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PRELIMINARY ESTIMATION OF ABILITY TO INFER EARTHQUAKE SOURCE PROCESSES IN JAPANESE STRONG-MOTION ARRAYS

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The ability of Japanese strong-motion arrays for inferring earthquake source processes is investigated using a source inversion method previously developed on the basis of the Wolberg's prediction analysis. The ability of the whole array and the contribution of individual array stations are estimated for three array networks existing in Japan. They are for the 1984 Naganoken-seibu earthquake, the 1978 Miyagiken-oki earthquake, and the anticipated Tokai earthquake.

The results indicate that two different kinds of stations are simultaneously required to infer detailed source processes. One is near-source stations, and the other is stations surrounding the earthquake fault with good azimuthal coverage.

Keywords : strong-motion array, earthquake source process, inversion method

1. INTRODUCTION

The present study provides an estimate for the ability of the whole array and the contribution of individual array stations in Japanese strong-motion arrays from a source inversion point of view. The ability of the whole array is defined as the accuracy of the source inversion solution, which is estimated from the array seismograms using a method[1)] previously developed on the basis of the Wolberg's prediction analysis[2)]. The contribution of individual array stations is evaluated with two station parameters, which were successfully used to intuitively understand the effectiveness of array layout in a previous study[3)]. The present study is intended to be helpful for learning the limitation of the ability of existing arrays. It also gives a guideline for future planning array installation and for addition of stations to existing arrays.

The decision of design earthquake motions for critical structures is the least understood problem in the field of earthquake engineering. It comes, mainly, from the lack of our information on the detailed source and propagation effects and on the wide variety of local conditions within near-surface layers. Due to the absence of a general approach to simulate high-frequency ground motions in the past, existing strong-motion records obtained at the other sites or artificial strong motions produced on the basis of statistical analyses were adopted as design earthquake motions at a specific site. However, there are few strong-motion data obtained within the near-source regions from infrequent large earthquakes. There is an increased awareness that such approaches are excessively unreasonable. Geophysical methods which are based on fault dislocation models have been gradually introduced to the field of earthquake engineering in the past decade. These methods are successfully applied to the estimation of earthquake motions over the period range from about 5 sec to 20 sec, which are less affected by small-scale heterogeneties. Inversion

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studies for the precise estimation of various parameters, which are used in fault dislocation models, should be recommended. However, pronounced inconsistencies are often recognized among the results of current inversion studies. For example, it is exemplified by the results of source studies on the 1979 Imperial Valley earthquake. This seems to provide motivation to estimate the accuracy of the inversion solutions, leading us to better understand the limitation of inversion studies.

Another necessity for the present study comes from the future installation of strong-motion arrays. The selection of sites for strong-motion seismographs has been done by earthquake engineers primarily interested in the earthquake responses of buildings and other structures. It is not surprising, therefore, that most strong-motion seismographs are concentrated near major population centers. The excessively biased installation has often been pointed out, and we should note that isolated single instruments provide insufficient information to understand the factors influencing strong ground motions. Under these circumstances, in 1978, the International Workshop on Strong-Motion Earthquake Instrument Arrays was held in Honolulu, Hawaii, and immediate installation of dense strong-motion array networks were strongly recommended in several regions where large earthquakes are expected to occur in the near future4). The accurate prediction of strong ground motions at various engineering sites will result in an enormous reduction of design and construction costs. Therefore, the cost of deploying strong-motion arrays, although great, is not excessive considering the magnitude of the benefit to be derived from the arrays. The deployment strategy of arrays, however, have not as yet been addressed. We need to answer the question of how we should distribute array stations.

We restrict ourselves to the investigation of source effects using only the S-waves that form the main parts of strong ground accelerograms. We developed a scheme1) to estimate the accuracy of the inversion solution on the basis of the Wolberg's prediction analysis2). It permitted us to systematically obtain relationships between the accuracy of source inversion and fault-array parameters. When we divided the entire fault into many subfaults, we derived a general relation, $\sigma \propto N_e^2/N_S$ (σ is the accuracy of source inversion, N_e is the number of subfaults, and N_S is the number of stations)3). Also, we evaluated the ability of existing arrays installed for earthquake faults such as the 1979 Imperial Valley earthquake and the anticipated Parkfield earthquake5). In the present study, we first estimate the ability of Japanese strong-motion arrays to infer earthquake source processes. Three existing strong-motion arrays are examined. They are for the 1984 Naganoken-seibu earthquake, the 1978 Miyagiken-oki earthquake, and the anticipated Tokai earthquake. Because it is relatively possible to predict when and where an earthquake occurs in the San Andreas (USA) fault system, strong-motion instruments were or are being intensively deployed at the Imperial Valley section6),7) or the Parkfield section8). On the other hand, the effective deployment of Japanese strong-motion arrays remains uncertain owing to rare target faults.

2. METHODS

The present study tries to estimate both the ability of the whole array and the contribution of individual array stations.

At first, the ability of the whole array is evaluated with the accuracy of source inversion, which is obtained by utilizing the theoretical array seismograms. As the method was explained in detail1),3), only a brief summary is given here. We calculate the accuracy of the solution of a waveform inversion from errors contained in the data by using the principle of an error propagation. This is done by solving normal equations only once for an overdetermined least-squares problem.

We treat a detailed rupturing behavior of an earthquake fault, so that we divide the entire fault into N_e subfaults and assume that the j-th subfault starts to slip at time t_0^j and release seismic moment m_j. Only the far-field S wave in a uniform elastic space is taken into account because the far-field S wave is of primary significance in short-period strong-motion studies. The theoretical displacement waveform of the z-th station at time t_i is expressed by1)

$$u^z(t_i)=\sum_{j=1}^{Ne}\frac{R^{jz}\cdot m_j\cdot S_j(t_i-r_{jz}-t_0^j)}{4\pi\rho\beta^3 r_{jz}}\cdots\cdots\cdots(1)$$

We denote by R^{jz} and r_{jz} the radiation pattern of the S wave and the distance from the j-th subfault to the z-th station, respectively, and also by ρ and β, the density and the S-wave velocity, respectively. A common source-time function $s_j(t_i)$ is assumed for each subfault, which depends upon the subfault size. The attenuation is simply treared by assuming an amplitude decay factor of $(-\alpha r)$. The constant α corresponds to the quality factor Q at a certain frequency.

The theoretical waveform is a function of both the unknown and known parameters. Denoting by a_k ($k=1, \cdots\cdots, p$) and x_l ($l=1, \cdots\cdots, q$) the unknown and known parameters, respectively, the theoretical displacement of the z-th station at the i-th time point can be expressed as $f_i^z(x_{1zi}, \cdots\cdots, x_{qzi}; a_1, \cdots\cdots, a_p)$. The unknown parameters are the seismic moment and the rupture onset time for each subfault. Normally distributed errors are independently assumed for the known parameters : the dip angle, the strike direction, and the slip angle of each subfault, and for the waveform amplitude and the arrival time. We define two residuals as the differences between the observed and estimated values,

$$\left.\begin{array}{l}R_{zi}=F_i^z-f_i^z\\ R_{lzi}=X_{lzi}-x_{lzi}\end{array}\right\}\cdots\cdots\cdots(2)$$

where F_i^z and X_{lzi} indicate the observed displacement and the true value of the l-th parameter of the z-th station at the i-th time point, respectively. We seek a solution which minimizes the weighted sum of the squares of the two kinds of residuals,

$$S=\sum_z\sum_i(w_{zi}R_{zi}^2+\sum_l w_{lzi}R_{lzi}^2)\cdots\cdots\cdots(3)$$

The weights, w_{zi}, w_{lzi} are defined as the reciprocals of the variances. From the minimization,

$$\delta S=0\cdots\cdots\cdots(4)$$

the normal equation which can be schematically written in matrix form can be obtained,

$$C\cdot A=B\cdots\cdots\cdots(5)$$

where an element of matrix A (A_k) indicates the difference between the value of unknown parameter a_k and its initial guess a_{k0}, i. e., $A_k=a_{k0}-a_k$. Elements of matrices B and C are expressed as follows,

$$\left.\begin{array}{l}B_k=\sum_z\sum_i\frac{\partial R_{zi}}{\partial a_k}\cdot\frac{R_{zi0}}{L_{zi}}\\ C_{mn}=\sum_z\sum_i\frac{\partial R_{zi}}{\partial a_m}\cdot\frac{\partial R_{zi}}{\partial a_n}\Big/L_{zi}\end{array}\right|\cdots\cdots\cdots(6)$$

where

$$L_{zi}=\frac{\left(\frac{\partial R_{zi}}{\partial f_i^z}\right)^2}{w_{zi}}+\sum_l\frac{\left(\frac{\partial R_{zi}}{\partial x_{lzi}}\right)^2}{w_{lzi}}$$

$$R_{zi0}=F_i^z-f_i^z(X_{1zi}, \cdots\cdots, X_{qzi};\ a_{10}, \cdots\cdots, a_{p0}).$$

Following Wolberg[2)], the uncertainty of the k-th unknown parameter can be estimated without solving normal equations, but by an inverse of matrix C in the normal equation,

$$\sigma_{ak}^2=C_{kk}^{-1}\cdots\cdots\cdots(7)$$

This technique called "prediction analysis" is more advantageous than the Monte Carlo simulation because we need to solve equations only once for a pair of a specific array and a certain rupture mode on a target fault. We define the accuracy of source inversion by the maximum standard deviation of errors in estimating the seismic moment for each subfault, which is normalized by the given seismic moment, because errors in estimating the rupture onset time turn out to be underestimated.

Secondly, the contribution of individual array stations is estimated by two parameters, "time separation" and "moment sensitivity". We explain below how the two parameters help to evaluate the contribution of individual stations. A previous study showed that the most preferable array for source studies involves two different kinds of stations : stations aligned along a line parallel and close to the fault, and stations surrounding the fault with good azimuthal coverage[3]. The "time separation" at each array station is defined by Δt, the minimum difference of the arrival times between seismic waves radiated from any two subfaults[3]. This parameter tends to take large values at distant stations in specific azimuths and represents an azimuthal-coverage condition. The "moment sensitivity" is defined by $\sum_{i,j}\frac{\partial\Delta r_i}{\partial m_j}$, the summation over times and subfaults of the partial derivatives, where $\Delta r_i = |g_1(t_i) - g_2(t_i)|$ is the absolute residual of wave amplitude at the i-th time point ($g_1(t_i)$: ovserved and $g_2(t_i)$: synthetic seismograms). This parameter takes large values at near-source stations and represents a near-source condition. Actually, instead of $\sum_{i,j}\frac{\partial\Delta r_i}{\partial m_j}$, $\sum_{i,j}\frac{\partial\Delta r_i}{\partial\dot{D}_j}$ is used for simplicity, where $\dot{D}_j$ is the dislocation velocity of the j-th subfault ($\dot{D}_j$ is proportional to m_j). We use the average of three seismogram components as the value of $\sum_{i,j}\frac{\partial\Delta r_i}{\partial\dot{D}_j}$.

The present study is not at the stage of practical application since the method is considerably simplified. The other kinds of waves except the far-field S waves, the crustal structures affecting seismic waves, and the seismograph characteristics are ignored. Nevertheless, this study undoubtedly provides a significant prelude to the estimation of the ability of existing arrays.

3. EARTHQUAKES AND ARRAYS EXAMINED

In this section, three kinds of earthquakes and arrays examined are mentioned.

(1) The 1984 Naganoken-seibu earthquake

This inland earthquake occurred at the western area of Nagano prefecture. Unfortunately, there were no working strong-motion insturuments at the immediate vicinity of the fault, as shown in Fig. 1. However, the azimuthal coverage of strong-motion stations appears to be satisfactory. A bilateral rupture mode over the vertical strike-slip fault was suggested[9),10)].

(2) The 1978 Miyagiken-oki earthquake

A large earthquake of a thrust mechanism with dip 20°W occurred off the Pacific coast of Miyagi prefecture. A relatively simple rupture, which initiated at the southern end of the fault zone, propagated unilaterally beyond a barrier located at the central part[11),12)]. As illustrated in Fig. 2, most strong-motion stations were distributed along the Pacific coastline, and a few stations were installed adjacently to the fault zone.

(3) The anticipated Tokai earthquake

According to Ishibashi[13], both the seismic gap since 1854 and the considerable amount of strain accumulation on the Suruga-trough thrust suggest a fairly high probability of a large earthquake occurrence in the near future. A specific strong-motion array network composed of 18 high-quality accelerographs with a 20 km–30 km station spacing was deployed in this region[14] (Fig. 3 (a)). Besides this network, several stations are distributed on the west and north sides of the fault zone (Fig. 3 (b)). The anticipated Tokai earthquake is of major interest because approximately one half of the predicted fault zone underthrusts beneath the land.

(4) Simulations

Faulting parameters for the above three earthquakes are summarized in Table 1[10),11),13)]. Two faulting models with different subfault sizes are tested for respective earthquakes, and the effects of three kinds of networks (five kinds of networks for the anticipated Tokai earthquake) are investigated in each faulting model. Three rupture modes are assumed only for the anticipated Tokai earthquake.

4. RESULTS

The results of these simulations are summarized in Table 2, and are illustrated in Figs. 1 through 3. Table 2 indicates the maximum standard deviation of errors in estimating the subfault seismic moments,

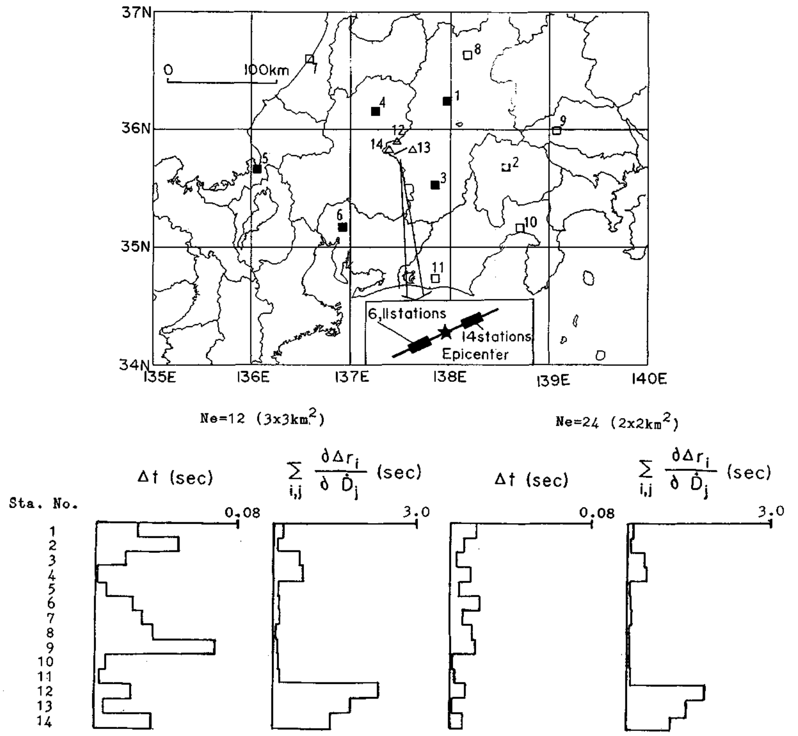


Fig. 1 Local map of central Japan, showing the fault zone of the 1984 Naganoken-seibu earthquake and the locations of strong-motion recording stations. The subfault with the largest inversion uncertainty, which is determined for the case of 24 subfaults, is indicated by the shadowed portion. "Time separation", Δt and "moment sensitivity", $\sum_{i,j}\frac{\partial \Delta r_i}{\partial \dot{D}_j}$ are evaluated at individual stations. N_e is the number of subfaults and the numerical value inside the parenthesis is the subfault area.

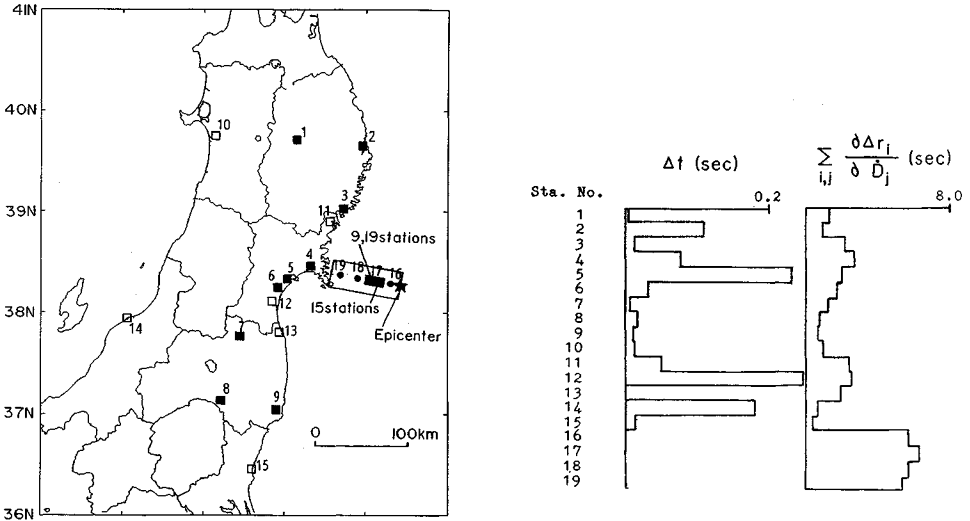
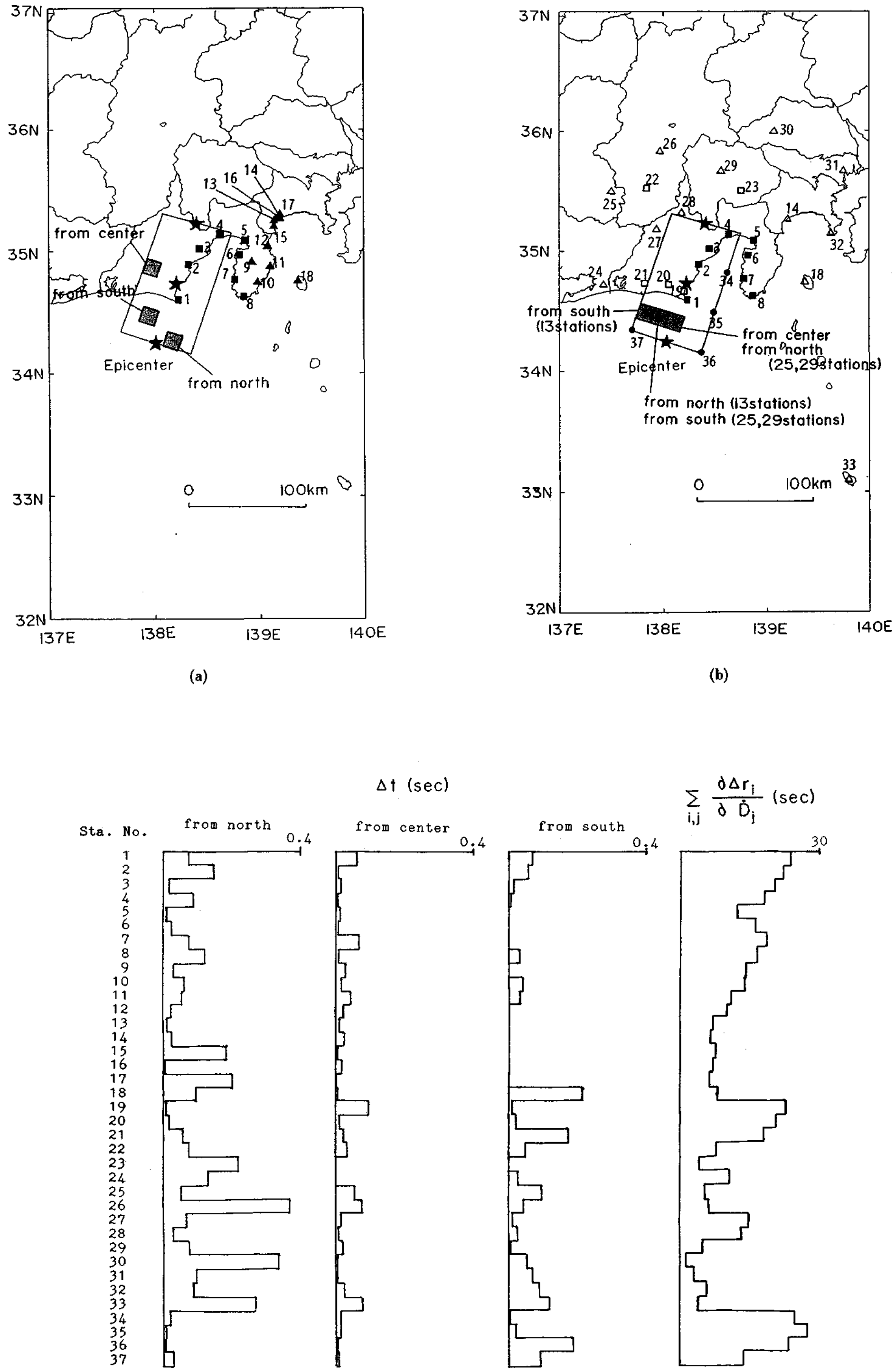


Fig. 2 Local map of the Tohoku district, showing the fault zone of the 1978 Miyagiken-oki earthquake and the locations of strong-motion recording stations. The subfault with the largest inversion uncertainty, which is determined for the case of 24 subfaults, is indicated by the shadowed portion. "Time separation", Δt and "moment sensitivity", $\sum_{i,j}\frac{\partial \Delta r_i}{\partial \dot{D}_j}$ are evaluated at individual stations for the case of 24 subfaults.



(a) (b)

Fig. 3 Local map of the Tokai district, showing the fault zone of the anticipated Tokai earthquake and the locations of strong-motion recording stations. The subfault with the largest inversion uncertainty, which is determined for the case of 40 subfaults, is indicated by the shadowed portion. "Time separation", Δt and "moment sensitivity", $\sum_{i,j} \frac{\partial \Delta r_i}{\partial \dot{D}_j}$ are evaluated at individual stations for three rupture modes in the case of 40 subfaults.

Table 1 Faulting parameters assumed for estimating effects of three strong-motion array networks.

	1984 Nagano-ken-seibu	1978 Miyagi-ken-oki	Anticipated Tokai
Fault area	12kmx 9km 12kmx10km	30kmx75km 30kmx80km	125kmx75km 120kmx75km
The number of subfaults, Ne	12(=4x3) 24(=6x4)	10(=2x5) 24(=3x8)	15(=5x3) 40(=8x5)
Subfault area	3kmx3km 2kmx2km	15kmx15km 10kmx10km	25kmx25km 15kmx15km
Strike direction, ϕ (mesured clockwise from north)	70.0°	10.0°	18.0°
Dip angle, δ	74.0°	20.0°	34.0°
Slip direction, λ	24.0°	76.0°	71.0°
Final offset, D	1.0m	1.8m	4.0m
Rupture mode	bilateral	unilateral	unilateral bilateral
Rupture velocity, Vr	2.5km/sec	3.2km/sec	2.5km/sec
The depth of the top of fault, h	1km	9.3km 7.6km	2km
S-wave velocity, Vs	3.5km/sec	4.0km/sec	3.5km/sec
The density of medium, ρ	3.0gm/cm^3	3.0gm/cm^3	3.0gm/cm^3
Quality factor, Q	300.0	600.0	300.0

Table 2 The maximum standard deviation of errors in estimating subfault seismic moments, which is normalized by the given seismic moment. N_e is the number of subfaults, N_s is the number of stations, and the numerical value inside the parenthesis is the subfault area.

(1) 1984 Naganoken-seibu earthquake

Ne \ Ns	6	11	14
12(3x3km^2)	2.13	1.56	0.52
24(2x2km^2)	29.05	15.99	5.17

(2) 1978 Miyagiken-oki earthquake

Ne \ Ns	9	15	19
10(15x15km^2)	0.075	0.058	0.035
24(10x10km^2)	0.45	0.37	0.18

(3) Anticipated Tokai earthquake

Ne	rupture mode \ Ns	8	18	13	25	29
15 (25x25km^2)	from north	0.040	0.027	0.023	0.017	0.017
	from center	0.060	0.054	0.032	0.027	0.026
	from south	0.168	0.144	0.048	0.029	0.026
40 (15x15km^2)	from north	0.24	0.18	0.15	0.12	0.10
	from center	0.40	0.34	0.21	0.15	0.14
	from south	2.40	2.02	0.34	0.16	0.14

which is normalized by the given seismic moment. Roughly speaking, for example, 0.52 is considered as a 52 % error. First of all, we find that the subfault size is the dominant factor for the accuracy of source inversion throughout all the cases. In Figs. 1 through 3, "time separation", Δt and "moment sensitivity", $\sum_{i,j} \frac{\partial \Delta r_i}{\partial D_j}$, two measures for station contribution are shown at individual array stations. The subfault at which the seismic moment has been estimated with the largest uncertainty is shadowed.

(1) The 1984 Naganoken-seibu earthquake

Three cases of stations are tested for the 1984 Naganoken-seibu earthquake. They are effective 6 stations (indicated by the solid square), 11 stations located in the Chubu district (the solid and open squares), and all the 14 stations including 3 hypothetical near-source ones (Fig. 1).

The lack of near-source stations causes a large decrease in the accuracy of source inversion, clearly suggesting a contribution of the near-source stations. The result indicates that, if the fault is divided into 3 km×3 km subfaults or smaller, the error becomes unacceptably large. Also, we may point out a remarkable contrast between a large decrease in the Δt values and a small decrease in the $\sum_{i,j} \frac{\partial \Delta r_i}{\partial \dot{D}_j}$ values when the number of subfaults is increased.

(2) The 1978 Miyagiken-oki earthquake

Three cases of stations tested are : 9 stations aligned along the Pacific coastline (the solid squares), 15 stations located in the Tohoku district including a few hypothetical stations (the solid and open squares), and all the 19 stations supplemented by 4 hypothetical ocean bottom stations (Fig. 2).

A 10 km×10 km subfault is the minimum size allowable to perform a meaningful source inversion procedure. We find that the inversion uncertainty is considerably improved by ocean bottom stations. Whereas large $\sum_{i,j} \frac{\partial \Delta r_i}{\partial \dot{D}_j}$ values are restricted to the near-source stations, the stations with large Δt appear to be distributed rather randomly.

(3) The anticipated Tokai earthquake

Five networks examined are : 8 stations involved in the Suruga-Izu array (the solid square, Fig. 3(a)), all 18 stations involved in the array (the solid square and the solid triangle, Fig. 3(a)), 13 land stations (the solid and open squares, Fig. 3 (b)), 25 land stations including several hypothetical ones (the squares and the open triangle, Fig. 3(b)), and 4 hypothetical ocean bottom stations added to the 25 land stations (29 stations, Fig. 3(b)).

The accuracy of source inversion greatly depends on the faulting rupture mode, especially when the stations are distributed with an azimuthal bias. An addition of stations on the west and north sides of the fault zone is required. Regarding this earthquake, the effects of installing ocean bottom stations are unexpectedly low. By using the land network alone, a reliable inversion solution will be obtained for subfaults larger than 15 km×15 km. Fig. 3 indicates the change in Δt values for different faulting rupture modes, implying the effectiveness of stations located at the opposite side of the rupture direction.

(4) Summary

Three simulations performed in the present study suggest that near-source stations and stations surrounding the fault zone are simultaneously required. Undoubtedly, ocean bottom stations are necessary for offshore faults. Besides, in an array with incomplete azimuthal coverage, the accuracy of source inversion much depends on the faulting rupture direction. Finally, we should add that our method cannot be applied to differential arrays. Differential arrays are being installed for the anticipated Tokai earthquake[15].

5. CONCLUSIONS

The ability of Japanese strong-motion arrays for source inversion studies has been investigated. The ability of the whole array and the contribution of individual array stations have been revealed for three existing array networks. The arrays for the 1984 Naganoken-seibu earthquake, the 1978 Miyagiken-oki earthquake, and the anticipated Tokai earthquake have been examined.

The main results are : (1) Near-source stations are lacking for the 1984 Naganoken-seibu earthquake. (2) Strong-motion, ocean bottom instruments are required for a further improvement of the inversion analysis of the 1978 Miyagiken-oki earthquake. (3) An addition of stations on the west and north sides of the fault zone is desirable to the present network for the anticipated Tokai earthquake. In conclusion, the inclusion of some near-source stations and some stations encircling the fault with good azimuthal coverage is essential for a strong-motion array to investigate a detailed source process.

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