. Shot

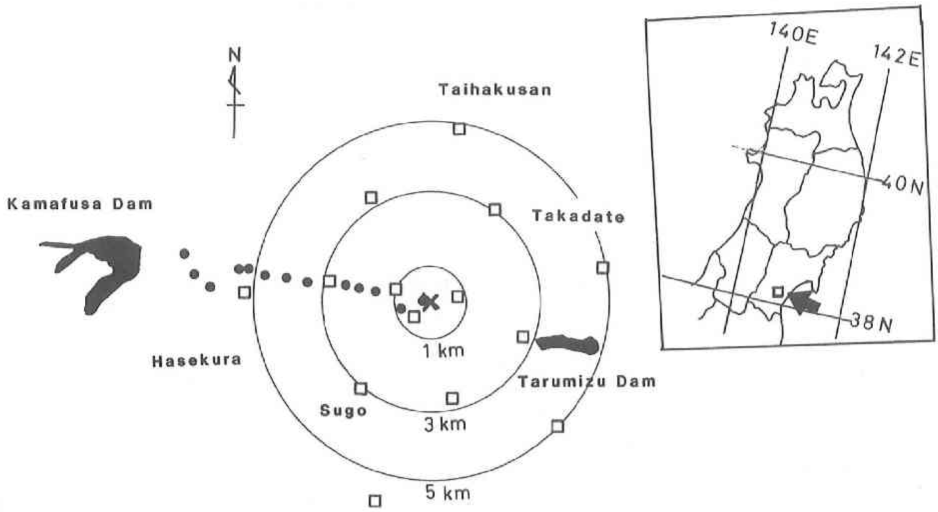

Fig. 1 Location of quarry explosion (cross) and observation points (solid circles and open squares). Open squares indicate the observation points used for determination of shot position, and solid circles those used for determination of the velocity model.

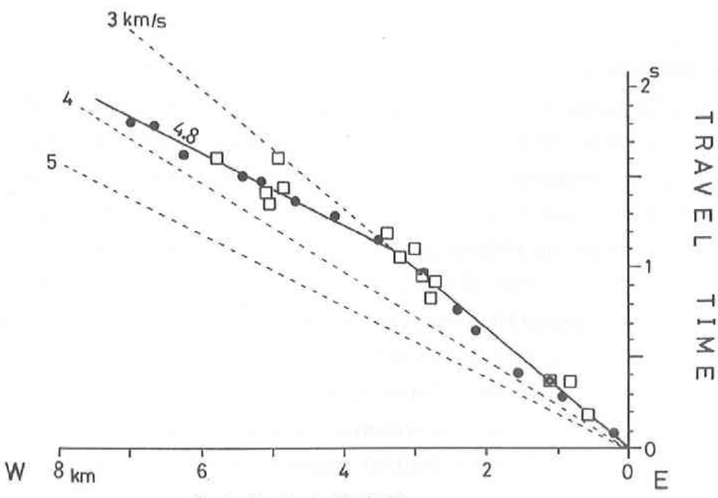

Fig. 2 Travel time curve. Open squares indicate the data used for determination of the shot position, and solid circles those used for determination of the velocity model. Solid lines are the travel times expected theoretically for model I given in Table 1.

times were recorded by using a disposable pick-up (a small speaker) which was put on the explosive hole. We observed signals for every shot at the point (reference point) where the travel time from the shot position was accurately determined. When shot times were not recorded on the explosive hole, we calculated them from the arrival time at the reference point.

In this region a seismic refraction profile was investigated by Nishizawa *et al.* (1988). In this study, however, we derive a simpler velocity model from the travel time data of the quarry blasts. Travel times observed are shown in Fig. 2. Using the data shown by the solid circles, the velocity structure was approximated by a two-layer model with P-wave velocities of 3.0 and 4.8 km/sec and a layer boundary at 0.65 km depth. The standard deviation of residuals of all travel time data is 0.06 sec and is much larger than reading error (0.02 sec).

3. Determination of Shot Position

We determined the shot position for three different velocity models given in Table 1. Model I is the two-layer model obtained from observation data. Model II is a single layer model, in which the P-wave velocity is roughly equal to the average velocity of

Table 1. Velocity Models Used to Determine the Shot Position

Model	Velocity (km/sec)	Layer Thickness (km)
I	3.0, 4.8	0.65, ∞
II	4.0	∞
III	5.0	∞

Table 2. Obtained Depth and Origin Time

	Depth (km)			Origin Time (sec)		
Model	I	II	III	I	II	III
(a)	0.1	−0.1	−0.1	0.04	0.20	0.38
(b)	−0.1	−0.2	−0.2	0.00	0.20	0.39
(c)	−0.1	−0.2	−0.2	−0.02	0.16	0.41
(d)	0.1	−0.1	−0.1	0.13	0.26	0.44, 0.48
(e)	−0.2	−0.2	−0.2	−0.05	0.17	0.34, 0.42
(f)	0.1	−0.3	−0.1	0.14	0.31	0.50, 0.55
(g)	−0.5	−0.2	−0.2	−0.16	0.14	0.42
(h)	0.1	−0.1	−0.1	0.10	0.24	0.49, 0.51
(i)	0.1	−0.2	−0.2	0.05	0.18	0.38, 0.43
(j)	0.1	−0.2	−0.2	0.11	0.26	0.47, 0.52

True depth and origin time are −0.2 km and 0.00 sec, respectively. Origin time of (d)-(f) and (h)-(j) did not converge, but oscillated for model III.

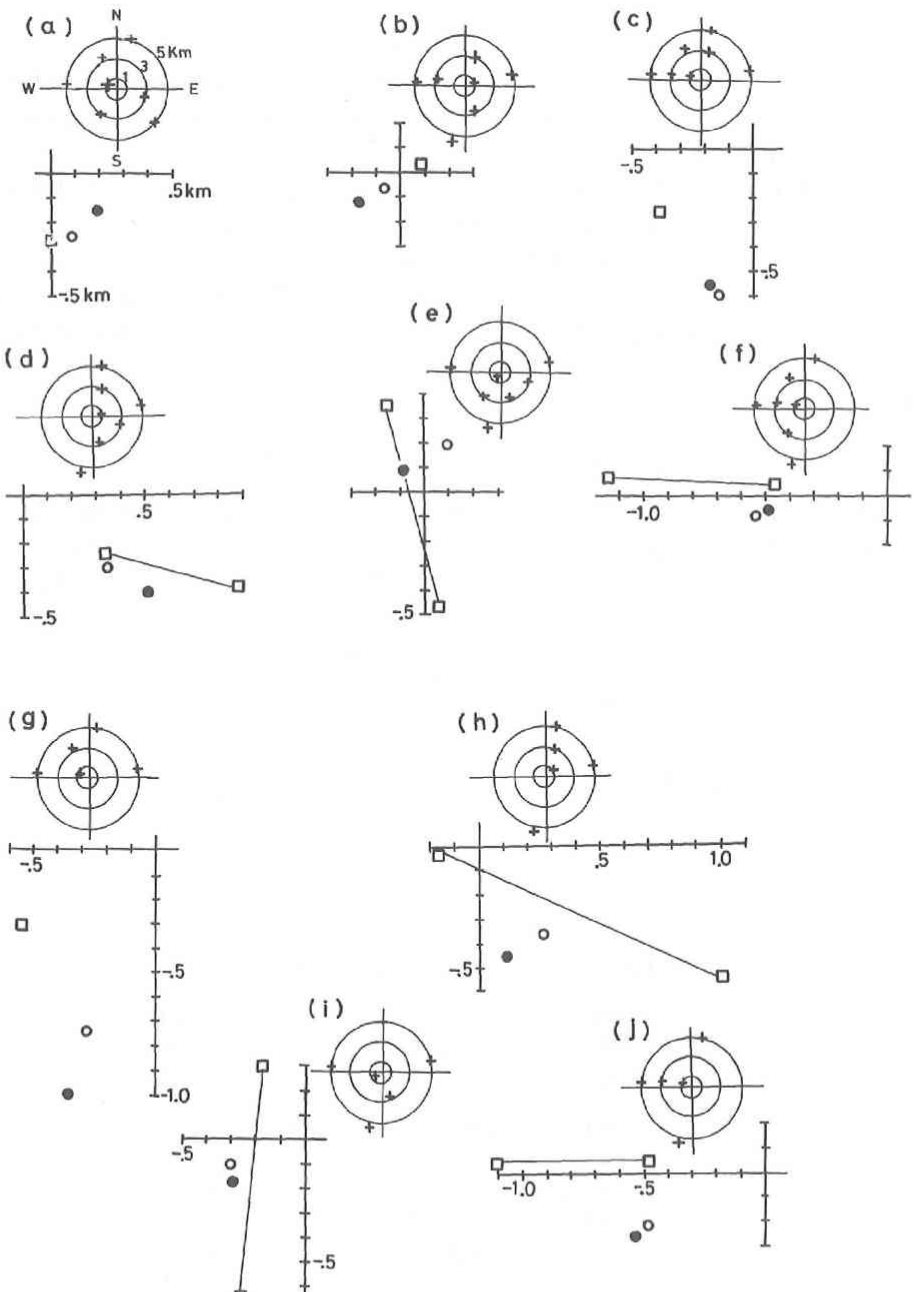

Fig. 3 Epicenter locations determined for model I (solid circles), II (open circles) and III (open squares). The true location is at the origin of coordinates. Open squares connected by a line indicate that the solution did not converge, but oscillated between them. Location of observation points are also shown by crosses.

Model I. As can be seen in Fig. 2, a line with 4.0 km/sec slope fits approximately the travel time data. Model III is also a single layer model, and its velocity is assumed to be higher than that of model II. Shot position was determined by using Geiger's method. In order to get stable solutions, the epicenter and origin time were calculated for fixed values of the shot depth. Depths were varied at 0.1 km intervals and the solution that gives the least sum of squared residuals was found.

Table 2 and Fig. 3 show the results for various sets in configuration of observation points relative to the shot position. The deviation from the true location for model II is similar in extent to that for model I. This indicates that a knowledge of the average velocity structure like model II is very useful when only hypocenter positions are concerned. The location errors found for model III are not large compared with those for the other models when observation points are distributed uniformly around the epicenter (cases (a) and (b)). However, the solutions for model III do not converge in the cases of (d) through (f) and (h) through (j). This suggests that some knowledge of the velocity structure is necessary to get stable solutions in the case of a biased distribution of observation points. Comparing cases (c) to (f) with (g) to (j), it can be said the velocity structure is more important than the number of stations, so long as the azimuthal coverage of observation points is the same.

4. Estimated Error and Actual Error

Now we compare the deviation from the true position for model I with the errors estimated in the following three different ways. *1) The parameter standard errors obtained with the least squares solution.* This may be the most conventional error estimates. *2) Errors computed through a numerical simulation.* The data for the simulation were produced by computing travel times from the true shot position for model I and then adding errors which are caused by reading errors and velocity fluctuations. Considering quality of data and scatter of travel times in Fig. 2., we assume that the reading errors are normally distributed with the standard deviation of 0.02 sec, and that the velocity fluctuations are uniformly distributed between -10 and 10%. The travel time error resulting from a velocity fluctuation is given as

$$\Delta T = T \times \Delta V/V \qquad (1)$$

where T is a travel time and $\Delta V/V$ is a velocity fluctuation. The shot position was determined for 50 different data sets based on the method used in the preceding section, and then the standard deviation of 50 samples of hypocentral and origin time errors were calculated. This procedure is similar to that used by Lilwall and Francis (1978) and Duschenes *et al.* (1983) for evaluating hypocenter resolution of small seismic networks. *3) Error bounds.* Pavlis (1986) has shown that the total error in hypocenter determination is a combination of three terms; the measurement error, modeling errors (difference between the velocity model and the true structure) and a nonlinear term (errors due to linearization of the nonlinear problem). Hypocentral errors due to the second term are bounded as

$$|\Delta h_i| \leq |\Delta u| \sum_j |A^{\dagger}_{ij}| S_j \qquad (2)$$

where Δh_i is error of the i-th parameter, Δu is an upper bound of slowness error $1/V_{true} - 1/V_{model}$, $A^{\dagger}_{ij}$ is an element of the pseudoinverse of the matrix A with elements $\partial T_j/\partial h_i$, and S_j is the length of ray path. If we assume the standard deviation of measurement error to be 0.02 sec and the upper bound of slowness error to be $+/-10\%$, the measurement error term is negligible compared with the modeling error term. Nonlinear term is almost impossible to evaluate without *a priori* information about the size of hypocentral error, and is usually small compared with the modeling error term (Pavlis, 1986). Therefore we estimate hypocentral errors by the bounding criteria given by (2). The error in the depth cannot be obtained by the parameter standard error and the bounding criteria, because the least squares equation is solved for the fixed focal depth.

Table 3 gives the estimated errors with errors in the determined shot position for three different configurations of observation points. The standard deviation of 50 samples of errors obtained by the simulation tends to give underestimated errors. Twice the parameter standard errors is also sometimes slightly smaller than the errors in the determined shot position. Since underestimation of errors are not desirable, the errors in hypocenter determination should be estimated by the maximum error obtained through simulation or by the bounding criteria. The bounding criteria may be more preferable due to the following two reasons. Firstly the values in column 3) in Table 3

Table 3. Errors of the Shot Position

		0)	1)	2)-1	2)-2	3)
(b)	ΔX	0.19	0.48 (.29)	0.16 (−.03)	0.37 (.18)	0.57 (.38)
	ΔY	0.15	0.68 (.53)	0.18 (.03)	0.40 (.25)	0.63 (.48)
	ΔZ	0.10	—	0.18 (.08)	0.40 (.30)	—
	ΔOT	0.00	0.10 (.10)	0.04 (.04)	0.09 (.09)	0.08 (.08)
(d)	ΔX	0.51	0.50 (−.01)	0.34 (−.17)	0.66 (.15)	0.72 (.21)
	ΔY	0.40	0.34 (−.06)	0.18 (−.22)	0.41 (.01)	0.38 (−.02)
	ΔZ	0.30	—	0.28 (.02)	0.40 (.10)	—
	ΔOT	0.13	0.08 (−.05)	0.09 (−.04)	0.19 (.06)	0.13 (.00)
(f)	ΔX	0.49	0.46 (−.03)	0.40 (−.09)	0.88 (.39)	0.87 (.38)
	ΔY	0.06	0.34 (.28)	0.16 (.10)	0.43 (.37)	0.48 (.42)
	ΔZ	0.30	—	0.27 (.03)	0.40 (.10)	—
	ΔOT	0.14	0.10 (−.04)	0.10 (.04)	0.18 (.04)	0.12 (−.02)

ΔX, ΔY, and ΔZ are the errors (in km) in the east-west, north-south and the vertical directions, respectively. ΔOT is the origin time error (in sec). Column 0) is the deviation of the shot position determined for model I from the true position. Column 1) is twice the parameter standard errors. Column 2)-1 and 2)-2 are the standard deviation and the maximum absolute value of 50 samples of errors calculated for 50 different data sets, respectively. Column 3) is errors calculated by using the bounding criteria given by equation (2). Numerals in parentheses are the difference from the values given in column 0). The cases (b), (d) and (f) correspond to those in Fig. 3.

are nearly the same as or larger than those in column 2)-2. This indicates that the bounding criteria gives fairly exact error bounds. Secondly error bounds can be calculated in the process of the hypocenter determination with minor modification of the computer program.

5. Summary

The results in this study are summarized as follows. (1) Errors in determined shot position are small irrespective of velocity models if the network is developed so as to surround the shot point. (2) An improper model causes unstable solutions in cases of biased distribution of observation points. (3) A knowledge of the average velocity structure can make a considerable contribution to determining the shot position so long as the origin time is not concerned. (4) It is preferable that hypocentral errors caused by the modeling error are estimated by the bounding criteria.

In the present study, data were restricted to P-wave arrival times. In the case of hypocenter determination of natural earthquakes, S-wave data are also used and other conditions such as velocity structure, focal depth and reading errors may be different in each case. However, studies using artificial earthquakes with known positions and origin times may be helpful to understand problems in hypocenter determination.

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