

A METHOD FOR SIMULATING THREE-COMPONENT, NEAR-FAULT, STRONG GROUND MOTIONS USING STOCHASTIC GREEN'S FUNCTION

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SUMMARY

We extend the stochastic simulation method to allow computation of three-component strong ground motions. The method incorporates the effects of source, propagation path, and local site conditions. The moment rate function is obtained using a conventional stochastic simulation method. Three types of body waves (P, SV, and SH waves) evaluated from the moment rate function are radiated from subfaults. The effect of the propagation path is evaluated by the dynamic ray tracing and the effect of the local site conditions is evaluated using a flatly layered model of sediments. Putting all the three effects together, three-component (NS, EW, and UD) time-histories from each subfault are generated and, summing up contributions from each subfault, we obtain three-component strong ground motions for a total fault. We examine the reliability of this method. We first compared peak acceleration with the attenuation relationship. The peak accelerations show agreement with the attenuation relationship in an area close to an earthquake fault. We then try to reproduce near-fault strong ground motions for the 1995 Hyogo-ken Nanbu earthquake. Simulated accelerations and velocities show agreement with recorded ones in the area close to the fault except for the vertical component.

INTRODUCTION

Recent development of seismic strong motion observation has revealed several characteristics of near-fault strong ground motions: a large amplitude difference between fault-normal and fault-parallel components (Somerville et al., 1997), large amplitude of the vertical component in comparison with horizontal components (for example, see Figures 3, 4, and 5 in Smith et al. (1982)). These characteristics indicate that three-component strong motions are required for the earthquake-resistance design in areas close to earthquake faults, especially for high-rise and base isolated buildings.

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Simulation methods of strong ground motion have made rapid progress since the 1980's (Hartzell, 1978; Uebayashi et al., 1992; Frankel, 1993). At present, the empirical Green function method (Irikura, 1986), the stochastic simulation method (Boore, 1983), and the finite difference method (Graves, 1996) are often employed for practical use in such areas as earthquake-resistance and earthquake hazard mitigation. The stochastic simulation method for a point source (Boore, 1983: Chin and Aki, 1991) and for a finite source (Kamae and Irikura, 1992; Beresnev and Atkinson, 1997) is a useful and practical tool to simulate high-frequency strong ground motions. However, this method has the shortcoming of generating only average seismic motion of the two horizontal components. Therefore, it is desirable to extend the method to allow it to compute three-component seismic motions.

In this study, we first show an extension of the stochastic simulation method to compute three-component seismic motions. Then, we examine the reliability and applicability by two comparisons. The first comparison is made with the attenuation relationship of peak acceleration, and the second comparison is made with recorded strong ground motions of the 1995 Hyogo-ken Nanbu (Kobe) Earthquake.

METHOD

In numerical modeling the effects of source, path, and local site condition are appropriately evaluated and they should be combined. In this section we describe how to introduce these effects into the computation.

Source effect

Far field shear wave acceleration time history $a_s(r,t)$ radiated from a point source in a homogeneous isotropic media is specified as

$$a_{s}(r,t) = \frac{1}{4\pi\rho\beta^{3}} F^{s} \frac{1}{r} \frac{d^{3}M(t-r/\beta)}{dt^{3}}$$
(1)

where ρ and β are the density and the shear wave velocity, and r denotes a distance between the observation point and the point source. M is a time-dependent seismic moment and F^s is the radiation coefficient for the shear wave. This equation is the same as equation (4.32) in Aki and Richards (1980). Hereafter, we simply refer to d^3M/dt^3 as the moment rate function.

As can be seen in equation (1), the moment rate function is necessary to compute seismic motions. We show that this function is obtained by using a conventional stochastic simulation method, which was originally proposed by Boore (1983) to generate acceleration time histories based on the ω -squared (ω^{-2}) acceleration spectra radiated from a point source. The radiated source spectra are expressed as

$$A(f) = \frac{1}{4\pi\rho\beta^{3}} F^{s} \frac{1}{r} M_{0} S(f, f_{c}) P(f, f_{m})$$
(2)

where f_c , f_m and M_0 are the corner frequency, the cutoff frequency, and the seismic moment. Equations $S(f, f_c)$ and $P(f, f_m)$ are specified in Boore (1983). Putting the acceleration time history generated from the source spectra specified by equation (2) on the left-hand side in equation (1), we can derive the moment rate function. Therefore, we regard the conventional stochastic simulation method as the method to generate the moment rate function d^3M/dt^3 . Hereafter, the moment rate function obtained by using Boore's technique is specified as d^3M_c/dt^3 . An example of calculated d^3M_c/dt^3 , dM_c/dt , and M_c is shown in Figure 1 for the source parameters: $M_0 = 5*10^{23} dyne*cm$, $f_m = 10Hz$, the rise time $\tau = 0.16s$, and the stress parameter $\Delta\sigma = 100bar$. As can be seen from the bottom diagram, since the calculated seismic moment is almost the same as a given seismic moment, the moment rate function is considered to be calculated appropriately.



Fig. 1 An example of the moment rate function estimated using a conventional stochastic simulation method. d^3M_c/dt^3 , dM_c/dt , and M_c are shown at the top for source parameters $M_0 = 5 \times 10^{23} dyne \times cm$, $f_m = 10Hz$, and $\tau = 0.16s$.

Radiated shear waves are decomposed into SH and SV waves and are expressed as

$$a_{SH}(r,t) = \frac{1}{4\pi\rho\beta^3} F^{SH} \frac{1}{r} \frac{d^3M(t-r/\beta)}{dt^3}$$
(3)
$$a_{SV}(r,t) = \frac{1}{4\pi\rho\beta^3} F^{SV} \frac{1}{r} \frac{d^3M(t-r/\beta)}{dt^3}$$
(4)

where F^{SH} and F^{SV} are the radiation coefficients for SH and SV waves. Similarly, radiated P waves are expressed as

$$a_{P}(r,t) = \frac{1}{4\pi\rho\alpha^{3}} F^{P} \frac{1}{r} \frac{d^{3}M(t-r/\alpha)}{dt^{3}}$$
(5)

where F^{P} is the radiation coefficient for P wave. Replacing the term $d^{3}M/dt^{3}$ in equations 3, 4, and 5 with the term $d^{3}M_{c}/dt^{3}$, we can obtain SH, SV and P acceleration time histories having ω -squared spectra radiated from a point source in an infinite homogeneous media.

We next describe how to compute the moment rate function for a large earthquake event. The fault surface of the large event is divided into subfaults and P, SV, and SH waves are radiated from each of them as schematically shown in Figure 2. However, equations 3, 4, and 5 cannot be regarded as the radiated body waves only by replacing the term d^3M/dt^3 with the term d^3M_c/dt^3 , because the moment rate function for a large earthquake is different from that for a small earthquake due to the difference in the rise time and the stress parameter. Irikura (1986) proposed a correction function of the moment rate function under the condition that both the source spectra of the small and the large earthquakes meet the -squared radiated spectra. This function is often used in the empirical Green function method and is substantiated to work well (Pitarka et al., 1999). However, this function has a drawback. Thus, we use a modified function.

The moment rate function of the large event $d^3M_c^l/dt^3$ is corrected by the equation $M_c^l(t) = I(t) * M_c(t)$ (6)

where * denotes the convolution. I(t) is a correction function by Irikura (1986) and is given as

$$I(t) = \delta(t) + \sum_{k=1}^{(n-1)m} \frac{1}{m} \delta(t - \frac{(k-1)\tau}{(n-1)m})$$
(7)

where *n* is the ratio of the rise time for the large earthquake event τ to the rise time for the small event and δ is the delta function.

The thin line in Figure 3 shows the Fourier spectra of the Irikura correction function for $\tau = 1.6s$, n = 10, and m = 10 and exhibits periodic peaks and troughs because of the equi-distance impulse series of equation (7). Thus, this function may generate spurious spectral peaks and troughs in synthetic seismograms. To remove these peaks and troughs we use a different correction function, which is derived from a slip rate function by Brune (1970). It is expressed as

$$V(t) = \frac{\Delta\delta}{\mu}\beta\exp(-\frac{t}{\tau})$$
(8)

where μ denotes the rigidity. After a simple manipulation, we obtain the Brune correction function

$$B(t) = \left(\frac{1}{\tau_s} - \frac{1}{\tau_l}\right) \exp\left(\frac{-t}{\tau_l}\right) + \delta(t)$$
(9)

where τ_l is the rise time for the large event and τ_s is the rise time for the small event.

The thick line in Figure 3 shows the Fourier spectra of the Brune correction function. It exhibits no spurious peaks and troughs and agrees with the average of the Irikura correction function in the frequency range above $1/\tau_1$ Hz (approximately 0.6 Hz). However, in the frequency range below $1/\tau_1$ Hz, they are different. Thus, we use a hybrid correction function: the Brune correction function in the frequency range above $1/\tau_1$ Hz and the Irikura correction function in the frequency range below $1/\tau_1$ Hz.



Propagation-path effect

As shown in Figure 2, three types of body waves, SH, SV, and P waves, are radiated from subfaults, and propagate to the uppermost part of the crust along each ray path. In general, the propagating media is inhomogeneous so that they alter waveform during propagation. We incorporate the effects of the inhomogeneity of the propagating media using the dynamic ray theory (Cerveney et al. 1977), specifically, the attenuation due to the geometrical spreading is evaluated by the geometrical spreading factors, \Re_p and \Re_s , for P and S waves, and the amplification is evaluated by the impedance ratios between a source region and the uppermost part of the crust.

The inhomogeneity of the propagating media affects the radiation coefficients as well. Along with propagation, the radiation coefficients, F^{SH} , F^{SV} , and F^{P} , for SH, SV, and P waves change due to scattering from theoretical values dependent on the take-off angle (Aki and Richards, 1980, p. 115) to isotropic values expressed in equations (10), (11), and (12) as

$$(F^{P})^{2} = 4/15 \qquad (10)$$

$$4(F^{SV})^{2} = \sin^{2} \lambda (14/15 + 1/3\sin^{2}(2\delta)) + \cos^{2} \lambda (4/15 + 2/3\cos^{2} \delta) \qquad (11)$$

$$4(F^{SH})^{2} = 2/3\cos^{2} \lambda (1 + \sin^{2} \delta) + 1/3\sin^{2} \lambda (1 + \cos^{2}(2\delta)) \qquad (12)$$

where λ and δ denote the strike and the dip angles. The manner of change is controlled by the statistical properties of the inhomogeneity. However, at present, we lack sufficient knowledge of these properties. Thus, we assume that the radiation coefficients change as follows

$$\begin{cases} if & Dt < L_1 \times Wl & theoretical value \\ if & L_1 \times Wl < Dt < L_2 \times Wl & Interpolation between theoretical and isotropic values (13) \\ if & Dt > L_2 \times Wl & isotropic value \end{cases}$$

where Dt and Wl denote the travel distance and the wavelength. When $L_1 \times Wl < Dt < L_2 \times Wl$, the radiation coefficients are computed using a linear interpolation between the theoretical and the isotropic values. In actual computations, we assume that the factors L1 and L2 are set at 1 and 5 for P and S waves.

The effect of damping is also incorporated into computation using frequency- and depth- dependent Q values.

Combining the above-mentioned effects and using the corrected moment rate function, we obtain acceleration waveforms for three types of body waves propagating from each subfault to the uppermost part of the crust. Their Fourier spectra are expressed as

$$A_{SH}(x,f) = \left(\frac{\widetilde{M}_{c}^{l}(f)\exp(i2\pi ft_{s})}{4\pi\rho_{0}\beta_{0}^{3}}\right) \frac{(\rho_{0}\beta_{0})^{0.5}}{(\rho_{1}\beta_{1})^{0.5}} \frac{F^{SH}}{\Re_{s}}\exp\left(\int_{r_{s}}\frac{-\pi f}{\beta Q_{s}}dz\right)$$
(14)

$$A_{SV}(x,f) = \left(\frac{\tilde{M}_{c}^{l}(f)\exp(i2\pi ft_{s})}{4\pi\rho_{0}\beta^{3}}\right) \frac{(\rho_{0}\beta_{0})^{0.5}}{(\rho_{1}\beta_{1})^{0.5}} \frac{F^{SV}}{\Re_{s}}\exp\left(\int_{r_{s}}\frac{-\pi f}{\beta Q_{s}}dz\right)$$
(15)

$$A_{p}(x,f) = \left(\frac{M_{c}^{l}(f)\exp(i2\pi ft_{p})}{4\pi\rho_{0}\beta_{0}^{3}}\right) \frac{(\rho_{0}\beta_{0})^{0.5}}{(\rho_{1}\beta_{1})^{0.5}} \frac{F^{p}}{\Re p} \exp\left(\int_{r_{p}} \frac{-\pi f}{\alpha Q_{p}} dz\right)$$
(16)

where $\tilde{M}_{c}^{l}(f)$ is the Fourier transform of the moment rate function of the large event $d^{3}M_{c}^{l}(t)/dt^{3}$. ρ_{0} , α_{0} , and β_{0} are the density, the P-wave velocity, and the S-wave velocity in the source region, and ρ_{1} , α_{1} , and β_{1} are the density, the P-wave velocity, and the S-wave velocity at the uppermost part of the crust. Q_{p} and Q_{s} denote quality factors for P and S waves along seismic ray paths. r_{s} and r_{p} represent seismic ray paths for S and P waves.

Effect of local-site conditions

Our primary concern is the strong ground motions inside sedimentary basins. Because seismic waves are greatly amplified by sediments, the effect of local site conditions should be incorporated into the computation. As shown in Figure 2, the sediments are modeled as flatly layered media and the three body waves are independently incident to sediments as plane waves. Incident angles are obtained from ray tracing (Cerveney et al. 1977). We calculate the responses of sediments on ground surfaces to these wave incidences by Silva (1976).

Three-component accelerations on ground surface

Multiplying the response of sediments on ground surfaces due to SH wave incidence by equation (14), the transverse component of shear waves on ground surfaces are obtained. Similarly, multiplying the vertical and the radial responses due to SV-wave incidence by equation (15), the vertical and radial components on ground surfaces are obtained. The vertical and radial components due to P wave incidence are obtained, in the same way that the vertical and the radial components are obtained due to SV wave incidence. Repartitioning the radial and transverse components into north-south (NS) and east-west (EW) components, and summing up contributions from individual subfaults for each component, we obtain the NS, the EW, and the vertical component acceleration time histories for a total fault.

SIMULATION OF NEAR-FAULT, THREE-COMPONENT, HIGH-FREQUENCY MOTIONS

We investigate the reliability of this method by comparing the peak accelerations with the attenuation relationship of peak horizontal accelerations for shallow (<30 km) Japanese earthquakes (Fukushima and Tanaka, 1990). We prepare 4 earthquakes of magnitude 7.0, 6.5, 6.0, and 5.5. The source parameters are shown in Table 1. These parameters are derived from the regression formulae (Sato, 1989) $\log M_0 = 1.5M_w + 16.2$

$$M_{w} = 2(\log L + 1.88)$$

$$W = L/2$$

$$\tau = 10^{(0.5M_{w} - 1.4)} / 80$$
(17)

where M_w , L, and W denote the moment magnitude, the fault length, and the fault width. N_L and N_W are segment numbers for fault length and width. The top of the four faults is at a depth of 3km. The fracture velocity is 2.5 km/s and the slip is uniform over the fault surface. The structure model is slightly modified from that of Horikawa et al. (1995), which was used for the source inversion of the 1995 Hyogo-ken Nanbu Earthquake, and is shown in Figure 4. The Q values are from Akamatsu (1980) with slight modifications.



Fig. 4 Structure model of basement rock. The thin line and the thick line are the S Velocity and the P Velocity, respectively. The dotted thin ine and the dotted thick line are Q_{S0} value and Q_{P0} value, respectively. The quality factors for the S wave and P wave are given by the equations

$$Q_{s} = Q_{s0}\sqrt{f}$$
 and $Q_{p} = Q_{p0}\sqrt{f}$, respectively.



Fig. 5 A plane view of the configuration of the fault (solid line) and the observation points (small circles). Capital letters A to D denote the group of observations sites on lines.

with the attenuation relationship of peak norizontal acceleration							
	M_{W}	L (km)	W (km)	M ₀ (dyne*cm)	τ (sec)	$N_L^*N_W$	⊿ σ (bar)
	7.0	41.68	20.33	5.01*10 ²⁶	1.57	20*10	80
	6.5	23.44	11.72	8.91*10 ²⁵	0.885	10*10	80
	6.0	13.18	6.59	1.585*10 ²⁵	0.50	10*10	80
	5.5	7.40	3.70	2.82 [*] 10 ²⁴	0.28	10*10	80

Table 1The source parameters for comparing the simulated peak accelerationswith the attenuation relationship of peak horizontal accelerations.

Features of near-fault strong motions

Figure 6 shows an example of simulated accelerations for an earthquake of $M_w = 7.0$ for the strike-slip vertical fault on observation lines A, B, C, and D. A plane view of the configuration of the fault and the observation lines is shown in figure 5. The fracture is initiated at the middle subfault of the left fault edge.



Fig. 6 An example of simulated ground motions for a vertical fault with strike slip. (a) On line A. The capital letters A1 to A4 are observation sites from the closest observation site to the fault to farther site. The fault-parallel, the fault-normal, and the vertical components are shown in the left, in the middle, and the right columns. (b) On line B. (c) On line C. (d) On line D.

We can see a clear directivity effect. The duration of earthquake motion reduces in order of lines A, B, C, and D. Besides this, the fault-normal component is larger in amplitude than the fault-parallel component at sites close to the fault. For example, on line B, the fault-normal component at site B1 and B2 is larger than the fault-parallel component, but at site B4 the opposite is the case. However, amplitude on line D is almost the same as amplitude on line A. This may result from random superposition of high frequency motions.

The contours of peak accelerations for the three components are depicted in Figure 7. We can see many more clear directivity effects in the figure. Firstly, comparing the contour maps between the two horizontal components shows that the fault-normal component obviously prevails in amplitude over the fault-parallel component within an area of distance of less than 10 km from the fault. Secondly, the strong ground shaking area increases along with the propagation of the fracture, especially for fault-parallel components. Specifically, for example, the bright area gradually widens from the left edge of the fault to the right edge. These results suggest that the computation of three components is required even for high frequency motions.



Fig. 7 Contour maps of peak acceleration of the simulated motions for the vertical fault with the strike slip. The top, the middle, the bottom depict the fault-parallel, the fault-normal, and

vertical components. The solid line in each contour map is a surface projection of the fault.



Fig. 8 Comparison of simulated mean peak acceleration of the two horizontal components with the attenuation relation for earthquakes of magnitude 7.0, 6.5, 6.0, and 5.5. The long solid curve denotes the attenuation relation of rock (S wave velocity > 0.7 km/s) by Fukushima and Tanaka (1990). Short solid and dash lines denote

mean peak accelerations simulated for the vertical fault with the strike slip and the vertical fault with the dip slip. The two types of lines are generated from five random seeds, respectively.

COMPARISON WITH THE ATTENUATION RELATIONSHIP

Figure 8 shows a comparison of the geometric mean of the peak accelerations of the two horizontal components calculated for the earthquake events of magnitude 7.0, 6.5, 6.0, and 5.5 by this method with the attenuation relationship of rock for Japanese shallow earthquakes (Fukushima and Tanaka, 1990). This relationship is based on the magnitude scale determined by the Japan Meteorological Agency (Mj). Although this magnitude is different from the moment magnitude, the discrepancy does not exceed 0.1 in the moment magnitude range 5.5 to 7.0 (Utsu, 1982) so that we regard Mw as Mj.

It can be seen that the peak values of the simulated motion are consistent with the attenuation relationship at short-distance sites, but are smaller at long-distance sites. This discrepancy may be caused by the lack of contributions from surface waves and scattered waves that cannot be incorporated into the simulation method, indicating that this method is applicable only to simulate near-fault strong ground motions.

COMPARISON WITH RECORDED NEAR-FAULT GROUND MOTIONS

Source model

In this section, we investigate whether this method is usable for quantitative simulation of three-component near-fault strong motions. For this purpose we try to reproduce strong ground motion recordings of the 1995 Hyogo-ken Nanbu earthquake at three sites, Kobe University (KBU), the Kobe Marine Observatory of the Japan Meteorological Agency (JMA Kobe), and the Osaka Observatory of the Japan Meteorological Agency (JMA Kobe), and the Osaka Observatory of the Japan Meteorological Agency (JMA Osaka). The first two sites are very close to the fault and the last one is located at a distance of about 30 km. The there sites are selected because they are situated on hard sediments so that the non-linear effect is negligibly small. The locations of the three sites and the fault are shown in Figure 9(a).





We adopt the source model of the earthquake (Figure 9(b)) by Yamada et al.(1999), which is an improvement of the model in Kamae and Irikura (1998). The geometry of the asperities and the rupture velocity are shown in Table 2, and the fault parameters are shown in Table 3. The rupture is initiated at the bottom of the boundary between asperities 1 and 3, and the rupture of asperity 4 is initiated from the left lower corner at 8 s after the rupture initiation.

Table 2The geometry of the asperities and rupture velocity of the fault model
for 1995 Hyogo-ken Nanbu earthquake.

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Subevent	Strike	Dip	Vr(km/s)
1	N53 $^{\circ}$ E	90°	2.8
2	N53 $^{\circ}$ E	90°	2.8
3	N45 $^{\circ}$ E	82°	2.8
4	N233° E	85°	2.8

1					
Subovent	Δσ	Scale	Area	Mo	τ
Supevent	(bar)	(km)	(km^2)	(dyne*cm)	(sec)
1	234	4.8*4.8	23.0	1.1*10 ²⁵	0.4
2	256	8*6.4	51.2	2.3*10 ²⁵	0.5
3	86	11.2*16	179.2	8.5*10 ²⁵	0.6
4	86	12.8*8	102.4	3.7*10 ²⁵	0.6

 Table 3
 The fault parameters for the fault model for 1995 Hyogo-ken Nanbu earthquake.

We next describe the computation of the moment rate function of subfaults. As mentioned previously, this function is obtained by using the Boore Technique, and we follow it except for the cut-off frequency. The cut-off frequency for this earthquake is 6Hz.

Acceleration time history

Figure 10 shows the simulated ground accelerations at the three sites. Subsurface structure models for the sites are shown in Tables 4, 5, and 6. At the two near-fault sites, KBU and JMA Kobe, simulated motions agree comparatively well with the observed motions in amplitude and waveform except for the vertical motion.

At site JMA Osaka, the agreement of the waveform is worse in comparison with the near fault sites, but the amplitudes are reproduced comparatively well, not only the horizontal component but also the vertical component.



Fig. 10 Comparison of the simulated acceleration motions (thin line) with the observed acceleration motions (thick line). (a) At site KBU. The top two traces, the middle two traces, and the bottom two traces denote NS, EW, and vertical components, respectively. The observed motions are depicted with the thick line and the simulated motions are depicted downward with the tin line. The horizontal line at the top of each diagram shows the data window for the Fourier analysis. The vertical bar is a scale for 500 cm/s². (b) At site JMA Kobe. The vertical bar is a scale for 500 cm/s². (b) At site JMA Osaka. The vertical bar is a scale for 200 cm/s².

for the site KBU.									
Lovor	Vp	Vs	ρ	Qp	Qs	Depth			
Layer	(km/s)	(km/s)	(g/cm^3)			(km)			
1	3.2	1.8	2.1	300	200	0			
-	5.15	2.85	2.5	400	250	0.4			

Table 4The subsurface structure model
for the site KBU.

Table 6The subsurface structure model
for the site JMA Osaka.

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Lovor	Vp	Vs	ρ	On	Oc	Depth
Layer	(km/s)	(km/s)	(g/cm^3)	Qþ	QS	(km)
1	0.92	0.24	1.81	46	12	0
2	1.16	0.43	2.0	58	22	0.017
3	1.03	0.25	1.7	52	13	0.024
4	1.03	0.34	1.98	52	17	0.033
5	1.21	0.30	1.77	61	15	0.039
6	1.21	0.38	1.89	61	19	0.044
7	1.97	0.38	1.89	99	19	0.053
8	1.97	0.33	1.75	99	17	0.062
9	1.97	0.4	1.93	99	20	0.071
10	1.51	0.34	1.83	76	17	0.078
11	1.6	0.35	1.70	80	18	0.099
12	1.8	0.55	1.80	90	28	0.184
13	2.5	1.0	2.1	125	50	0.436
-	5.4	3.2	2.7	500	250	0.91
-						

Table 5The subsurface structure model
for the site JMA Kobe.

Layer	Vp (km/s)	Vs (km/s)	ρ (g/cm ³)	Qp	Qs	Depth (km)
1	0.47	0.24	1.94	25	12	0
2	0.87	0.28	1.96	40	14	0.007
3	1.2	0.39	2.01	60	20	0.013
4	1.55	0.44	2.1	80	22	0.024
5	1.83	0.47	1.84	90	24	0.05
6	2.42	0.61	1.62	120	31	0.067
7	2.04	0.52	1.53	100	26	0.076
8	2.15	0.57	1.75	110	28	0.082
9	1.86	0.44	2.09	90	22	0.109
10	1.97	0.56	2.13	100	28	0.124
11	2.22	0.85	2.32	110	43	0.138
12	2.26	0.72	2.30	110	36	0.173
13	2.31	0.83	2.30	115	41	0.181
14	2.01	0.62	2.08	100	31	0.191
15	2.36	0.75	2.18	120	38	0.205
16	2.00	0.56	1.9	100	28	0.236
17	2.55	1.1	2.26	130	55	0.247
18	1.96	0.57	2.3	100	28	0.256
19	2.13	0.7	2.32	105	35	0.271
20	2.13	0.76	2.31	105	38	0.291
21	2.27	0.67	2.2	115	34	0.311
22	2.66	0.85	2.35	133	42	0.337
23	2.5	1.1	2.3	125	55	0.357
24	5.5	3.2	2.6	700	400	0.497
-	6.0	3.46	2.7	1000	600	0.557

Acceleration Spectra

Figure 11 shows a comparison of acceleration spectra between the simulated and the observed motions. Reflecting the degree of the reproduction in time histories as described previously, the simulated acceleration spectra for the two horizontal components are in good agreement with the observed spectra at the three sites. As expected from the time histories, with regard to the vertical component, the simulated spectra are underestimated at sites KBU and JMA Kobe below 1Hz. However, at site JMA Osaka the acceleration spectra are reproduced well.

Velocity time history

In addition to the comparison of the acceleration time histories and their spectra, we compare the velocity time histories to examine the validity of the simulation method in a lower frequency range. Figure 12 shows the comparison of the velocity time histories at the three sites. At the two near-fault sites, the agreement of the two horizontal components is improved in comparison with the acceleration time histories. However, the vertical component of simulated motions is much smaller as expected from the vertical spectra in Figure 11. At site JMA Osaka, the simulated velocity time histories are reproduced well in amplitude for the three components.

The above comparisons for the acceleration and the velocity time histories suggest that better agreement between simulated and observed motions is obtained by an improvement of the subsurface structure models and the source model. However, we do not carry it out, because it is beyond the scope of this study.



Fig. 11 Comparison of the spectra for the simulated acceleration (thin line) with the spectra for the observed acceleration (thick line). (a) At site KBU. The left diagrams are for the East-South component, the middle diagrams are for the North-South component, the bottom diagrams are for the vertical component, respectively. (b) At site JMA Kobe. (c) At site JMA Osaka.



Fig. 12 Comparison of the simulated velocity motions (thin line) with the observed velocity motion (thick line). (a) At site KBU. The top two traces, the middle two traces, and the bottom two traces denote NS, EW, and vertical components, respectively. The observed motions are depicted with the thick line and the simulated motions are depicted downward with the thin line. The horizontal line at the top of each diagram shows the data window for the Fourier analysis. The vertical bar is a scale for 50 cm/s. (b) At site JMA Kobe. The vertical bar is a scale for 50 cm/s. (c) At site JMA Osaka. The vertical bar is a scale for 20 cm/s.



DISCUSSION

We discuss why the simulated vertical motions are much smaller than the observed motions. We compute the ratios of the peak horizontal motions to the peak vertical motions for point sources of the vertical fault with the strike slip located at depths of 5 km, 10 km, 15 km, and 20 km. Observation sites are located at 8 points on con-centered circles of the radii in a range from 3km to 50km. The ratios rapidly increase for the deep sources of 15 km and 20 km and for sites of close distance from the fault of less than 10 km (Figure 13). This may be explained for as follows. Seismic rays from the deep sources to the sites of short epicentral distance are incident almost vertically to the ground surface as plane waves so that the contribution to vertical components from SV waves is very small, which results in a small amplitude of vertical motions at sites close to faults.



5 km, 10 km, 15 km, and 20 km.



In reality, however, this kind of extreme phenomenon does not occur as shown in Figure 14. This figure shows the ratios for aftershock events of the Hyogo-ken Nanbu Earthquake. As can be seen, the ratio are scattered in almost the same range between 1 and 3, irrespective of the focal depth and the epicentral

distance. In general, seismic motions in the near-field cannot be expressed as plane waves especially for long-period motions. However, this method uses the ray theory of plane waves so that vertical motions are underestimated, especially for deep faults.

As can be seen from the configuration of the asperities and the observation sites (Figure 9(b)), asperities 1, 2, and 4 primarily contribute to strong motions at sites KBU and JMA Kobe. These asperities are located at deep parts on the fault surface. Furthermore, two sites, KBU and JMA Kobe, are close to the fault. This is why the vertical component of simulated motions is smaller than the observed motions at the two sites. This explanation is verified by the result that the difference in the vertical motions between the simulated and the observed motions is much smaller at the far site JMA Osaka than at the two near sites (see Figure 11(c)), because the ray is not incident vertically. Thus, this simulation method underestimates the vertical motions at sites close to faults containing the asperities in the deep portions of the faults.

CONCLUSIONS

We have presented a new stochastic simulation method to generate three-component, near-fault, strong ground motions. This method takes account of the effects of the source, the path, and the local site conditions. A fault is divided into subfaults. The moment rate function for each subfault is calculated by the conventional stochastic simulation method. Using this moment rate function and correcting the radiation coefficients, three types of body waves (P, SV, and SH waves) radiated from the source are calculated. Then, these three types of body waves propagate from the source up to sediments. The effect of the propagation path is incorporated into this method by dynamic ray tracing. The effect of the local site conditions is evaluated modeling them as flatly layered sediments. Multiplying the responses of sediment by incident three-type body waves respectively, transverse, radial, and vertical component time histories from each subfault are obtained. Repartitioning the radial and transverse components into north-south (NS) and east-west (EW) components and summing up contributions from every subfault, three-component strong ground motions are obtained.

We examined the validity of this method. We first compared it with the attenuation relationships and found that this method is useful in the proximity of earthquake faults. Then, we tried to reproduce strong ground motions observed at sites close to the fault of the 1995 Hyogo-ken Nanbu Earthquake. This method reproduced recorded strong ground motions comparatively well except for the vertical component at sites very close to the fault. Therefore, we conclude that this method is a useful tool for simulating near-fault strong ground motions for horizontal components.

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