ESTIMATION OF STRONG GROUND MOTION IN EPICENTRAL REGION OF THE 1976 TANGSHAN, CHINA, EARTHQUAKE (M_s 7.8) BY SEMI-EMPIRICAL METHOD

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1. Introduction

The 1976 Tangshan earthquake of M_s 7.8 caused huge damage to northeast China and it enhanced the development of earthquake-resistant design of structures in China. There have been many reports on this earthquake with regard to loss of life, damage to structures and grounds, the source mechanism, seismic activities, crustal structures, and so on. However, few investigations have been performed to estimate the characteristics of the strong ground motion in the epicentral region by seismological or earthquake-engineering approaches, although they provide better guidelines for the earthquake-resistant design of structures.

Dan *et al.* (1989 a, 1989 b)^{*1,*2}, based on an approximate source spectrum for the far-field shear wave, proposed a semi-empirical method for synthesizing earthquake ground motions using small-event records as Green's functions. They simulated the far-field accelerograms from the main shock of the Tangshan earthquake by using the records of its second largest aftershock of M_s 6.9 in order to show the applicability of their method to an earthquake with a magnitude of about 8 and to obtain the appropriate fault models for the main shock. It was concluded that the peak accelerations, the durations, and the spectral characteristics of the accelerograms were simulated well by the semi-empirical method and that the appropriate fault models were obtained among different source parameters that were determined from low-frequency-motion analysis in seismology.

In this paper, the accelerograms in the epicentral region of the 1976 Tangshan earthquake are estimated by using the records of several small aftershocks with magnitudes of about 5 which were observed in the damaged area. In order to arrive at the reason for the huge damage, the peak values of the simulated accelerograms are compared with those evaluated by empirical formulas that were obtained from other large earthquakes. The durations and the acceleration response spectra of the synthesized motions are also compared with those for some records observed in the epicentral regions of the 1971 San Fernando, California, earthquake, the 1979 Imperial Valley, California, earthquake, and the 1985 Michoacan, Mexico, earthquake.

2. The 1976 Tangshan, China, earthquake

A large earthquake of M_s 7.8 (lat. $39^{\circ}38'N$, long. $118^{\circ}11'E$, focal depth 11 km)^{*3} hit Tangshan, a city located in Hebei Province, northeast China, on July 28, 1976. According to the State Seismological Bureau (SSB)^{*4}, the highest seismic intensity on the Chinese scale was XI. The area of intensity over X was 370 km² which represents 58.7 % of Tangshan, and the area of intensity over IX was 1,800 km² which covers the entire city and some neighboring counties. The seismic intensity on the Chinese scale is generally equivalent to that on the Modified Mercalli (MM) scale, although some differences may arise between the characteristics of structures in China and those in other countries to which damage is observed to determine the seismic intensities. Another large earthquake

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Fig. 1 Locations of the fault model for the main shock (straight solid lines), aftershocks used as Green's functions (small circles) and observation stations (solid triangles).

- (1) $M_S 7.8$, $M_0 2.0 \times 10^{27}$ dyne-cm
- (2) $M_S 7.1$, $M_0 2.0 \times 10^{26}$ dyne-cm
- (3) $M_S 6.9$, $M_0 5.2 \times 10^{25}$ dyne-cm
- (4) $M_S 6.2$, $M_0 4.9 \times 10^{24}$ dyne-cm

Fig. 2 Relationship between M_S and M_0 of the 1976 Tangshan, China, earthquake and its major aftershocks.

of $M_S 7.1$ (lat. $39^{\circ}50'N$, long. $118^{\circ}39'E$, focal depth 10 km)^{*3} occurred 45 km away from Tangshan on the same day 15 hours following the main shock.

These large earthquakes caused tremendous damage to Tangshan, killed 242,000 persons and injured 164,000 persons seriously. The big cities of Beijing and Tianjin were also severely affected. The damaged area exceeded 30,000 km² and the shock was felt in over one-third of China's area. 4.76-million-m² of floor area of civil buildings (94 % of the total) and 6.71-million-m² of floor area of industrial buildings (80 % of the total) collapsed or were extensively damaged in Tangshan. Municipal public facilities were also seriously damaged. No earthquake-resistant design was employed for these buildings and structures, except that a seismic intensity of VII at maximum was considered in the design of a few industrial facilities. The direct loss of property was estimated to be 8 billion Yuan RMB.

In the region of 56 to 400 km away from the epicenter, 175 accelerograms were recorded during the main shock and major aftershocks of $M_S 7.1$ and 6.9. After the main shock occurred, temporary strong-motion observations of aftershocks in the damaged area began to operate and fortunately obtained about 100 records of 35 aftershocks ($M_L 3.5 \sim 5.8$) at five stations. Most of the records were observed by RDZ 1-12-66-type strong-motion accelerograph, whose reliable frequency range is from 0.5 to 35 Hz (IEM, 1986)^{*5}.

Zhang (1988)^{*6} estimated the effective peak acceleration in the epicentral region of the main shock by considering a complex inhomogeneous source model. He regarded the rectangular fault of the main shock as an aggregate of many circular sub-sources. The average dynamic stress drop of each sub-source was obtained to be 206 bars from the Fourier spectra of the accelerograms recorded at Beijing Hotel station. The effective peak acceleration in the epicentral region was estimated to be 700~1,500 Gal by considering the locality of the average dynamic stress drop whose level was 300 bars near the hypocenter. In his research, however, there remains uncertainty on determining the distribution of the average dynamic stress drop.

3. Fault model for the main shock

Dan *et al.* (1989 a, 1989 b)^{*1, *2} proposed a semi-empirical method based on an approximate source spectrum for the far-field S wave proposed by Brune (1970)^{*7}, one of the ω -square models, and simulated accelerograms from the main shock at two stations of Beijing Hotel and Fengcun Bridge, whose epicentral distances are 154 and 398 km, respectively. They used the records of the second largest aftershock as Green's functions. After examination of 416 different fault models that were determined from the results of research by seismologists, the appropriate fault models for the main shock were obtained as follows: the ruptured fault width W is 15 km, the seismic moment M_0 is $1.6 \sim 2.1 \times 10^{27}$ dyne-cm, and the rupture velocity v is 2.3~2.5 km/sec. The rigidity μ , the S-wave velocity β , and the

Table 1 Source parameters of the main shock and its aftershocks used as Green's functions.

	M_S	M_0 1) [dyne·cm]	L 2) [km]	W 3) [km]	D 4) [cm]	σ_e 5) [bar]
Main shock 6)	7.8	2.0×10^{27}	90	15	423	63
Aftershock #1 (Jul. 31)	5.0	1.0×10^{23}	1.48	0.74	26.1	78
			1.59	0.80	22.5	63
	5.5	5.6×10^{23}	2.63	1.32	46.4	78
			2.83	1.42	40.0	63
Aftershock #2 (Aug. 8)	5.1	1.4×10^{23}	1.66	0.83	29.3	78
			1.79	0.89	25.2	63
	4.8	5.0×10^{22}	1.18	0.59	20.7	78
			1.27	0.63	17.9	63
Aftershock #3 (Aug. 15)	4.2	6.3×10^{21}	0.59	0.29	10.4	78
			0.63	0.32	9.0	63
	4.6	2.5×10^{22}	0.93	0.47	16.5	78
			1.01	0.50	14.2	63
Aftershock #4 (Aug. 31)	5.5	5.6×10^{23}	2.63	1.32	46.4	78
			2.83	1.42	40.0	63
	5.6	7.9×10^{23}	2.95	1.48	52.0	78
			3.18	1.59	44.9	63
Medium	Rigidity μ	3.5×10^{11}	dyne/cm ²	S-wave velocity β	3.5	km/sec
	Density ρ	2.9	gram/cm ³	Quality factor Q	1,000	

1) $\log M_0 = 1.5M_S + 15.5$. 2) $L = 2W$. 3) $W = \sqrt[3]{M_0/(\pi\sigma_e)}$. 4) $D = M_0/\mu LW$. 5) Two effective stresses of 78 bars and 63 bars are adopted. The former is taken after the stress drop of the aftershock of M_S 6.9, which was used as the Green's function to simulate the far-field accelerograms. The latter is taken after the stress drop of the fault model for the main shock. 6) After Dan *et al.* (1989b)*2.

quality factor Q were 3.5×10^{11} dyne/cm², 3.5 km/sec, and 500, respectively. The rupture of the fault was assumed to propagate radially from the hypocenter. The location of the fault is shown by the straight solid lines in Figure 1. The fault length L is 45 km in a direction of N 61.0°E and another 45 km in a direction of S 37.8°W. We adopt, in this paper, $M_0 = 2.0 \times 10^{27}$ dyne·cm and $v = 2.3$ km/sec as one of the most appropriate fault models for the main shock. In this case, the average dislocation D and the stress drop $\Delta\sigma$ are evaluated to be 423 cm and 63 bars.

We should note here a rough index of error for our method because it will be applied to the epicentral region. Taking only the terms of intermediate-field transverse components generated by a double-couple force (Aki & Richards, 1980)*8, the Fourier spectrum of the displacement can be limited by

$$\left| \frac{2 M_0(\omega)}{4 \pi \rho \alpha^2 r^2} \right| + \left| \frac{3 M_0(\omega)}{4 \pi \rho \beta^2 r^2} \right| = \frac{11 M_0(\omega)}{12 \pi \rho \beta^2 r^2}, \quad (1)$$

where α is the P -wave velocity, $M_0(\omega)$ is the Fourier transform pair of the time-dependent seismic moment $M_0(t)$, and α is assumed to be equal to $\sqrt{3} \beta$. Since the Fourier spectrum of the far-field transverse components can be written by $[\omega M_0(\omega)]/[4 \pi \rho \beta^3 r]$, the error for the approximation of treating the records as far-field motions can be limited by $(11 \beta)/(3 r \omega)$. Here, the common vector to the intermediate-field motion and the far-field motion is neglected.

4. Estimation of strong ground motion in the epicentral region

In Figure 1, the solid triangles indicate five temporary observation stations. The seismic intensities on the Chinese scale were reported to be XI at Tangshan Cement Mill (CM, lat. 39°38'30"N, long. 118°11'29"E) station, X at Tangshan Airfield (AR, lat. 39°39'33"N, long. 118°08'17"E) station, VII at Qianan (QI, lat. 39°57'21"N, long. 118°43'52"E) and Changli (CH, lat. 39°45'29"N, long. 119°05'44"E) stations, and VI at Yutian (YU, lat. 39°53'02"N, long. 117°44'54"E) station. The epicenters of the aftershocks used as Green's functions are also plotted by small circles. Two different M_s of aftershocks #1, #2 and #4 are listed, which are taken from two different references (SSB, 1982 and Zhang *et al.*, 1980)*4,*9. M_L of aftershock #3 is listed because its M_s was not reported. Here, we adopt 4.6 and 4.2 as the upper and lower limits of M_s of aftershock #3 based on the relationship between M_s and M_L .

Fig. 3 Observed accelerograms used as Green's functions and their Fourier amplitude spectra. The smooth lines on the right are modeled spectra for each M_s obtained by different researchers^{*4, *9}. The solid lines are for the effective stress of 78 bars and the dotted lines for 63 bars.

of the earthquakes in the Tangshan area.

In order to determine the source parameters for each aftershock, we assume the relationship between M_s and M_0 which is described by the form of $\log M_0 = 1.5 M_s + a$. Using the data of the main shock and the three major aftershocks, we obtain the relationship of $\log M_0 (\text{dyne} \cdot \text{cm}) = 1.5 M_s + 15.5$ by the least squares method. The data and the result are shown in Figure 2. We adopt two effective stresses of 78 bars and 63 bars. The former is taken after the stress drop of the aftershock of $M_s 6.9$, which was used as a Green's function to simulate the far-field accelerograms. The latter is taken after the stress drop of the fault model for the main shock. Here, the effective stress σ_e is assumed to be equal to the stress drop $\Delta\sigma$. All source parameters for each aftershock can now be determined, because, given M_s and σ_e , M_0 and W are calculated by $\log M_0 = 1.5 M_s + 15.5$ and $W = \sqrt[3]{M_0 / (\pi \Delta\sigma)}$. Here, L and $\Delta\sigma$ are assumed to be equal to $2W$ (Geller, 1976)^{*10} and $(2\mu D) / (\pi W)$ (Kanamori & Anderson, 1975)^{*11}. The source parameters of the main shock and its aftershocks used as Green's functions are summarized in Table 1.

The accelerograms in Figure 3 are chosen for each station on condition that the small earthquakes used as Green's functions occurred on or near the fault plane of the main shock and that the accelerograms have sufficient quality for the simulation. All of them are EW components. The distances to the hypocenter of each aftershock and to the fault plane of the main shock are 18.8 and 5.0 km for CM, 29.1 and 6.9 km for AR, 17.7 and 16.1 km for QI, 36.6 and 39.4 km for CH, and 68.7 and 46.8 km for YU. On the right, the Fourier amplitude spectra of the accelerograms are compared with the modeled spectra (Dan *et al.*, 1989 a)^{*1} for each M_s and each σ_e . The quality factor of the medium Q is assumed to be 1,000. The predominant frequencies are from 1 to 20 Hz. The modeled spectra represent the observed ones well with distances from 17.7 to 68.7 km.

An example of the estimated accelerograms for each station is shown in Figure 4 with its shortest distance to the fault plane of the main shock. It is the largest result among four cases. For the baseline correction, the synthesized accelerograms are low-cut with a cosine-type function from 0.3 to 0.6 Hz. The peak acceleration of station CM, for

Fig. 4 Largest example among four estimated accelerograms for each station in the epicentral region of the 1976 Tangshan earthquake. For the baseline correction, the synthesized accelerograms are low-cut with a cosine-type function from 0.3 to 0.6 Hz.

which the seismic intensity was reported to be XI , is about 1,200 Gal and the duration of the strongest part is about 10 seconds. Further characteristics will be discussed in the next section.

5. Discussion

(i) Peak acceleration

Four different results were obtained for each station because of two different M_s and two different σ_e . The peak accelerations are summarized in Table 2. The mean value and the mean value $\pm$ one standard deviation range in Gal is [643-857-1,142] for CM, [464-723-1,127] for AR, [279-343-423] for QI, [115-137-164] for CH, and [147-195-260] for YU. Here, we assume a log-normal probability distribution for peak accelerations which is described by

$$P(a) = \frac{1}{\sqrt{2\pi}qa} \exp\left[-\frac{(\ln a - p)^2}{2q^2}\right]. \quad (2)$$

The two parameters of p and q are determined by

$$p = \frac{1}{n} \sum_{i=1}^n \ln A_i, \quad (3)$$

$$q^2 = \frac{1}{n} \sum_{i=1}^n (\ln A_i - p)^2. \quad (4)$$

Here, A_i is the synthesized peak acceleration and n is 4. The range in Table 2 corresponds to $[\exp(p-q), \exp(p), \exp(p+q)]$.

Several theoretical studies have been performed concerning the movement of the rupturing fault itself. Brune (1970)^{*7} formulated the maximum near-source acceleration as $(2\sigma_e)/(\rho\beta\Delta t)$, where σ_e is the effective stress working on the fault, ρ is the density of the medium, β is the S -wave velocity, and Δt is a small time interval we focus upon. The peak acceleration of the rupturing fault itself can be evaluated to be 620~1,240 Gal, where $\sigma_e=63$ bars, $\rho=2.9$ gram/cm³, $\beta=3.5$ km/sec, and $\Delta t=0.1\sim0.2$ second.

Kanai (1983)^{*12} obtained the relationship between the seismic intensity on the MM scale and the peak acceleration

Table 2 Peak acceleration estimated by the semi-empirical method in this study (EW component).

Station	Distance [km]	Intensity	Peak acceleration ¹⁾ [Gal]	Range ²⁾ [Gal]	Kanai ³⁾ [Gal]	Fukushima <i>et al.</i> ⁴⁾ [Gal]
CM	5.0	XI	(571 753 1,067 1,177)	[643-857-1,142]	1,238	[336-546-885]
AR	6.9	X	(404 551 1,034 1,188)	[464-723-1,127]	818	[320-520-843]
QI	16.1	VII	(252 320 409 422)	[279-343-423]	236	[257-417-676]
CH	39.4	VII	(103 142 149 164)	[115-137-164]	236	[159-257-417]
YU	46.8	VI	(139 156 252 266)	[147-195-260]	156	[138-224-364]

1) Four results are obtained because two different seismic moments and two different effective stresses are assumed for each aftershock used as Green's function.

2) The range corresponds to the mean and the mean $\pm$ one standard deviation of the four estimated peak accelerations on the assumption of a log-normal probability distribution.

3) Estimated values from Kanai's formula described by equation (5).

4) Estimated values from Fukushima & Tanaka's formula described by equation (6).

as

$$A_{\max} = 1.6 \times T_c^{-1.3} \times 10^{0.18/I_{MM}}, \quad (5)$$

where $A_{\max}$ is the peak acceleration in Gal, T_c is the predominant period at the site in seconds, and I_{MM} is the seismic intensity on the MM scale. The range of $A_{\max}$, T_c , and I_{MM} is 30~330 Gal, 0.2~0.9 second, and 5.75~8, respectively. Since the seismic intensities were reported to be XI for CM, X for AR, VII for QI and CH, and VI for YU, the relationship provides 1,238 Gal for CM (extrapolated), 818 Gal for AR (extrapolated), 236 Gal for QI and CH, and 156 Gal for YU, with a predominant period T_c of 0.2 second.

Since the 1940 Imperial Valley earthquake of M_s 7.1, a number of records whose peak accelerations are over 300 Gal have been observed in the epicentral regions of earthquakes with magnitudes of about 7. Typical examples of these accelerograms are the records observed during the 1966 Parkfield earthquake of M_s 6.4, the 1971 San Fernando earthquake of M_s 6.6, and the 1979 Imperial Valley earthquake of M_s 6.9. The attenuation relationships of peak accelerations including the data in the epicentral regions mentioned above were formulated by Joyner & Boore (1981)*¹³, Campbell (1981)*¹⁴, Fukushima & Tanaka (1988)*¹⁵, and so on. Fukushima & Tanaka obtained the attenuation relationship of

$$\log A_{\max} = 0.41 M_s - \log [R + 0.032 \times 10^{0.41 M_s}] - 0.0034 R + 1.30, \quad (6)$$

where $A_{\max}$ is the peak horizontal acceleration in Gal, R is the shortest distance in km from the station to the fault plane, and the standard deviation of the formula is 0.21 in log-scale. The relationship provides the mean value and the mean value $\pm$ one standard deviation range of [336-546-885] for CM, [320-520-843] for AR, [257-417-676] for QI, [159-257-417] for CH, and [138-224-364] for YU.

In Japan, on the other hand, investigations on the strong ground motion in epicentral region have been carried out by many researchers. Okamoto (1968)*¹⁶ suggested that the upper and lower limits of the peak accelerations in Gal should be $12 M^2$ and $6 M^2$ with a magnitude M varying from 5.0 to 8.4. His results were obtained from field investigations of 14 different earthquakes, such as the behavior of tombstones and masonry structures, damage analysis of houses, and records observed by accelerograph. Omote *et al.* (1978)*¹⁷ estimated the peak accelerations in the epicentral regions of 4 earthquakes with magnitudes of 6.5~7.3. They suggested that the peak acceleration should be limited by 500~600 Gal for earthquakes with magnitudes beyond 7. Hisada *et al.* (1978)*¹⁸, considering the field investigations, proposed $9 M^2$ as an averaged peak acceleration at rock sites in the epicentral regions. For the upper and lower limits of the peak accelerations, 693 and 347 Gal are obtained from $12 M^2$ and $6 M^2$. Here, the relation of $M = 0.79 M_s + 1.44$ (Hayashi & Abe, 1984)*¹⁹ is used to transfer M_s to M , where M is a magnitude reported from the Japan Meteorological Agency (JMA). The average peak acceleration at rock sites is evaluated to be 520 Gal from $9 M^2$. The range of [347-520-693] is two-thirds of the results for CM and AR.

Consequently, it can be concluded that the peak accelerations in the epicentral region of the 1976 Tangshan earthquake were slightly higher than those for the same magnitude and the same distances obtained or estimated by

Fig. 5 Comparison of the duration of ground motion as a function of magnitude. The closed circles and the broken line are taken from Hisada & Ando (1976)^{*22}. The open circles are obtained from the accelerograms for Pacoima Dam (PD) of the 1971 San Fernando earthquake of M_s 6.6, Bonds Corner (BC) of the 1979 Imperial Valley earthquake of M_s 6.9 and La Union (LU) of the 1985 Michoacan earthquake of M_s 8.1.

Michoacan earthquake of M_s 8.1. The durations of the synthesized accelerograms are found to be comparable to those for the earthquakes with the same magnitude.

(iii) Acceleration response spectrum

The acceleration response spectra for the estimated motions are shown in Figure 6. They represent the seismic wave forces which should be applied to structures. The damping factor h is 0.05 and the range of the natural periods is from 0.05 to 5 seconds. In Figure 6, (a) shows the spectra for CM, (b) the spectra for AR and YU, and (c) the spectra for QI and CH. The three solid lines for CM, AR and QI are the mean value and the mean value $\pm$ one standard deviation. The dotted lines for YU and CH are the mean values. The synthesized result for CM shows a high value over 2,000 Gal and that for AR shows a value over 1,500 Gal in the period range between 0.05 and 0.15 second.

The estimated acceleration response spectra for the five stations show a high level in the period range from 0.05 to 0.15 second. These spectral characteristics are due to the properties of the aftershocks used as Green's functions. Since we use three different aftershocks, this tendency should be considered common to the earthquakes in the Tangshan area.

Figures (d), (e) and (f) compare the acceleration response spectra for CM and AR with those for PD, BC and LU. The response spectra for CM and AR show higher values than those for PD and BC in the period range below 0.15 second. However, they are half of the response spectra for PD and BC, and twice of that for LU in the period range between 0.2 and 0.8 second.

Subsequently, not only the large epicentral region with its length of 90 km but also the large force which acted on the structures with short natural periods is thought to have caused the huge damage in and around Tangshan. This is because most of the structures were made of brick whose natural periods were about 0.1 second, and because no earthquake-resistant design was considered for them before this earthquake occurred.

other researchers.

(ii) Duration of strong ground motion

According to Jennings *et al.* (1968)^{*20}, the envelope function of accelerograms can be expressed by

$$E(t) = \begin{cases} 0 & 0 \leq t \leq t_a \\ A(t - t_a)^2 / (t_b - t_a)^2 & t_a \leq t \leq t_b \\ A & t_b \leq t \leq t_c \\ A \exp[-B(t - t_c)] & t_c \leq t \leq t_d \end{cases} \quad (7)$$

Here, t_a is the time when the seismic wave reaches the station, t_b is the time when the strong part of the motion starts, t_c is the time when the strong part of the motion terminates and the exponential decay of the motion starts, A is the amplitude of the strong part, and B is the coefficient for the exponential decay. The parameters t_a , t_b , t_c , A and B are determined by the least squares method (Dan & Watanabe, 1989)^{*21}, and, in this paper, the termination time of the motion is defined by $t_d = (\log 10)/B + t_c$. The duration of the strong ground motion is obtained by $t_d - t_a$.

Figure 5 compares the duration as a function of magnitude. The closed circles and the broken line are taken from Hisada & Ando (1976)^{*22}. The open circles are obtained from the accelerograms for Pacoima Dam (PD) of the 1971 San Fernando earthquake of M_s 6.6, Bonds Corner (BC) of the 1979 Imperial Valley earthquake of M_s 6.9, and La Union (LU) of the 1985

Fig. 6 Comparison of the acceleration response spectra with the damping factor h of 0.05. Figures (a), (b) and (c) show the spectra of synthesized accelerograms. Figures (d), (e) and (f) show comparison of the spectra for CM and AR with those for Pacoima Dam (PD) of the 1971 San Fernando earthquake of M_s 6.6, Bonds Corner (BC) of the 1979 Imperial Valley earthquake of M_s 6.9, and La Union (LU) of the 1985 Michoacan earthquake of M_s 8.1.

(iv) Estimation error of peak acceleration

The coefficient of variation (*c. o. v.*; percentage of the standard deviation to the mean value) of the log-normal probability distribution can be obtained by $\sqrt{\exp(q^2)-1}$. From the peak accelerations listed in Table 2, the *c. o. v.* is calculated to be 29 % for CM, 47 % for AR, 21 % for QI, 18 % for CH, and 29 % for YU.

Meanwhile, the error due to the approximation of treating the records as far-field motions is limited by $(11\beta)/(3r\omega)$. When we adopt the shortest distance to the fault plane of the main shock as r and the predominant frequencies of 1~20 Hz as ω , the limitation of the approximation error is calculated to be 41~2.0 % for CM (here 41 % corresponding to 1 Hz and 2.0 % to 20 Hz), 30~1.5 % for AR, 13~0.63 % for QI, 5.2~0.26 % for CH, and 4.4~0.22 % for YU. If we roughly assume that the limitation should correspond to $2\sqrt{\exp(q^2)-1}$, the *c. o. v.* due to the approximation is obtained to be half of the error calculated above.

Consequently, the square root of the summation of the two kinds of *c. o. v.* leads to the total *c. o. v.* of 36~29 % for CM, 49~47 % for AR, 22~21 % for QI, 18 % for CH, and 29 % for YU. It is concluded that the deviation of the synthesized results due to the uncertainty of the source parameters of the aftershock predominates over the deviation due to the approximation of treating the records as far-field motions except for the case of CM, the nearest station. The *c. o. v.* due to the approximation for CM can also be negligible, however, when we take 10 Hz as a representative frequency from the peak points in Figure 6 (a).

6. Conclusions

The accelerograms in the epicentral region of the 1976 Tangshan earthquake were estimated by using the records of several aftershocks with magnitudes of about 5 which had been observed in the damaged area. The fault model for the main shock was selected among the most appropriate models for the simulation of far-field accelerograms, and the source parameters for the aftershocks used as Green's functions were determined from some theoretical and empirical relationships.

Based on the resultant estimation presented here, we can conclude as follows.

- 1) The peak accelerations in the epicentral region were slightly higher values than those estimated for the same magnitude and the same distances from some empirical formulas obtained by other researchers.
- 2) The durations of the strong ground motions were comparable to those for the earthquakes with the same

magnitude.

- 3) The large accelerations over 1,500 Gal acted on the structures with natural periods shorter than 0.15 in the region close to the fault.
- 4) Temporary strong-motion observations of aftershocks at the damaged area are very useful for the estimation of the strong ground motion in the epicentral region of the main shock.

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半経験的波形合成法による1976年中国唐山地震 ($M_s 7.8$) の 震央域における強震地動の推定 (梗概)

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1. 序

1976年に起こった $M_s 7.8$ の唐山地震は中国北東部に甚大な被害をもたらした。これをきっかけに中国における構造物の耐震設計は急速に発展した。この地震については、人的被害をはじめ、構造物や地盤の被害、震源メカニズム、地震活動、地殻構造などに関する多くの研究報告がある。しかしながら、より合理的な耐震設計を行うために必要な震央域における強震動の推定については、地震学あるいは地震工学的な方法による研究はほとんど行われておらず、困難とされてきた。

筆者ら (1989 a, 1989 b)*^{1,2} は、遠方場 S 波の震源スペクトルに基づく半経験的波形合成法を提案し、この方法により $M_s 6.9$ の余震記録を用いて、本震の遠方場における加速度波形を合成した。その結果、低周波数の地震波に関する解析により決定された震源パラメータの中から、高周波数の地震波に対する最適な断層モデルが得られ、最大加速度、震動継続時間、スペクトル特性が再現できた。

そこで本論文では、まず唐山地震の震央域における加速度波形を、被災地域で得られた $M_s 5$ クラスの余震記録をグリーン関数に用いて合成する。次に、得られた合成波の最大加速度、震動継続時間および加速度応答スペクトルを、他の大地震の記録や構造物の挙動から得られた値と比較し、大被害を受けた原因を入力地震動の立場から考察する。

2. 1976年唐山地震およびその断層モデル

1976年7月28日、中国北東部の河北省唐山市を、 $M_s 7.8$ の強い地震が襲った。中国地震局 (SSB) によると、最も激しく揺れたところで震度 XI (MM 震度階 11 にほぼ相当) であった。また、震度 X 以上の地域の

面積は 370 km^2 で唐山市の 58.7 %、震度 IX 以上の地域の面積は $1,800 \text{ km}^2$ で唐山市全域をおおい、その近郊の地方に及んだ。

この地震により被害を受けた地域は $30,000 \text{ km}^2$ のほり、中国全土の 3 分の 1 で揺れを感じた。唐山市では、建築・土木構造物の 94 % が、工業施設の 80 % が崩壊あるいは大きな被害を受けた。これらの構造物は、ごくわずかの工業施設が震度 VII の耐震設計を施されていた以外は、地震に対する配慮が全くされていなかった。

本震発生後ただちに、被災地において臨時の余震観測が始められ、5つの観測点で 35 地震 ($M_L 3.5 \sim 5.8$) の約 100 記録が得られた。記録のほとんどは、周波数帯域 $0.5 \sim 35 \text{ Hz}$ の RDZ 1-12-66 型強震加速度計で記録されたものである (IEM, 1986)*⁵。

筆者ら (1989 b)*² は、遠方場 S 波の震源スペクトルに基づく半経験的波形合成法により、 $M_s 6.9$ の余震記録を用いて、比較的遠方 (北京飯店 $\Delta = 154 \text{ km}$ および馮村橋 $\Delta = 398 \text{ km}$) における本震の加速度波形を合成した。その結果、本震の断層の長さは震源から N 61.0°E の方角へ 45 km , S 37.8°W の方角へ 45 km , 幅は 15 km , 地震モーメントは $1.6 \sim 2.1 \times 10^{27} \text{ dyne} \cdot \text{cm}$, 破壊速度は $2.3 \sim 2.5 \text{ km/sec}$ のモデルが適当であることが分かった。ここに、断層は鉛直右横ずれ型、媒質の剛性率は $3.5 \times 10^{11} \text{ dyne/cm}^2$, S 波速度は 3.5 km/sec , Q 値は 500 とし、破壊は同心円状に広がるものと仮定している。

本論文では、最適モデルの 1 例として地震モーメント $2.0 \times 10^{27} \text{ dyne} \cdot \text{cm}$, 破壊速度 2.3 km/sec を選んだ。このとき、平均くい違い量は 423 cm , 応力降下量は 63 bar となる。Fig. 1 に断層モデルの位置を太い実線で示す。

3. 震央域における強震地動の推定

Fig. 1 に 5 つの臨時観測点を三角印で示す。発表された震度は Tangshan Cement Mill (CM) で XI, Tangshan Airfield (AR) で X, Qianan (QI) と Changli (CH)

論文の内容の一部は、日中地震学会合同大会 (中国北京, 1989 年) で発表したものである。

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でⅦ, Yutian (YU) でⅥである。小さい白丸は、グリーン関数に用いた余震の震央で、その M_s は SSB (1982)^{*4} と Zhang *et al.* (1980)^{*9} で異なっているため、各余震に対して2つの値を示しておいた。なお、#3の余震は M_L しか発表されていないので、唐山地区の M_s と M_L の関係から M_s の上限値と下限値を4.6と4.2と仮定した。

各余震の震源パラメーターを決めるため、 M_s と M_0 の関係を本震と主な余震のデータを使って最小自乗法で求め、 $\log M_0 = 1.5 M_s + 15.5$ を得た。Fig. 2 は、使ったデータと得られた回帰直線である。一方、実効応力としては、 M_s 6.9 の余震の実効応力と等しく78 barであると仮定したとき、および本震の断層モデルの実効応力と等しく63 barであると仮定したときの2通りを考えた。断層の長さは幅の2倍 (Geller, 1976)^{*10}、実効応力と応力降下量は等しいと仮定し、 M_s と σ_e だけから他のすべての震源パラメーターを決めた。本震およびグリーン関数に用いる余震の震源パラメーターを Table 1 に示す。

Fig. 3 に、各臨時観測点に対してグリーン関数として用いるのに最も適していると思われる記録を示す。記録は、本震の断層面上あるいはその近傍で発生した余震による記録のうち S/N 比のよいものを選択した。図にはまた、各波形のフーリエ振幅スペクトルと、上で求めた震源パラメーターにより計算されるスペクトルモデルを示す。スペクトルモデルはいずれも M_s が2通り、実効応力が2通りであるから4本存在する。図から、余震記録のフーリエ振幅スペクトルは図示した4本のスペクトルモデルでほぼ包含されていることが分かる。なお、ここでは Q 値として1,000を採用した。

Fig. 4 に、各観測点における合成波形を断層までの最短距離とともに示す。図はすべて EW 成分で、4ケースのうち最も大きい結果である。波形は、基線補正のため0.3~0.6 Hz の間で余弦関数で滑らかに変化するフィルターを用いて、低周波数成分を除去している。

4. 考 察

(i) 最大加速度

Table 2 に合成波形の最大加速度を、Kanai (1983)^{*12} の震度と最大加速度との関係式による推定値および Fukushima & Tanaka (1988)^{*15} が震央域の加速度記録を考慮して得た距離減衰式による推定値とともに示す。また、Okamoto (1968)^{*16} や Hisada *et al.* (1978)^{*18} が震央域における構造物の挙動等から求めた最大加速度と M との関係式によれば、唐山地震の震央域の場合、最大加速度は [347-520-693] となる。したがって、唐山

地震の震央域における地動の最大加速度は、震度やマグニチュードをパラメーターとした経験式により推定される値と比べてやや大きい値であったといえる。

(ii) 震動継続時間

本論文では (7) 式で示される Jennings *et al.* (1968)^{*20} の包絡関数を考え、最小自乗法によりパラメーター t_a , t_b , t_c , A および B を決めた (Dan & Watanabe, 1989)^{*21}。このとき継続時間は、包絡関数の振幅が強震部分の10分の1になる時間を t_d とし、 $t_d - t_a$ で定義した。Fig. 5 は地震波の継続時間とマグニチュードとの関係で、黒丸と破線は Hisada & Ando (1976)^{*22} から引用したもの、白丸は1971年 San Fernando 地震 (M_s 6.6) の Pacoima Dam (PD), 1979年 Imperial Valley 地震 (M_s 6.9) の Bonds Corner (BC) および1985年 Michoacan 地震 (M_s 8.1) の La Union (LU) における記録に関する結果である。図より、合成波の継続時間は、同規模の地震と比べるとほぼ平均的な値であることが分かる。

(iii) 加速度応答スペクトル

合成波形の加速度応答スペクトルを Fig. 6 に示す。(a) は CM, (b) は AR と YU, (c) は QI と CH のスペクトルである。固有周期0.05~0.15秒で、CM は2,000 Gal 以上、AR は1,500 Gal 以上の値となっている。一方、図の (d)~(f) は断層に近い CM と AR の応答スペクトルを、PD, BC および LU の応答スペクトルと比較したものである。固有周期0.05~0.15秒で PD や BC のスペクトルより高くなっているが、0.2~0.8秒では PD や BC の半分、LU の2倍となっている。以上より、短周期の卓越した非常に強い地震波がレンガ造などの構造物に作用したことがわかる。

5. 結 論

本論文では、唐山地震の震央域における加速度波形を、被災地域で得られた M_s 5 クラスの余震記録を用いて合成した。その結果、以下の4点が結論としてあげられる。

- 1) 最大加速度は、震度やマグニチュードをパラメーターとした経験式により推定される値と比べてやや大きい値であった。
- 2) 震動継続時間は、同規模の地震と比べるとほぼ平均的な値であった。
- 3) 断層の近傍では、加速度応答値で1,500 Gal を超えるような非常に強い地震波が、レンガ造などの短周期構造物に作用した。
- 4) 被災地における余震の臨時観測は、本震時の地動を推定するのに非常に有用である。