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Estimation of Rupture Process of the 1995 Hyogo-Ken-Nanbu Earthquake and Its Simulation

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ABSTRACT

The 1995 Hyogo-Ken-Nanbu Earthquake was the first inland earthquake since the modern observation of strong ground motion was begun in Japan in 1958. For disaster prevention purposes, it is important to know how strong ground motion near the epicenter of such an earthquake is caused. This paper proposes simple model for the source and rupture process of the Hyogo-Ken-Nanbu Earthquake. The simple model is derived by using semi-empirical methods and by referring to the travel times of a remarkable phase of strong ground motion identified in records from near-field observation stations. Simulated strong ground motions created with the simple source and rupture process model agree well with seismogram records gathered on rock in the near field (Δ<30km) and surrounding field (Δ<100km).

KEYWORDS

strong ground motion, source process, semi-empirical method

INTRODUCTION

The 1995 Hyogo-Ken-Nanbu Earthquake destroyed thousands of lives and structures in just a few seconds of violent shaking. It was the most destructive earthquake to have occurred below a city in Japan since modern observation of strong ground motion in Japan began in 1958. It was a typical inland earthquake different from the other destructive ones.

Many observation stations in and around Kobe created seismograms of the event, and some of these records have been published. It was widely known that, though the magnitude of the earthquake was not so large, ground motion was remarkably strong. Since strong ground motion near an epicenter is a consequence of source structure, it is important to simulate near-field strong ground motion in order to learn about the source and the rupture process.

Some source process models, such as the one proposed by Kikuchi (1995), were inferred from teleseismograms. While these models were able to describe a whole rupture process, it was desired, from engineering viewpoint, to specifically trace the details of a rupture process which affect strong ground motion in the near field. Wald (1995), Yoshida et al.(1995), Irikura et al. (1995) and Kakehi et al. (1995) have devised source models using near-field seismograms. Their models are possibly attributing the effect of propagation to the irregularity of the source.

The model proposed in this paper is constructed by using the semi-empirical method with the Green's function including the effect of propagation. Near field records of strong ground motion are also utilized. After constructing the simple source model, simulation analysis is conducted to reproduce strong ground motions and to compare with observation records at several near-field stations .

DATA

Many records of strong ground motion were obtained during the Hyogo-Ken-Nanbu Earthquake. This paper uses velocity records obtained at some near-field stations of the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA), as well as acceleration records released by the Japan Meteorological Agency (JMA), the Railway Technical Research Institute of Japan Railway Co. and the government of Kobe City. Figure 1 shows the locations of observation stations, and Figure 2 shows examples of records.

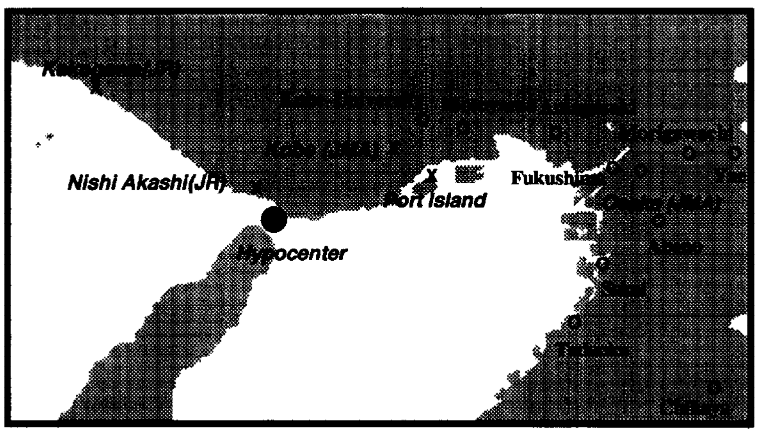

Figure 1. Stations from which digital recordings supplied data used in this study. CEORKA stations are labeled with plain type and other stations are labeled with italic type. Sites marked with open circles are sites for which the model proposed here was used to simulate strong ground motions. Sites marked with X's are sites from which travel times (deduced from strong ground motion records) were used to determine the source model.

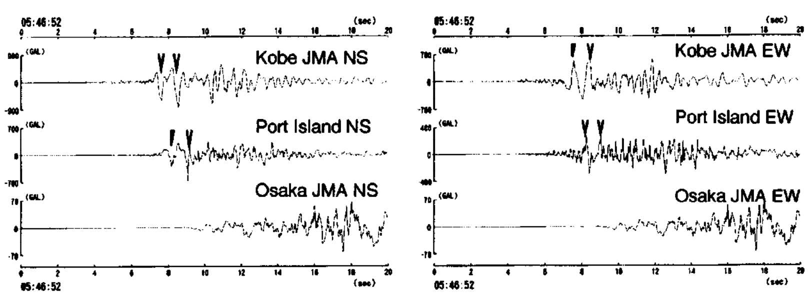

Figure 2 Sample records of the Hyogo-Ken-Nanbu Earthquake recorded by accelerometer. The arrows point to the parts of the records that are crucial for this study.

METHODS

Estimation of source model

Two typical horizontal wave phases are evident in near-field seismograms of the main shock, as indicated by the allows in Figure 2. Here we call the first horizontal wave phase Sa and the second Sb originated from

S. Since almost all records in the data set show these prominent phases, it is reasonable to conclude that they originated at the seismic source. This implies that there were two large asperities (Sa and Sb) at the source. In order to identify the locations of these asperities, the travel times of each phase are introduced according to Hamada's structure model (1983A).

Figure 3 shows the relation of travel times of each phase by assuming that depths of asperities Sa and Sb were coincident with the hypocenter of the earthquake. Table 1 describes Sa-S and Sb-S, hypocentral distances and azimuths of each station. This relation suggests that asperity Sa was near the hypocenter and asperity Sb was rather northeast of the hypocenter. The distances between asperities Sa and Sb, and hypocenter were estimated 0.7 km and 10.8 km respectively, while time lags of start time were 0.8 sec. and 2.6 sec. respectively. The location of asperities Sa and Sb as determined by travel times of Sa and Sb phases are shown in Figure 4.

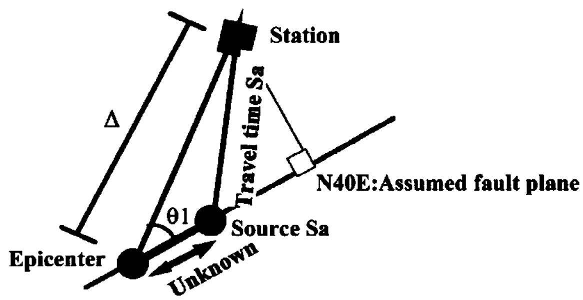

Figure 3 Relations between locations and travel times of the hypocenter, Sa and Sb.

Table 1 Sa-S times, Sb-S times, hypocentral distances and azimuths of stations.

Station	Δ	Sa-S time	Sb-S time	θ1
Nishi-Akashi	8.9km	0.7sec	2.7sec	-88.7°
Kakogawa	31.8km	0.7sec	2.9sec	-98.6°
JMA-Kobe	15.6km	0.8sec	1.5sec	13.7°
Kobe-Univ.	22.3km	0.8sec	1.6sec	14.0°
Motoyama	25.1km	0.8sec	1.6sec	20.0°
Amagasaki	35.7km	0.8sec	1.7sec	29.7°
Chihaya	59.5km	0.7sec	—	68.1°

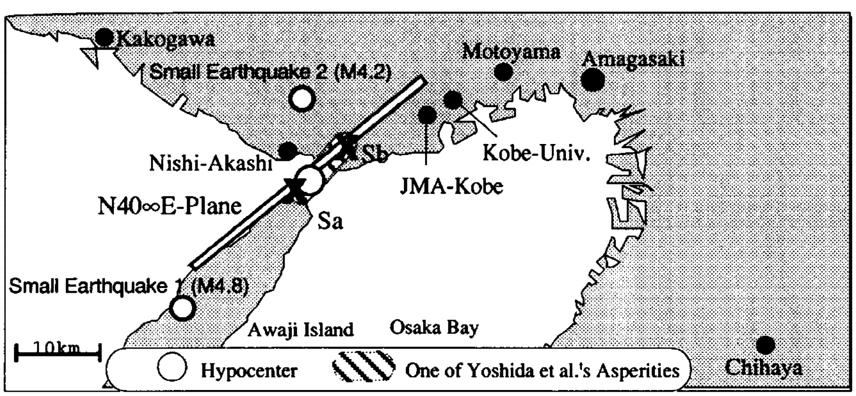

Figure 4 Location of asperities Sa and Sb as determined by travel times of Sa and Sb phases.
The locations of these asperities are similar to the locations of asperities in the model by Yoshida et al. That model includes an area of strong energy radiation about 10km long under the Akashi Strait. The area corresponds to the locations of asperities Sa and Sb. Yoshida et al. state that much energy was released during the first four seconds of the event.

It should be noted that the source model and rupture process proposed here should be regarded as simplified with respect to other models which are also based on near-field records of strong ground motion.

Based on the distribution of aftershocks, we adopted values for fault dip angle and strike angle of 90° and N40°E, respectively. We also adopted the length of fault L to be 24 km and width W to be 12 km based on the appearance of the Nojima fault on Awaji Island. We assumed the size of asperity Sa to be the same as that of asperity Sb because no information in the data set suggests differences between the two asperities. Since there is not enough in formation about variations of asperities in the vertical direction, we assumed lateral rupture on the fault plain.

The value of rupture velocity (VR) 2.7km/s and the value of shear wave velocity (VS) 3.1 km/s were assumed after Irikura (1995). The moment magnitude (Mw) of the main shock 6.9 was also assumed after Kikuchi (1995) and JMA (1995).

Simulation of the mainshock

In order to verify the source model described above, we performed simulation analyses of strong ground motions caused by the main shock using semi-empirical method. It was possible to take into account heterogeneous faulting as proposed by Irikura (1983) and Ikeura and Takemura (1990). In this procedure, the heterogeneity of the source model was attributed to asperities Sa and Sb and the other segment of the model was assumed to have no asperities. For calculations with the semi-empirical method, Irikura's method was used for asperities Sa and Sb and Ikeura and Takemura's method is used for the other segment of the model.

The rupture processes of both asperities was assumed to be bilateral starting from the center of the segment while a unilateral rupture process starting from northeast end is assumed for the other segment. The origin times of ruptures at each asperity were determined by travel times deduced from records; thus the rupture at asperity Sa started at one second after the origin time and the rupture at asperity Sb started at three seconds after the origin time.

Many records of aftershocks were created by CEORKA stations. To select aftershocks for analysis, we limited the choice to those greater than JMA magnitude (Mj) 4 because records of smaller earthquakes are in general noisy. We also considered directions from the stations because the effect of propagation must be included in the record as Green's function from source to site. Based on these considerations, we selected two aftershocks.

Figure 4 indicates the epicenters of these small earthquakes. The Mw values are 4.2 and 4.8; these values are taken to be the same as Mj values because Mj and Mw are nearly equal when Mj is smaller than 6.5 (Utsu 1982).

Comparison between simulation results and records

The source parameters of the Hyogo-Ken-Nanbu Earthquake and the small earthquakes must be determined to satisfy the similarity and scaling law. Table 2 lists parameters of the source model.

Table 2. Parameters of our source model

	Sa's area	Sb's area	Other's area	Total
Length	5km	5km	14km	24km
Width	12km	12km	12km	12km
Rupture process	Bilateral	Bilateral	Unilateral	
Moment rate	5 :	5 :	7	Mw = 6.9
Strike angle	N40°E	N40°E	N40°E	N40°E
dip angle	90°	90°	90°	90°
Shear waveVelocity	⟶	⟶	⟶	Vs=3.1km/s
Rupture Velocity	⟶	⟶	⟶	Vr=2.7km/s
Small Earthquake	2	2	1	

To determine the distribution of seismic moment among the three segments (asperities Sa and Sb, and another segment), six cases of distribution of seismic moment were calculated. The cases are described in Table 3. The Kobe University station was selected for these calculations due to its rock condition. The first case implies no asperity where all the moment rates are equal. The other five cases include asperities. Figure 5 compares the result of case 1 (with no asperities), case 5 (with two asperities) and the observed wave form. As for case 1, several phases are absent and amplitude is smaller than the observation record as predicted. However, the result of case 5 and other results of the case study show that our estimation of the rupture process, determined from the travel times of phases Sa and Sb, is consistent with observation records. Based on the results of this case study, we chose 2:2:1 as the ratio of seismic moment among segments Sa, Sb, and the other segment of our model.

Table 3 Case of distribution of seismic moment

	Slip Ratio Sa:Sb:other segment	Moment Ratio Sa:Sb:other segment	Max.NS Velocity
case 1	1 : 1 : 1	5 : 5 : 14	21cm/s
case 2	7 : 7 : 5	1 : 1 : 2	29cm/s
case 3	21:21:10	3 : 3 : 4	31cm/s
case 4	14:14:5	1 :1 :1	34cm/s
case 5	28:28:5	2 : 2 : 1	44cm/s
case 6	42:42:5	3 : 3 : 1	60cm/s

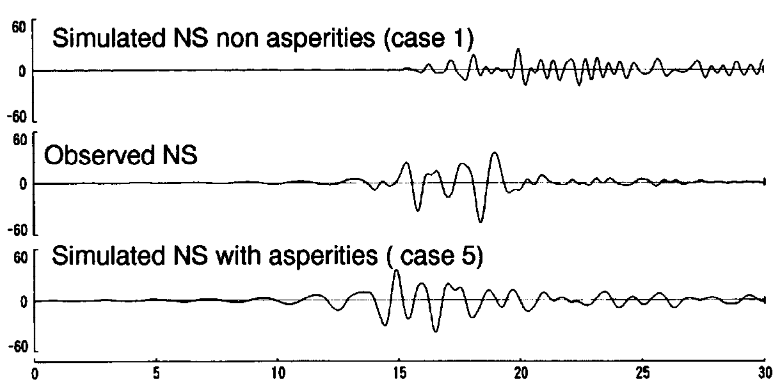

Figure 5 Comparison of the results of simulations with and without asperities for Kobe-University, and observation record from that station.

Figure 6 shows the comparison of the simulated strong ground motion with observed ones at the Kobe University and Chihaya station using the model proposed here. Both stations are on bedrock. The observation records and the simulation results were filtered with a bandpass filter of 0.5 to 2 Hz. This range of frequencies includes the frequencies of phase Sa and Sb. Figure 7 shows the pseudo velocity response spectra for the Kobe University station with a damping factor of 0.05, where good fitness between 0.2 seconds and 1.1 seconds in the NS direction is recognized.

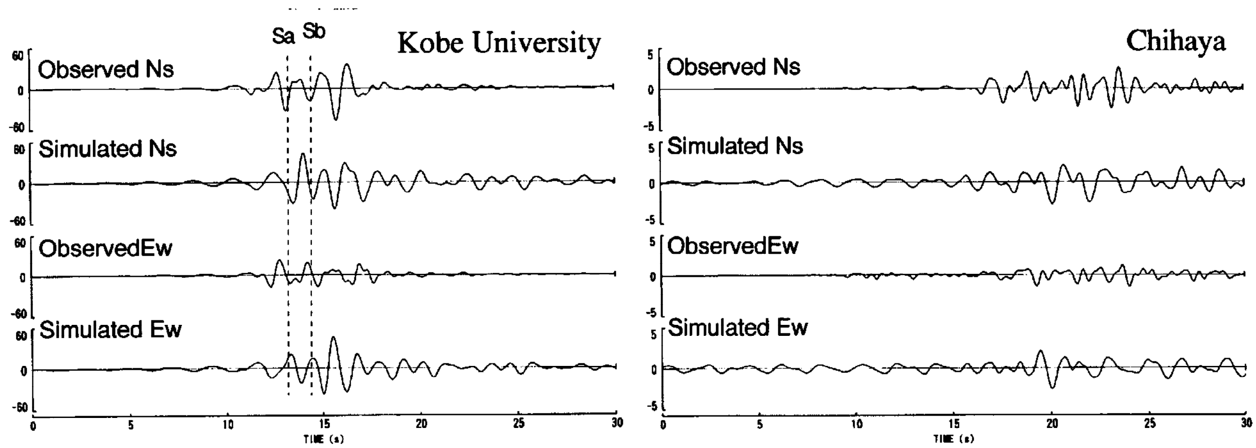

Figure 6 Result of simulation for Kobe University station (left) and Chihaya station (right), and observation records from those stations. Phases Sa and Sb are apparent in the simulation results.

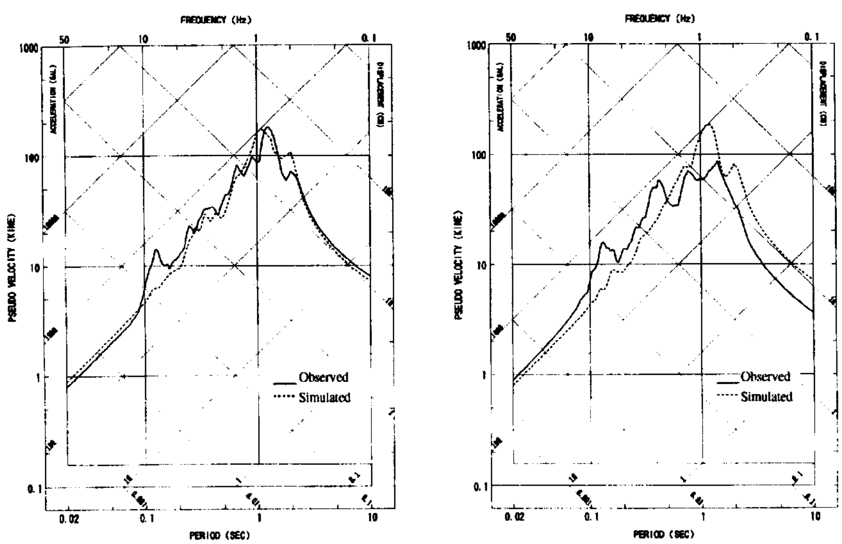

Figure 7 Comparison between simulated and observed response spectra for Kobe University station.

Although the simulation results for stations on bedrock were almost identical to observation records, further testing of the model was required. Figure 8 compares the results of simulations for other CEORKA stations with observation records. Sakai and Amagasaki stations are on soft soil, and Tadaoka station is on alluvium. Linear behavior must be used to compare simulation results and observation records because the semi-empirical method is valid only for linear conditions. The observed wave forms at these stations were non-linear after Sb. For phases Sa and Sb, the simulation results and observation records were consistent in the linear behavior range. Though simulation produced maximum velocity values different from those of observation records, the differences should be attributed to the fact that the simulation results represent linear behavior. It is ,therefore, concluded that the results of simulations agree well with observation records of the Sa and Sb phases of the Hyogo-Ken-Nanbu Earthquake.

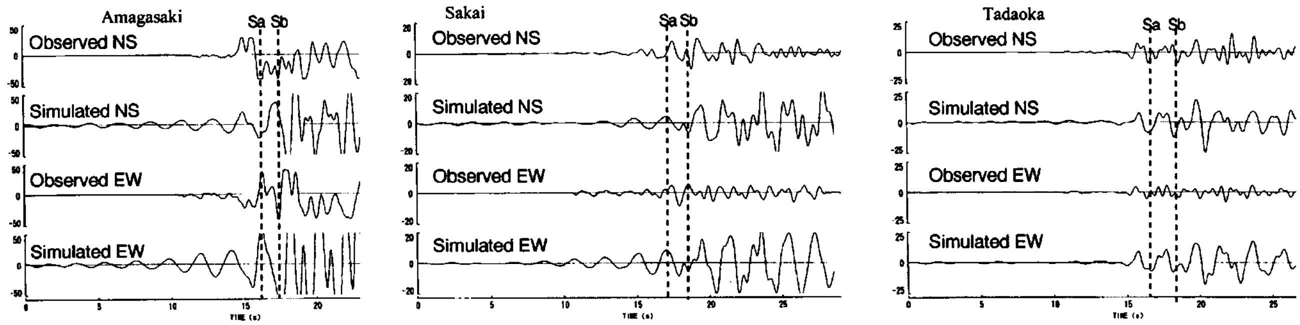

Figure 8 Results of simulations for Amagasaki (left), Sakai (middle) and Tadaoka (right) stations, together with observation records from these stations. Some clipping occurred during observation at Amagasaki station.

The aforementioned model by the authors corresponds to the first rupture of Kikuchi's model. By adding the second and the third ruptures of Kikuchi's model, it was possible to revise the model. Figure 9 shows the revised model and the results of its simulation, where it is possible to say that the proposed model is able to explain the entire process of the earthquake.

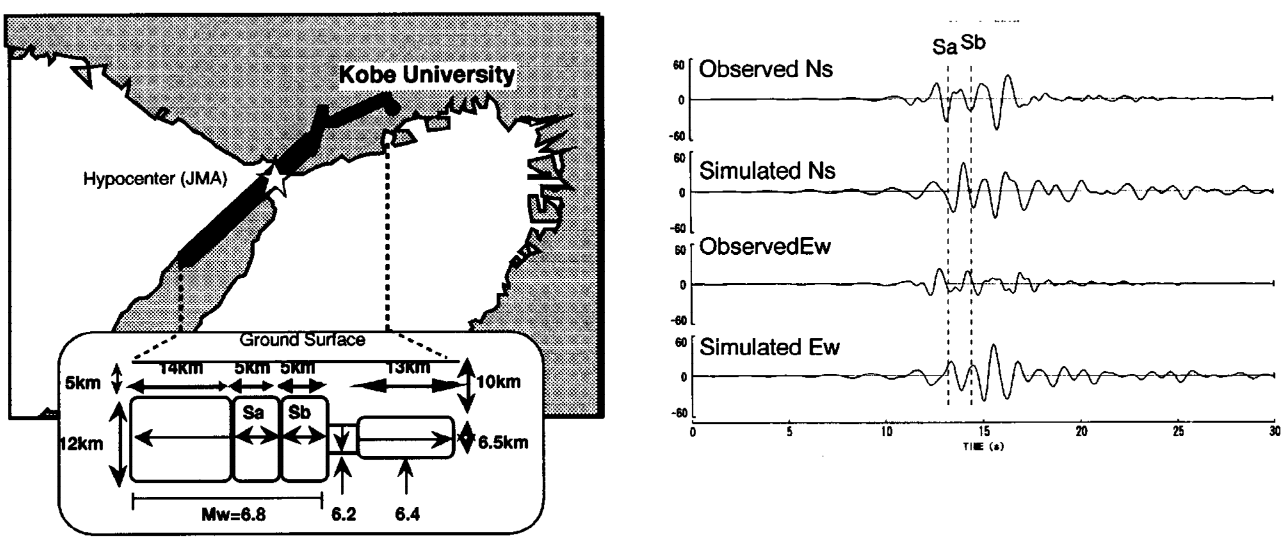

Figure 9 Source model which reflects Kikuchi's model (left) and results of simulation which reflects Kikuchi's source model (right), for Kobe University station, and observation records from that station.

CONCLUDING REMARKS

Through the detailed tracing works on the strong ground motions observed at several stations at and around Kobe, the source and rupture process of the destructive inland earthquake beneath the urbanized area was clearly identified. Two explicit phase differences were recognized in the strong ground motion records, which helped to construct, from engineering viewpoints, an advanced but relatively simple model. A semi-empirical method taking account of the effects of recognized asperities on the fault plane was applied to the model and several comparative case studies proved that it was able to simulate and reproduce the earthquake ground motion both in the base stratum as well on the surface layer of the damaged area on the Hyogo-Ken-Nanbu Earthquake.

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