Recipe for Estimating Strong Ground Motions from Active Fault Earthquakes

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Abstract. A methodology is proposed for estimating strong ground motions from scenario earthquakes caused by active faults. We summarize the procedure that is currently used to characterize earthquake rupture models for the prediction of ground motions, based on geological investigations of capable earthquake faults and seismological studies of source models. Total fault lengths of the scenario earthquakes are evaluated from geological and geophysical survey of segmentation and grouping of active faults for a long-term prediction of seismic activity. Fault widths are proportional to fault lengths for earthquakes less than Mw 6.5 but almost constant for larger earthquakes (>Mw 6.5) being saturated with the thickness of seismogenic zones. The seismic moments of the source faults are estimated by the empirical relationship between the fault area and seismic moment, and then average slips are automatically constrained from the seismic moment and source area. The scaling relations of modeling slip heterogeneity are constructed based on a systematic analysis of the source inversion results of crustal earthquakes ranging from 5.8 to 7.2 in moment magnitude (Mw). For strong motion estimation we adopt a asperity model satisfying scaling relations for the heterogeneity of slip on the fault surface in a deterministic manner. The validity and applicability of strong ground prediction are examined in comparison with the observed records and actual damage during the 1995 Hyogo-ken Nanbu (Kobe) earthquake (Mw 6.9) and the 1994 Northridge earthquake (Mw 6.7).

1. INTRODUCTION

Recent large earthquakes, such as the 1995 Hyogo-ken Nanbu (Kobe, Japan) earthquake, the 1999 Kacaeli (Turkey) earthquake, and the Chi-chi earthquake occurred on well-mapped active faults. However, no obvious precursory evidences appeared even near the faults before the events. Damage caused by the events showed characteristic distributions depending on rupture process as well as geological conditions. For example, heavy damage in Kobe area larger than in the Awaji area during the 1995 Hyogo-ken Nanbu earthquake is explained by a synergistic effect between source effects, such as slip heterogeneity and forward rupture directivity, and basin-edge effects due to basin structures. In the Awaji area there was less damage although surface breaks appeared along the Nojima faults. This means the importance of predicting ground motion from possible earthquake faults to mitigate disaster for future earthquakes.

Scenario earthquakes for subject areas have gradually been popular to make seismic disaster prevention measures by some governmental agencies and municipalities. However, most of strong motion estimations in earthquake hazard

analysis are still inclined to empirical methods. Peak ground acceleration, peak ground velocity and response spectrum for earthquake-resistant design are given by the empirical methods as a function of magnitude, fault distance, and ground condition. They have not been taken into account yet developments in seismology, such as source processes in earthquake faults and 3-D simulation in complex structures.

We attempted to make a recipe to popularize the prediction of ground motions for engineering purpose based on seismological fruits. Most of the uncertainties in predicting strong ground motion result from modeling source processes of future earthquakes. There are two main aspects of characterizing the earthquake sources, outer and inner source parameters.

The outer parameters are total fault length, width, seismic moment and so on, which are estimated from geological investigations of active faults and empirical relationships between source areas and seismic moment for past earthquakes due to the active faults.

The inner source parameters are slip heterogeneities inside the fault area, which are determined from the source inversion of crustal earthquakes. Based on the statistical analysis of the inverted results, we have studied the scaling relations of asperities satisfying the spatial heterogeneity of slip on the fault surface. Source modeling considering heterogeneous slip in the earthquake fault is given on the self-similar scaling relations of asperities with respect to seimic moments.

The validity and applicability of strong ground prediction are examined in comparison with the observed records and actual damage during the 1995 Hyogo-ken Nanbu (Kobe) earthquake and the 1994 Northridge earthquake.

2. SOURCE CHARACTERIZATION

2.1 Characteristic earthquakes

One of the most important issues for strong motion prediction is source characterization for a future earthquake. We take into account earthquakes caused by active faults. A question is "Do earthquakes due to specific active fault have repeatedly similar source process ?". If yes, it is possible to make source modeling for future earthquakes. One answer would be obtained from geological and geographical investigations so far done. Recently extensive researches of segmentation and grouping of active faults have been made for studying earthquake histories. They found that slip distributions along fault segments have similar features to the results from the source inversion using seismic data, e.g. slip is largest in the middle of the segment and decreases towards the edge as shown in Fig. 1 (Nakata *et al.*, 1998). The other possible answer comes from fault dynamics estimated by the waveform inversion of strong motion records. Bouchon *et al.* (1998) studied the characteristics of stress field before and after the 1995 Hyogo-ken Nanbu earthquake based on the results of the source inversion using near-field recordings. There is a good correlation between the initial and final stress
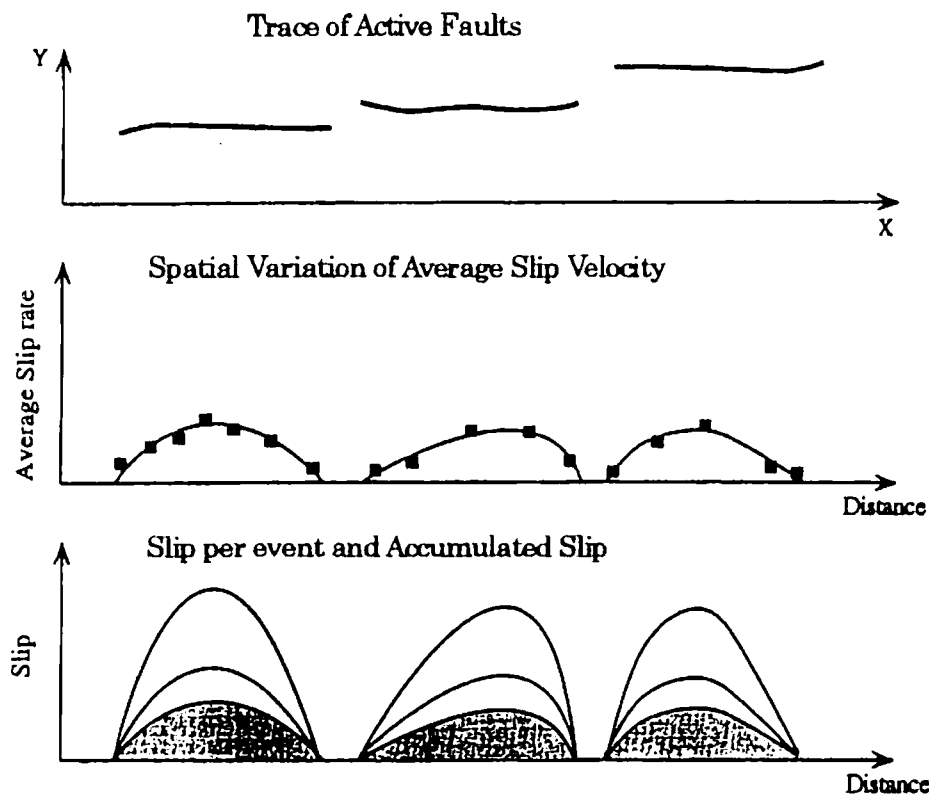
Fig. 1. Spatial distribution of fault traces, average slip velocity, and accumulated slip (Nakata *et al.*, 1998).

distribution, which suggests that intrinsic fault properties, not modified by the earthquake, control the spatial distribution of tectonic stress over fault. Those results suggest that earthquakes originating in the same active faults have a similar source process repeatedly, i.e. the validity of the idea of "characteristic earthquakes".

2.2 Characterized source model

For characterizing source model to estimate strong ground motions in a deterministic approach, we need to have two kinds of source parameters, outer ones and inner ones.

2.2.1 Outer source parameters

The outer source parameters are total fault length and width, average slip and slip duration, average rupture velocity, and so on, which are to characterize the macroscopic pictures of given source faults. They are estimated on the bases of geological investigations on possible earthquake faults and seismological studies on rupture processes of earthquake source.

Total fault lengths (L) of scenario earthquakes are be evaluated as the sum of fault segments that are simultaneously activated. Some attempts have been making to estimate segmentation and grouping of active faults based on branching features of seismic surface ruptures (Matsuda, 1998). **Strike** (ϕ) and **slip type** of every segment are estimated from geological surveys such as trenching. **Dip angle** (δ) is inferred from seismic reflection profile.
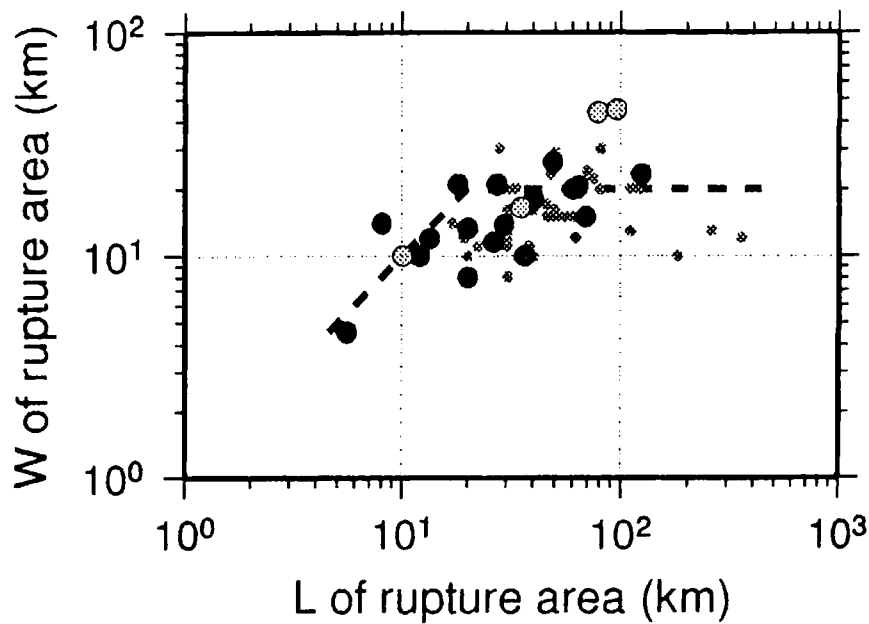
Fig. 2. Relation of fault width versus fault length for inland crustal earthquakes. ●: strike-slip and high-angle reverse fault and O: oblique fault by Somerville *et al.* (1999). ⊛ is compiled by Wells and Coppersmith (1994).

Fault width (W) cannot be directly determined from the geological survey, but mostly from source modeling for waveform simulations using observed records. We made a plot (Fig. 2) to show the relation of fault width (W) vs. length (L), from source characterization by Somerville *et al.* (1999) using the results of the source inversion and compiled source models for 87 inland earthquakes by Wells and Coppersmith (1994) (Irikura and Miyake, 2000). The saturation of the width yields for events larger than Mw 6.5, corresponding to the thickness of seismogenic zones. The seismogenic zones are infered from the depth-frequency distribution of small earthquakes (Ito, 1990). Recent study by Ito (1999) shows that the seismogenic zones have shallow limits as well as deep limits derived from the seimic-aseismic boundary in the mid-crust.

Seismic moment (Mo) of the possible earthquake faults are estimated by the empirical relationship between the source areas (A = LW) and seismic moment, then average slips are calculated by the seismic moment and source area (e.g. Somerville *et al.*, 1999).

It is also very important source parameters where rupture starts on the fault, to which directions it propagates, and where it terminates. In most of inland earthquakes rupture nucleates at the bottom of the seismogenic zones because of stress concentration in the seismic-aseismic boundary (Sibson, 1992). The starting point and propagation direction of the source rupture are identified from the patterns of surface traces from geographical investigations and theoretical modeling. Nakata *et al.* (1998) proposed a method to identify the direction of rupture propagation, the termination of rupture and in some cases, the epicenter location based on the branching features of active faults as shown in Fig. 3. Such ideas were examined by the dynamic theory of earthquake faulting. Kame and
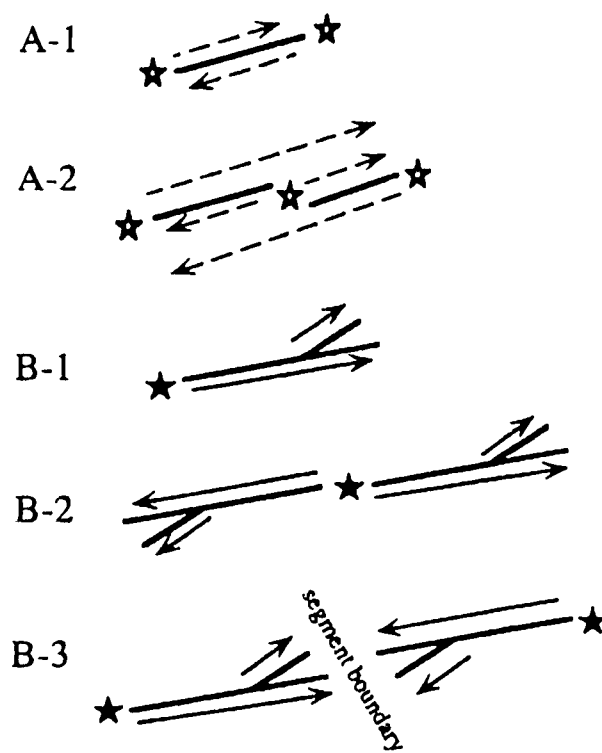
Epicenter	Directivity	Predictability
☆	_ _ _⟶	Unpredictable
★	⟶	Predictable

Fig. 3. Illustrative models of fault branching and rupture propagation (after Nakata *et al.*, 1998).

Yamashita (1999) numerically studied the effect of medium fracturing on the dynamic growth of earthquake rupture. It is suggesed that the faulting is needed to bend in the arresting of rupture or to make branching for its termination.

2.2.2 Inner source parameters—Fault heterogeneity or roughness—

The slip and slip velocity have been found not to be uniform in the source areas, in particular for large earthquakes with magnitude more than 7 as clarified from the waveform inversion of rupture process (Wald, 1996). We need to know slip and slip velocity distribution in the source area as well as the average slip to estimate strong ground motions. We here define inner source parameters that express fault heterogeneity or roughness. So far most of slip models have been derived from longer period ground motions using the forward modeling and the waveform inversion. Direct application of such long-period source models to strong ground motion estimation is not always available because higher-frequency ground motions than 1 Hz cannot be obtained. Nevertheless, we found that the asperity models are available for estimating broad-band ground motions of engineering interest (e.g. Kamae and Irikura, 1998). That is, the source models even for high-frequency motions are derived from the heterogeneous slip distribution using the waveform inversion of longer-period ground-motion recordings.
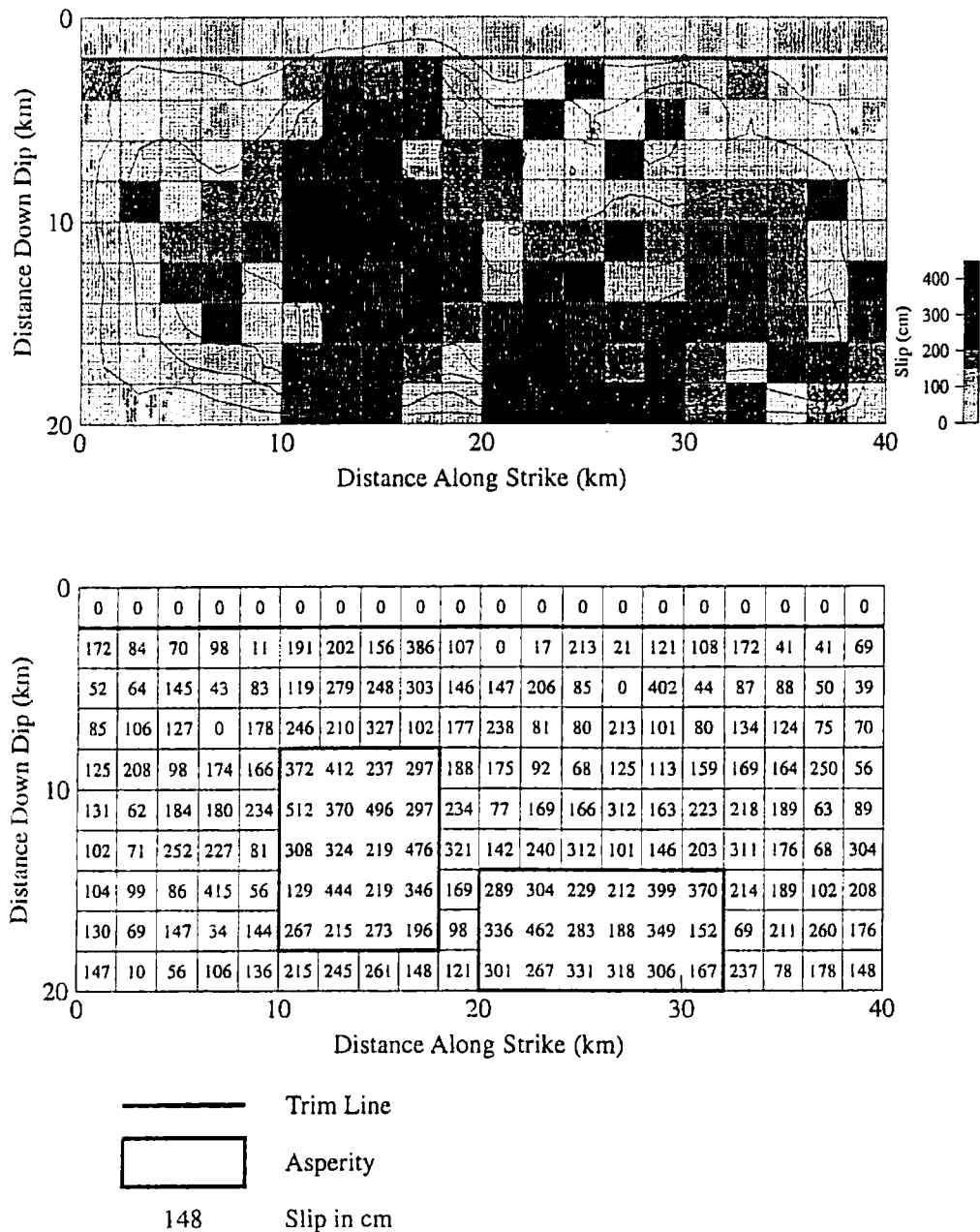
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172	84	70	98	11	191	202	156	386	107	0	17	213	21	121	108	172	41	41	69
52	64	145	43	83	119	279	248	303	146	147	206	85	0	402	44	87	88	50	39
85	106	127	0	178	246	210	327	102	177	238	81	80	213	101	80	134	124	75	70
125	208	98	174	166	372	412	237	297	188	175	92	68	125	113	159	169	164	250	56
131	62	184	180	234	512	370	496	297	234	77	169	166	312	163	223	218	189	63	89
102	71	252	227	81	308	324	219	476	321	142	240	312	101	146	203	311	176	68	304
104	99	86	415	56	129	444	219	346	169	289	304	229	212	399	370	214	189	102	208
130	69	147	34	144	267	215	273	196	98	336	462	283	188	349	152	69	211	260	176
147	10	56	106	136	215	245	261	148	121	301	267	331	318	306	167	237	78	178	148

——— Trim Line

▭ Asperity

148 Slip in cm

Fig. 4. Slip model of the 1989 Loma Prieta earthquake and identification of asperities (Somerville et al., 1999).

Somerville et al. (1999) analyzed the characteristics of slip models of totally fifteen crustal earthquakes ranging from about 6 to 7 in moment magnitude (Mw) for use in the prediction of strong ground motion. They define **fault asperities** in a deterministic manner to quantify the properties of heterogeneous slip models. The asperities are areas on the fault surface that have large slip relative to the average slip on the fault. An asperity is defined to enclose fault elements whose slip is 1.5 or more times larger than the average slip in the fault as shown in Fig. 4 (in detail refer to Somerville et al., 1999). The number of asperities in the slip models of those events is 2.6 on average. The slip contrast, the average slip on the asperities over average slip is about 2. The combined area of asperities on the average occupies about 22% of the total rupture area.

Total rupture area (A), combined area of asperities (Aa), and area of largest asperity (Am) scale in a self-similar manner with increasing seismic moment.

$$A \ (km^2) = 2.23 \times 10^{-15} \times Mo^{2/3} \ (dyne \cdot cm),$$ (1)

$$Aa \ (km^2) = 5.00 \times 10^{-16} \times Mo^{2/3} \ (dyne \cdot cm),$$ (2)

$$Am \ (km^2) = 3.64 \times 10^{-16} \times Mo^{2/3} \ (dyne \cdot cm).$$ (3)

Other parameters such as average asperity slip, hypocentral distance to closest asperities, slip duration are also scaled with seismic moment in the self-similar way.

The validity and applicability of strong ground motion prediction and the relation between strong ground motions and structure damage were examined in comparison with the observed records and actual damage during the 1995 Hyogo-ken Nanbu (Kobe) earthquake.

3. SIMULATION OF STRONG GROUND MOTION BASED ON HETEROGENEOUS SOURCE MODEL

3.1 The 1995 Hyogo-ken Nanbu earthquake (Mw = 6.9)

The source slip model of this earthquake was determined from the inversion of strong ground motion records by several authors (e.g. Sekiguchi et al., 1996; Wald et al., 1996; Yoshida et al., 1996). The slip distribution on the fault plane is roughly similar each other, although there are minor differences depending on frequency ranges of the data, smoothing techniques used there and etc. However, those inversion analyses were done using only low frequency motions less than 1 Hz, therefore they might not be useful for higher frequency motions of engineering interest. Fortunately, recent studies from high frequency envelop inversion of source process suggests that variable slip models derived from low-frequency ground motions are related to the radiation of high frequency motions from inland earthquakes (Kakehi et al., 1996; Hartzell et al., 1996).

We then attempted to make up the source model for broadband ground motions from the 1995 Hyogo-ken Nanbu earthquake taking into account heterogeneous source model, i.e. asperity model using the empirical Green's function model (Kamae and Irikura, 1998). The initial source model were assumed with three asperities based on the rupture process obtained from the inversion of strong ground motion records by Sekiguchi et al. (1996). For simplicity, we consider each asperity as a subevent with uniform stress drop in a finite extent. The ground motion from each asperity is synthesized using the empirical Green's function method (Irikura, 1986). Then, the initial model was revised by the forward modeling, i.e. comparison between the synthetic and observed ground motions. The final model consists of three subevents corresponding to those three asperities as shown in Kamae and Irikura (1998). Asperity 1 with stress drop of 163 bars lies under the Akashi Strait around the
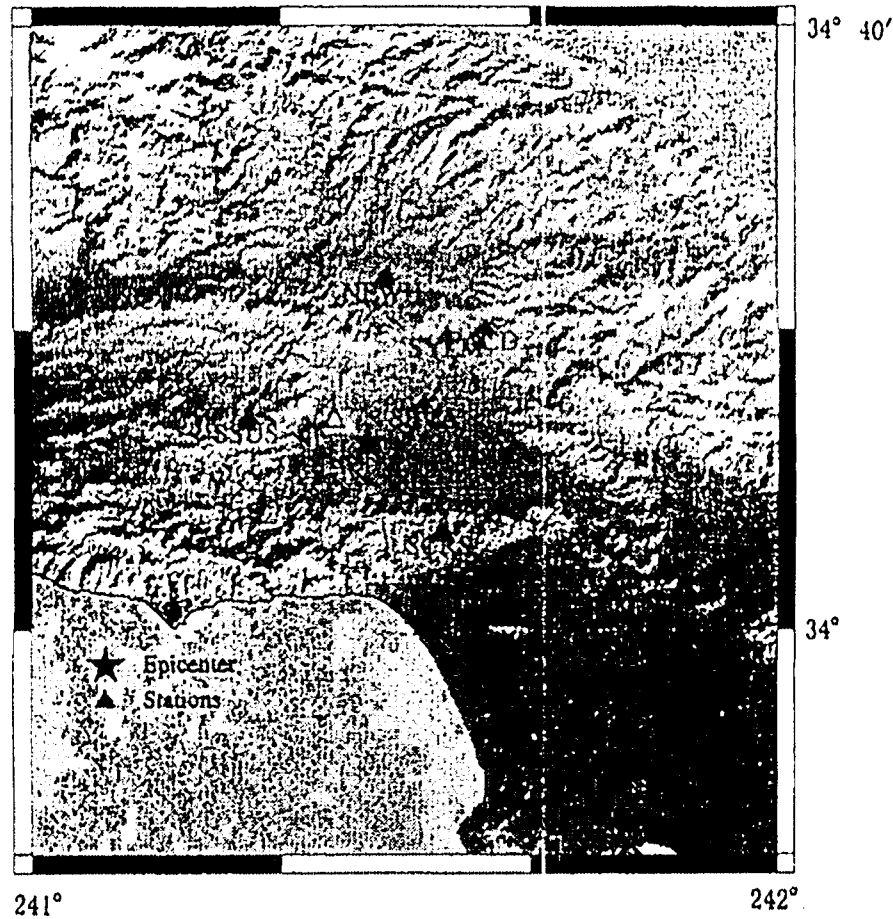
Fig. 5. Locations of the stations and epicenters of the mainshock of the 1994 Northridge earthquake (★) and its aftershock (▲) used as the empirical Green's function.

rupture starting point, Asperity 2 with stress drop of 86 bars, under the Nojima Fault in Awaji Island, and Asperity 3 with stress drop of 86 bars, under Kobe. The synthesized motions at KBU and MOT very close to the causative faults agreed well with the observed ones.

The total area of the asperities in the best-fitting model occupies about 25% of the total rupture area, coinciding well with the averaged slip model of compiled 15 earthquakes by Somerville *et al.* (1999).

3.2 The 1994 Northridge earthquake (Mw = 6.7)

Strong ground motions from the 1994 Northridge earthquake were widely recorded in the San Fernando valley and the Los Angeles basin. The locations of stations near the source area and the epicenters of the mainshock and an aftershock used as the empirical Green's function are shown in Fig. 5. The rupture process of the Northridge earthquake was determined from the inversion of strong motion data by Wald *et al.* (1996) as shown in Fig. 6(A). Simplifying the slip distribution, we assume two initial source models, one with two asperities and the other with three asperities. The best-fit model to observed records is shown in Fig. 6(B) consisting of three asperities. The stress drop in each asperity is assumed to
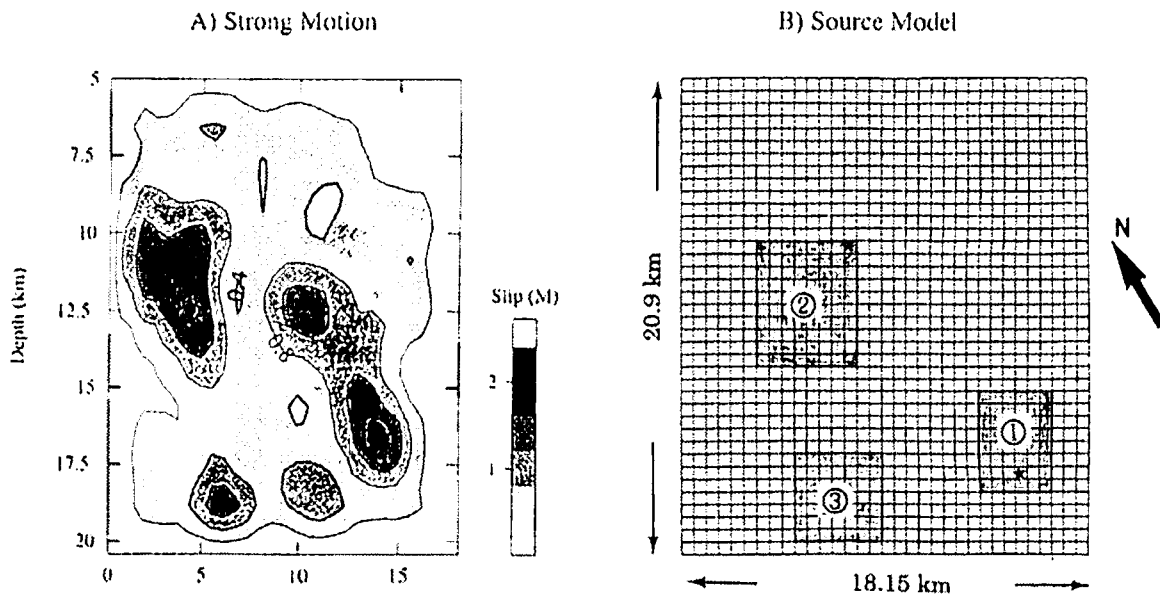
A) Strong Motion

B) Source Model

Fig. 6. (A) Slip distribution on the fault plane inverted from strong motion data for the 1994 Northridge earthquake. (B) Source model for simulating strong ground motions with three asperities. The starting point is indicated by ★. The rupture extends radially from the starting point with rupture velocity of 2.8 km/s. The rise time is assumed to be 0.6 sec for No. 1 and 3 and 1.0 sec for No. 2.

be 300 bars in Asperity 1 and 3 and 400 bars in Asperity. The synthesized motions, acceleration, velocity and displacement, at SPVA and NEWH are compared with the observed in Fig. 7. We found that the velocity and displacement agree well even in individual phases between the synthesized and observed, and the acceleration does in amplitude level and duration. The combined area of asperities in the best source model is about 14% of the total ruptured area, a little less than the average by Somerville et al. (1999). It means that some variance should be taken into account in characterizing such source parameters.

4. CONCLUSION

We summarized the procedure for predicting strong ground motions from future earthquakes caused by inland active faults as a recipe. The source characterizations for the future earthquakes are made by the statistical analysis of the slip distributions obtained from the waveform inversion using strong motion and teleseismic data. Referring to Somerville et al. (1999) we find that the combined area of asperities as well as total rupture area follows the self-similar scaling. It means that the characterized source models even with asperities are predictable. The validity and applicability of the source characterization for strong ground prediction are examined in comparison with the observed records and actual damage from recent large earthquakes such as the 1995 Hyogo-ken Nanbu (Kobe) earthquake and the 1994 Northridge earthquake. We conclude that the recipe proposed in this study is very successful for predicting strong ground motion from active fault earthquakes.
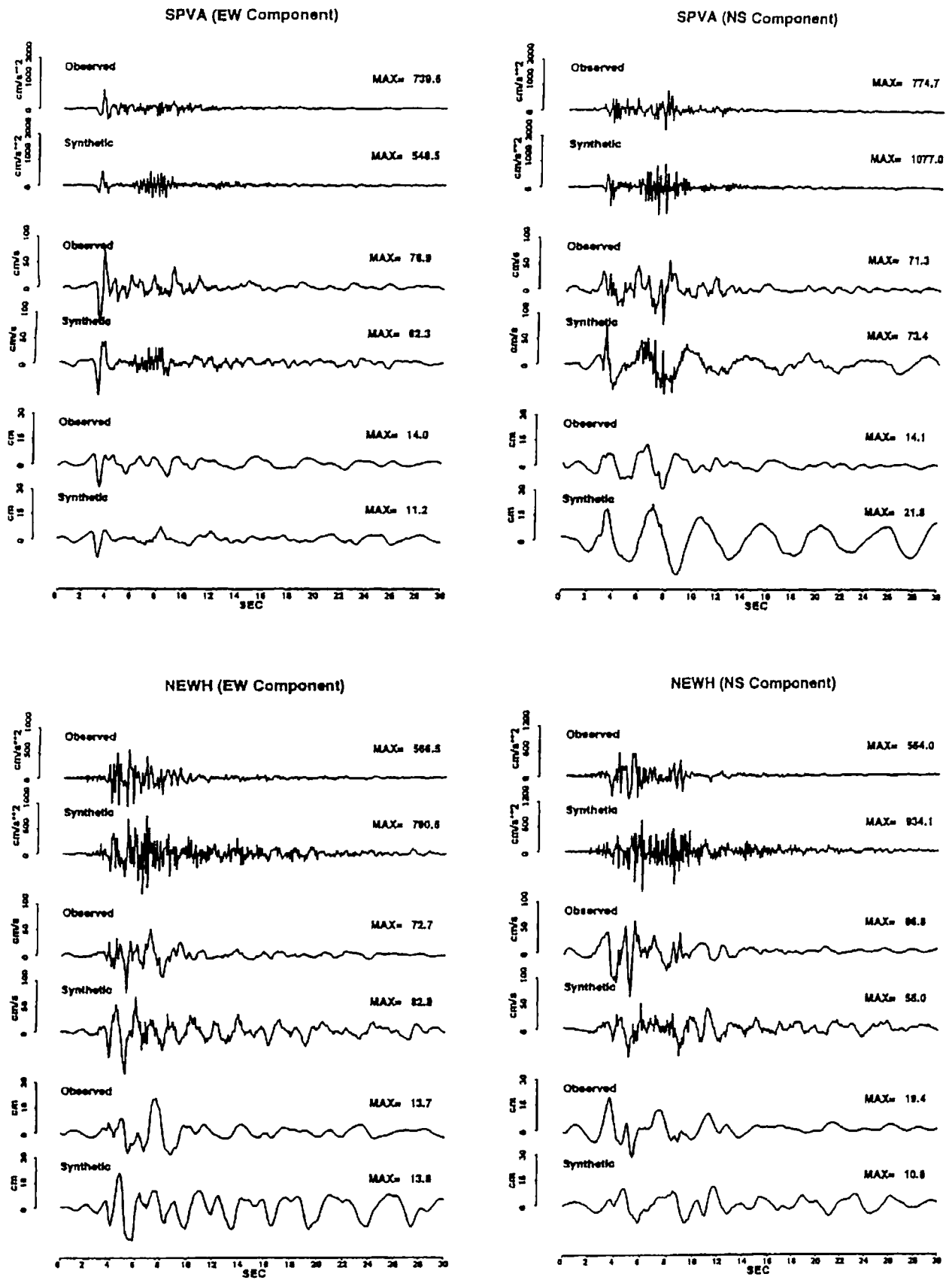
Fig. 7. Comparison between the synthetics by the empirical Green's function method and the observed records of the mainshock of the 1994 Northridge earthquake at SPVA and NEWH.

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