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Strong seismic ground motion array layout for source studies: Three attempts

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ABSTRACT: Source effects are dominant in near-source strong-motion seismograms even in the high-frequency range, and source inversion is the most powerful tool to investigate source effects. However, large inconsistencies have been seen among source inversion results. The cause seems to come mainly from insufficient resolving power of strong-motion arrays. Based upon our methods to evaluate the resolving power, we (1) obtain relationship between the accuracy of source inversion and fault-array parameters, (2) present the optimum array geometry for source inversion, and (3) investigate effects of existing array networks. Finally, it is shown that strong-motion array should be designed based upon frequency contents, fault mechanism, the spatial resolution, and the inversion accuracy.

1 INTRODUCTION

Understanding of the nature of high-frequency strong seismic ground motion is a crucial problem in both seismology and earthquake engineering. Although local site effects on strong-motion records have been undoubtedly verified by numerous studies, almost no study has been done to investigate source effects that are closely related to damage and intensity patterns in the high-frequency range. The most likely reason is luck of well instrumented earthquakes available for detailed source studies. The best example to demenstrate such source effects might be Hartzell and Iida's study (1990), which perhaps used the best instrumented earthquake to date.

Source inversion is the most powerful tool to investigate source effects. However, large inconsistencies have been often seen among source inversion results. Such typical inconsistency was exemplified in the 1979 Imperial Valley earthquake (e.g. Olson and Apsel 1982; Hartzell and Heaton 1983; Archuleta 1984). The inconsistencies seem to come mainly from the differencies in the model construction and insufficient station distribution.

At the International Workshop on Strong-Motion Earthquake Instrumented Arrays held in Honolulu, Hawaii in 1978 (Iwan), a preferable array configuration was first proposed on the basis of empirical judgement. According to the source type, three different array networks for source mechanism and wave propagation studies were presented. Only few quantitative attempts have been made to estimate effects of station array. Spudich and Oppenheimer (1986) measured the resolving power of a hypothetical, differential seismograph array by performing frequency-wavenumber analysis and ray-tracing. Olson and Anderson (1988) showed that the assumed solution was not recovered by their frequency-domain inversion method, and that the goodness of recovery was dependent upon the station array, while Iida et al. (1988) represented effects of array configuration by a single parameter on the basis of their method (Miyatake et al. 1986). Although these studies used too simple Green's functions, the significance of good strong-motion array was undoubtedly shown.

In our present study, we (1) obtain relationship between the accuracy of a source inversion and fault-array parameters, (2) present the optimum array geometry for the source inversion, and (3) investigate effects of existing array networks. Our conclusion is that we can reasonably design strong-motion array in a given condition.

2 METHODS

Since our method was explained in a previous study (Iida et al. 1990b), we give here a very brief summary. We use the Wolberg's prediction analysis (Wolberg 1967) to calculate the accuracy of a waveform inversion solution from errors contained in the data by using a principle of error propagation. We divide the entire fault into many subfaults to deal with a detailed

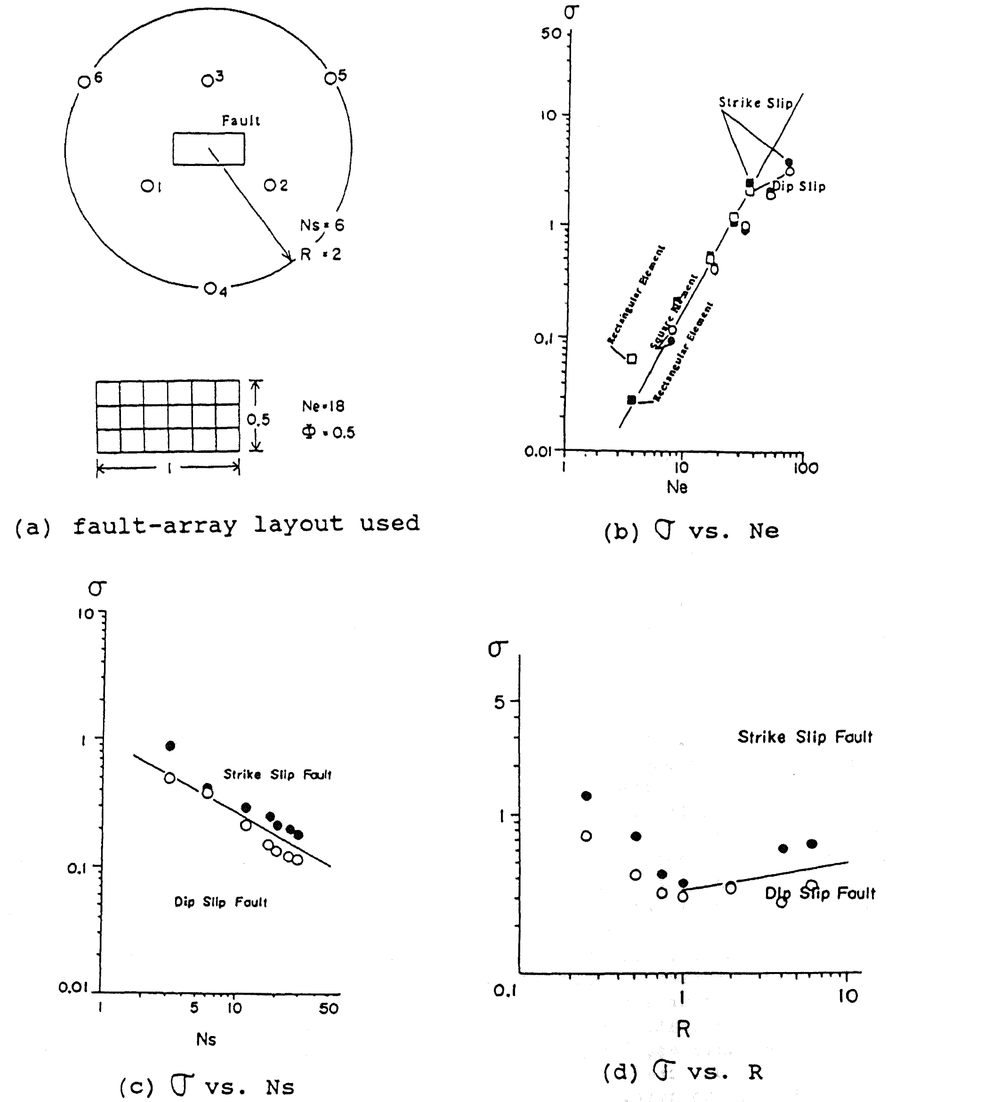


Figure 1. Geometrical arrangement of faults and array stations and relationship between the accuracy of a source inversion, σ and fault-array parameters: (a) 2 kinds of faults located at the center of an array: a strike-slip fault with a dip angle, $\delta = 90°$ and a dip-slip fault with $\delta = 30°$. All distances are normalized by the fault length; (b) the inversion uncertainty, σ vs. the number of subfaults, Ne; (c) σ vs. the number of stations, Ns; (d) σ vs. the array radius, R.

history of rupturing and use the displacement waveform representation for each subfault. A complete Green's function in a semi-infinite elastic space is used. The seismic moment and the rupture onset time for each subfault are chosen as unknown parameters. They are determined using a least-squares criterion. We estimate the accuracy of the source inversion, σ by the maximum standard deviation of seismic moments for all subfaults, normalized by the seismic moment. Three sorts of simulations are done in the following.

3 RELATIONSHIP BETWEEN THE ACCURACY OF SOURCE INVERSION AND FAULT-ARRAY PARAMETERS (1ST SIMULATION)

A systematic analysis is done to obtain relationship between the accuracy of a source inversion and fault-array parameters (Iida et al. 1990b). Strike-slip and dip-slip faults are assumed to be located at the center of a circular array (Fig. 1(a)). Several fault-array parameters are separately varied and their effects on the accuracy of the source inversion are evaluated.

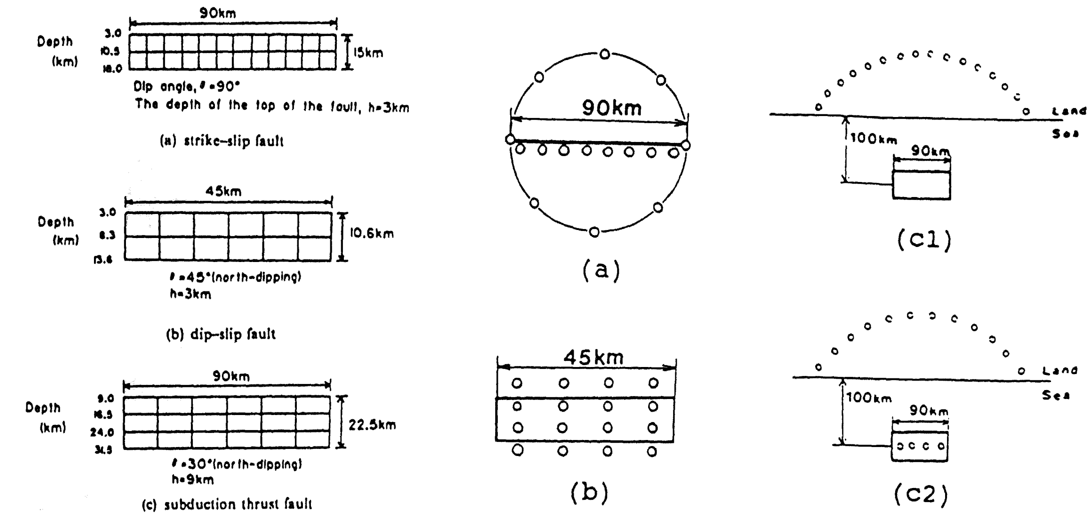


Figure 2. Fault geometries used for investigating effects of array configurations on the source inversion (side views) and the optimum array configuration obtained for each of 3 fault geometries: (a) strike-slip; (b) dip-slip; and (c) subduction thrust fault (2 cases (c1) without and (c2) with strong-motion ocean bottom seismographs).

Five fault parameters considered are (1) the number of subfaults, Ne; (2) the aspect ratio, Φ; (3) the dip angle, δ; (4) the fault depth, h; and (5) the rupture mode. We find that the normalized uncertainty, σ is roughly proportional to Ne^2, independent of fault mechanism (Fig. 1b). Depth resolution is worse than the resolution in the horizontal direction. The uncertainty does not depend much on the dip angle, the fault depth, and the rupture mode.

Array parameters are important because they can be controlled. Four parameters are examined: (1) the number of stations, Ns; (2) the array radius, R; (3) the azimuthal coverage of the source, ϕ; and (4) the components of the seismograms. The uncertainty, σ is found to roughly obey an inverse root dependence on Ns (Fig. 1c). Fig. 1d exhibits that the inversion uncertainty becomes minimum when the array radius, R is around 0.75 to 2.0 times the fault length. $\sigma \propto \phi^{-1}$ holds approximately in the case where Ns is kept proportional to ϕ, suggesting a remarkable contribution of the azimuthal coverage. The horizontal component parallel to the fault strike tends to contribute to a strike-slip fault, and the vertical component to a dip-slip fault. These simulations tell us that, while just an increase in the number of stations is not efficient, the azimuthal coverage of the source and the array size should be considered.

Furthermore, we attempt to demonstrate or refute the necessity of ocean bottom seismographs because no quantitative arguments on whether strong-motion ocean bottom seismographs are worth installing have yet been made (Iida et al. 1990b). It is doubtful that our results are a strong incentive to deploy permanent ocean bottom stations in subduction zones.

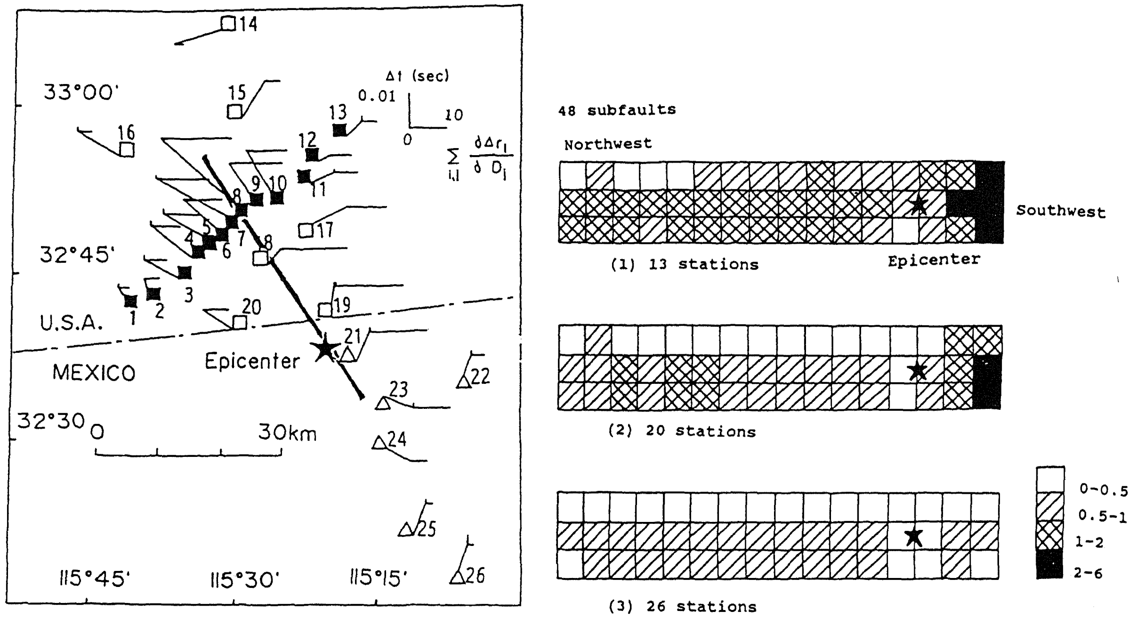
4 OPTIMUM ARRAY GEOMETRY FOR SOURCE INVERSION (2ND SIMULATION)

We estimate the optimum array configuration for source inversion by trial and error for each of 3 typical faults, as shown in Fig. 2 (Iida 1990). By 'optimum', we mean that the inversion solution becomes the most accurate with the same number of array stations and for the same process of fault rupturing. In some cases of the offshore fault simulation, validity of hypothetical strong-motion ocean bottom seismographs is again examined.

The optimum array configuration is presented in Fig. 2. The optimum array configurations are compared with the ones proposed at the Workshop (Iwan 1978). The rightness of the empirical Workshop judgement is corroborated, and we are confident that the goodness of array configuration can be quantitatively measured by our method.

5 APPLICATION TO EXISTING STRONG-MOTION ARRAYS (3RD SIMULATION)

We evaluate the resolving power of four existing array networks. (Iida et al. 1990a). They are for the 1979 Imperial Valley and anticipated Parkfield, California earthquakes, and the 1968 Tokachi-oki and the anticipated Tokai, Japan earthquakes. In



(a) Location map

(b) Inversion uncertainty

Figure 3. Location map of the Imperial Valley section of the San Andreas fault showing strong-motion recording stations in (a), and the inversion uncertainty at all the subfaults in (b). 3 kinds of station arrays examined are 1) El Centro array perpendicularly crossing the fault trace (13 stations indicated by the solid squares), 2) 20 stations distributed within the United States (the solid and open circles), and 3) all 26 stations. Each inversion uncertainty at 48 subfaults determined for the 3 kinds of arrays (13, 20, and 26 stations) is indicated by ranking in (b). 'Time separation' and 'moment sensitivity' are evaluated at individual stations in the case of 48 subfaults in (a). The length of vertical bars shows the time separation and that of horizontal bars shows the moment sensitivity.

an attempt to evaluate the contribution of each station, we introduce two station parameters: 'time separation' and 'moment sensitivity.' The exact definition of the two parameters are given in another paper (Iida et al. 1990a).

The results for the 1979 Imperial Valley earthquake are shown in the following. The surface fault trace of this earthquake and the locations of strong-motion recording stations are displayed in Fig. 3(a). Undoubtedly, the spatial resolution predetermined by the subfault size is the dominant factor. When we increase the number of subfaults from 20 (the corresponding subfault area, Ae = 5x5 km^2) to 48 (Ae = 3x3 km^2) for the same number of stations, the inversion accuracy greatly drops from 0.88 to 5.46 (for the 13 stations of El Centro array of Fig. 3(a)), from 0.41 to 3.19 (for 20 stations distributed within the United States), and from 0.18 to 0.94 (for all 26 stations). We also find drastic change in the inversion uncertainty at each subfault due to the change in the number of stations, and a significant contribution of Mexican stations, which is probably due to a better azimuthal coverage (Fig. 3(b)). According to the two station parameters, the most useful stations appear to be located closely to the fault trace or on its southeastern extension (Fig. 3(a)).

The main results for other earthquakes are: (1) The array installed for the anticipated Parkfield earthquake seems to be satisfactory because of the intensive installation of many stations. (2) Detailed source inversion analysis cannot be expected in the 1968 Tokachi-oki, Japan earthquake because of both the large fault area and the offshore location. (3) An addition of several land stations on the west and north sides of the fault area is desirable to the present network for the anticipated Tokai, Japan earthquake.

6 STRONG-MOTION ARRAY DESIGN FOR SOURCE INVERSION

In this chapter, invoking results of physical wave simulations (Iida et al. 1990b), basic guidelines and design policies of strong-motion array layout are provided.

The optimum station-array configuration heavily depends upon the physical (seismic) waves used for analysis (Iida et al. 1990b). Because information obtained from distant surface waves or far-field body waves at distant stations cannot be recovered using any other waves, stations encircling the fault area with good azimuthal coverage are primarily required to unravel the source structure. These stations resolve the earlier stage of the rupturing process, while body waves in the source region resolve the later stage (Iida et al. 1988).

Great dependence of the optimal array configuration on the fault mechanism is explainable. For a vertical strike-slip fault of strict phase requirements, stations immediately above the fault plane, which are robust at the vertical resolution, are needed. An inclined dip-slip fault favors a grid pattern of stations that appears to help many phases to be separated.

The simulations also present an important view concerning the choice in source inversion methods. Although a method of solving normal equations (e.g. Hartzell and Heaton 1983) or an iterative least-square method (Kikuchi and Kanamori 1982) may be general using stations which encircle the fault area, a differential array analysis using body-wave seismograms obtained from a source region (Spudich and Cranswick 1984) is another powerful way available for source studies.

In conclusion, a current plasible policy of array design may be in the following. If we consider intermediate frequency band (several seconds to several Hz), we should choose a method of solving normal equations or an iterative least-squares method using complete Green's functions. Then, the results from our studies are greatly available. First, according to the fault mechanism, a desirable array configuration is determined. Secondly, assuming the spatial resolution and the inversion accuracy required, the number of array stations is determined. When the target frequency range is very high (more than several Hz), a differential array analysis is recommended using only body waves. Exactly speaking, our techniques cannot be applied to this type of array since the analysis makes use of a difference in arrival times of distinguishable phases. Previously, our 1st (Iida et al. 1986) and 2nd (Iida et al. 1988) simulations were performed utilizing only far-field S waves. The results were considerably different from our present ones. They are able to make partial contribution to array layout design in that case.

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