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STRONG GROUND MOTION ATTENUATION IN THE SEA OF JAPAN (OKHOTSK-AMUR PLATES BOUNDARY) REGION

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SUMMARY

A new microplate has been confirmed in the area of sea of Japan which was previously thought as a part of Eurasian plate. Consequently the new tectonic setting is recognized as Okhotsk-Amur plates boundary in the eastern margin of sea of Japan. The earthquakes occurring in this tectonic boundary affect the cities lying in the coast of sea of Japan. In order to carry out seismic risk analysis in this region, attenuation relationship applicable to this region is needed. Therefore in this study, attenuation relationships for PGA and PSA have been developed for the Okhotsk-Amur plates boundary using the recent 8 years data recorded by K-NET strong motion recorders. Comparison is made with the existing relationships for Japan and Taiwan. The resulting attenuation relationship compares well with the existing relationships developed with K-NET data of all over Japan. When compared with the other relationship developed with JMA strong motion records, it predicts higher PGA in far field. The response spectral attenuation relationships predict lower values in the long period range (T>2s). The resulting attenuation relationships will increase the accuracy of seismic risk analysis of urban areas in the cities lying in the coast of sea of Japan.

INTRODUCTION

Even though the coast of sea of Japan in the northeastern Japan is considered seismically moderate in comparison to the Pacific coast of Japan, several damaging earthquakes have occurred in this region like Niigata earthquake (1964), Nihon-Khai Chubu earthquake (1983) and Kushiro-Oki earthquake (1993). Earlier, this region was considered as the boundary of Okhotsk and Eurasian plates. However, a new tectonic plate known as Amur is confirmed recently [1]. Consequently, this region is identified as the boundary of Okhotsk and Amur plates. Figure 1 shows the tectonic plates around Japan. The new microplate Amur is believed to be subducting under the Okhotsk plate and moving in the east direction in the relative rate of 10mm/year [1]. Consequently this region is drawing attention of earth-scientists as the new microplate has changed the previously thought situation of Eurasian-Okhotsk plates boundary.

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This study is the consequence of seismic hazard analysis of eastern margin of Sea of Japan in the north-eastern part of Japan in Okhotsk-Amur plates boundary. Geographic Information System (GIS) was employed to carry out the seismic hazard analysis of cities lying in the coast of sea of Japan [2]. Three earthquake source zones were identified when drawing the profile of earthquakes in this region: (1) Interplate earthquakes cased by relative movement of Amur and Okhotsk plates; (2) Intraplate earthquakes caused by local faults (3) Interplate earthquakes caused due to the subduction of Pacific plate to Okhotsk plate. These tectonic environments are quite distinguishing because of the depth and magnitudes of earthquakes. Most of the earthquakes in the source zones 1 and 2 are relatively shallower than that of the earthquakes of zone 3. The attenuation relationships developed in Japan to date do not distinguish such tectonic environments. The majority of database used for attenuation relationship is from the subduction environment of Pacific plate to Okhotsk plate including only few earthquakes that occurred around the sea of Japan. However, for the accurate seismic hazard analysis of cities lying in the coast of Japan, an attenuation relationship valid for this tectonic environment is needed.

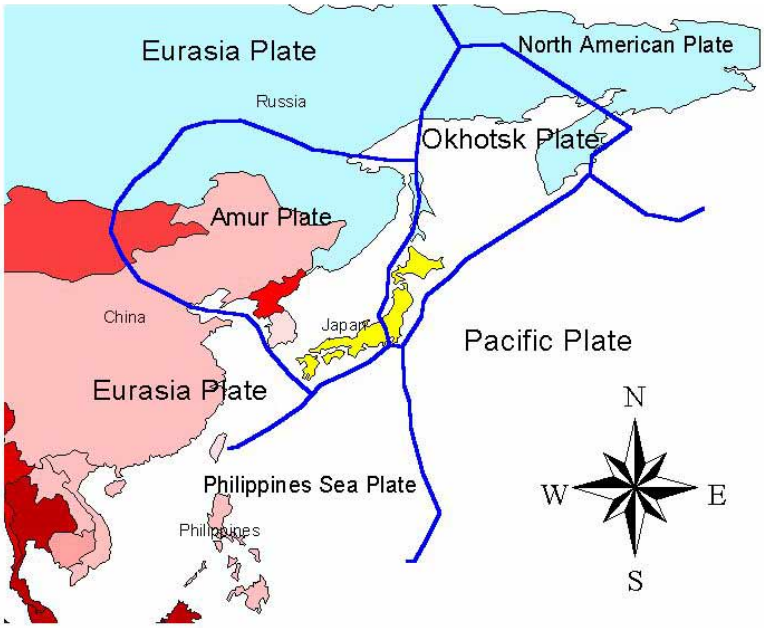


Fig. 1 Location of Okhotsk-Amur Plates Boundary

In this study, acceleration data of earthquakes in this region are collected to develop attenuation relationships for peak ground acceleration (PGA) and peak spectral acceleration (PSA) for the earthquakes occurring in the Okhotsk-Amur plates boundary. The Kyoshin Network (K-NET) data maintained by the National Research Institute for Earth Science and Disaster Prevention (NIED) of Japan has online records of earthquakes from May 1996 occurring all over Japan. The magnitude and hypocentral locations of these earthquakes are given by Japan Metereological Agency (JMA). These records are downloaded from K-NET website and regression analysis is carried out to arrive at the attenuation relationships. The peak ground acceleration is separated in two parts: (1) peak horizontal ground acceleration (PHGA) consisting of maximum acceleration of two horizontal components (N-S and E-W), (2) peak vertical ground acceleration (PVGA). The elastic response spectrum of each three component of acceleration records is computed. The peak horizontal spectral acceleration (PHSA) is considered to be maximum response of a

single degree freedom (SDOF) system of two horizontal components (N-S and E-W) of acceleration records in each structural period. The peak vertical spectral acceleration (PVSA) is the maximum response of SDOF system in each structural period. The damping is considered to be 5% of critical. The new attenuation relationship is expected to improve the accuracy of probabilistic seismic hazard analysis carried out for this area.

DATA USED IN THIS STUDY

To obtain the attenuation model for the eastern margin of sea of Japan, a query was made for the earthquakes lying in a rectangular area of points between (136^0E, 50^0N) to (141^0E, 36^0N) from the database of K-NET in the internet (http://www.k-net.bosai.go.jp). Altogether 193 earthquakes were identified in this rectangular zone. However, many earthquakes were identified to be nearer to the coast of Pacific ocean and believed to be generated by the subduction of Pacific plate to the Okhotsk plate. Forty five earthquakes are finally selected to be within the boundary of Okhotsk-Amur plates after querying in GIS environment. Among 45 earthquakes, three earthquakes have focal depths more than 100 km. One event has a magnitude of 6.6 with a focal depth of 254 km. It is believed to be caused by subduction of Pacific plate and possibly lies in the Wadati Benioff zone. Forty two earthquake events are finally considered after excluding these three events. The locations of earthquakes are shown in the Fig. 2 with the assumed area of influence of Okhotsk-Amur plates boundary. The characteristics earthquakes and the records considered are depicted in Table 1. The records with PGA less than 5 cm/s^2 are omitted as done by other researchers [4, 8]. There are total 667 set of three component acceleration data recorded in 225 stations all over North-eastern Japan. The largest earthquake in this database is M_J = 5.6 that occurred in 1997/11/23. All K-NET stations are installed at free-field sites and each recording station has S-waves velocity measured to a depth of 10-20 meters. The mean value of the S-waves velocity of soil beneath the site down to 30 meters (V_S^{30}) is commonly used in earthquake codes to represent the site conditions [3]. The V_s^{30} for 225 sites are calculated and included in the database.

Table 1 Summary of K-NET Data used in this Study

S. No.	Items	Statistics
1	Number of events	42
2	Number of records	667
3	Number of recording stations	225
4	Recording period	1996 June-2003 December
5	Instrument	K-NET95-type accelerometers
6	Recording Institution	National Research Institute for Earth Science and Disaster Prevention (NIED)
7.1	Magnitude Range	4.0-5.6
7.2	Mean value	4.72
8.1	Depth Range	8-43
8.2	Mean depth	20.8
9.1	Epicentral distance Range	3-264
9.2	Mean epicentral distance	84.67
10.1	Average shear wave velocity V_s^{30} range	39.29-760.25
10.2	Mean V_s^{30}	330.80 m/s
11	Peak horizontal ground acceleration range	4.15-411.56 cm/s^2
12	Peak vertical ground acceleration range	0.50-163.11 cm/s^2

METHOD USED TO DERIVE THE ATTENUATION LAW

Various attenuation models exist to relate the PGA and PSA to the source-site distance. Following attenuation model is used to derive the relation between PGA/PSA and source to site distance.

$$\log Y(T) = b_1(T)+b_2(T)M_J-b_3(T)D-b_4(T)\log(R) \quad (1)$$

where Y(T) is the maximum amplitude of the response spectra or ground acceleration under consideration. M_J is the JMA magnitude, D is the focal depth in kilometers, R is the source to site distance: hypocentral distance is taken in this study. The terms b_1 to b_4 are the regression coefficients to be determined for each structural period T. The term "$b_4(T)\log(R)$" ("αlogR" model) represents to geometric spreading. Most of the attenuation model developed in Japan [3, 4, 5] uses aneslatic attenuation in addition to geometric spreading ("αR – logR" model) to describe the distance attenuation. At first, the following attenuation model was considered to include the anelastic distance attenuation:

$$\log Y(T) = b_1(T)+b_2(T)M-b_3(T)D-b_4(T)\log(R)+b_5(T)R \quad (2)$$

The value of $b_4(T)$ is constrained to be 1.0 in this model. The value of $b_5(T)$ came out to be positive in most cases during regression analysis of whole data set. The regression was then carried out for stiff soil with average V_s^{30} value more than 300 m/s. There are 379 records in this category. Even though b_5 resulted positive in this case, the result is compared with the result of whole data to account the effect of site conditions.

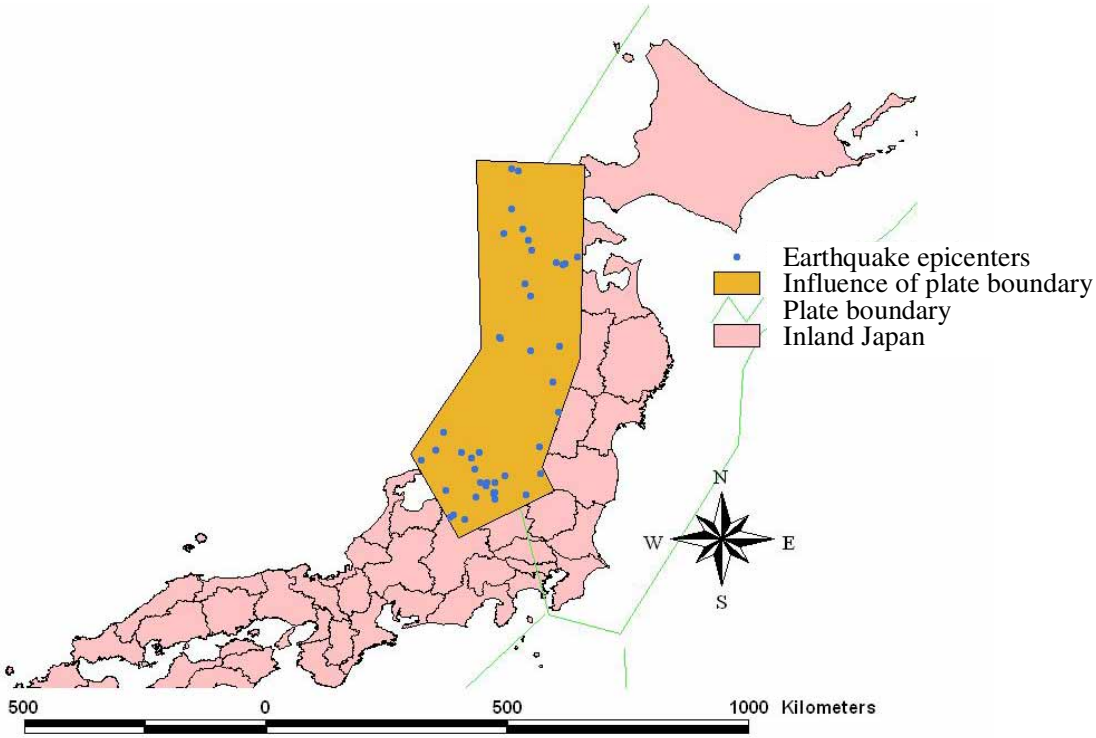


Fig. 2 Epicenters of Earthquakes considered in this Study

Two stage regression analysis used by Fukushima and Tanaka (1991)[4] is carried out to find the regression coefficients b_1, b_2, b_3 and b_4. At first the coefficient b_4 relating Y to distance is found. Subsequently b_1, b_2 and b_3 are found using least square regression method. The PHGA is taken as the maximum of two horizontal components (N-S and E-W). Separate equation is developed for PVGA. PVGA is the maximum peak ground acceleration in very few instances (5 out of 667).

The absolute acceleration and response spectra are calculated for the two horizontal and vertical components. The acceleration response spectrum used in this study is defined as the maximum response of a SDOF system with a damping coefficient five percent of critical for varying structural period T. Numerical integration is used to obtain the response of SDOF from the acceleration records. After calculating acceleration response spectra for two horizontal components, the larger of two in each period is taken as the peak spectral acceleration. Nineteen structural periods from 0.05s to 3s are selected and a regression analysis is performed separately for each structural period.

RESULTS AND DISCUSSIONS

Attenuation of PGA

Most of the attenuation relationships available for Japan are in terms of PGA and hypocentral distance [4, 5]. Recently Molas and Yamazaki (1996) [6], Shebastari and Yamazaki (2000) [7] and Lussou et al. (2001) [3] provide attenuation relation in term of spectral acceleration. The attenuation relationships for both PGA and PSA are developed in this study. The relation for PGA for the whole data is obtained as

$$\log(PHGA) = 1.1064+0.2830M_J-0.0076D-0.6322\log(R) \qquad \sigma = 0.303 \qquad (3)$$

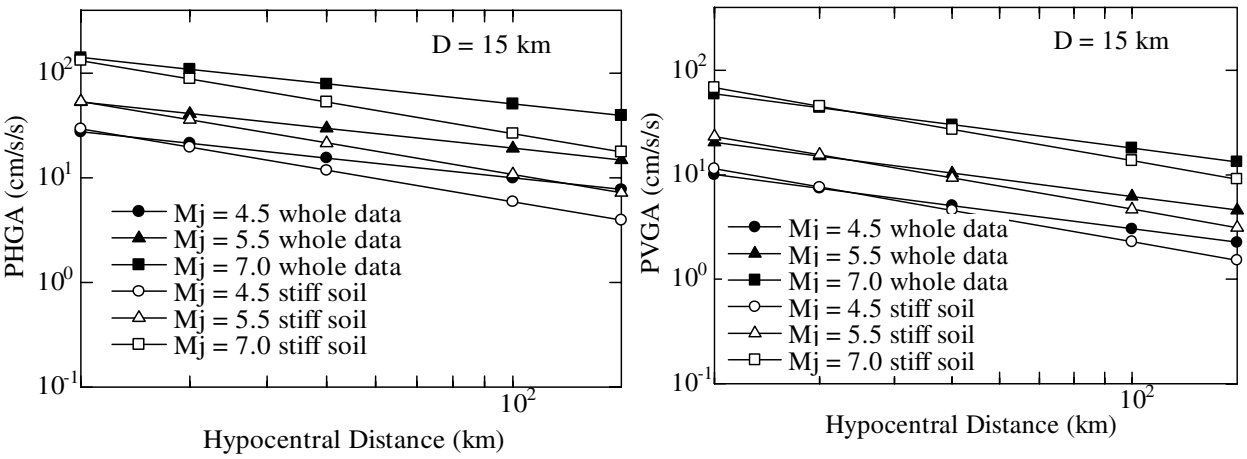
$$\log(PVGA) = 0.7134+0.3091M_J-0.0069D-0.7421\log(R) \qquad \sigma = 0.301 \qquad (4)$$

Where σ is the standard deviation in the regression analysis. Further, when only stiff sites are considered with anelastic distance attenuation, the relation come out to be:

$$\log(PHGA) = 1.6997+0.2608M_J-0.0069D-\log(R)+0.0021R \qquad \sigma = 0.309 \qquad (5)$$

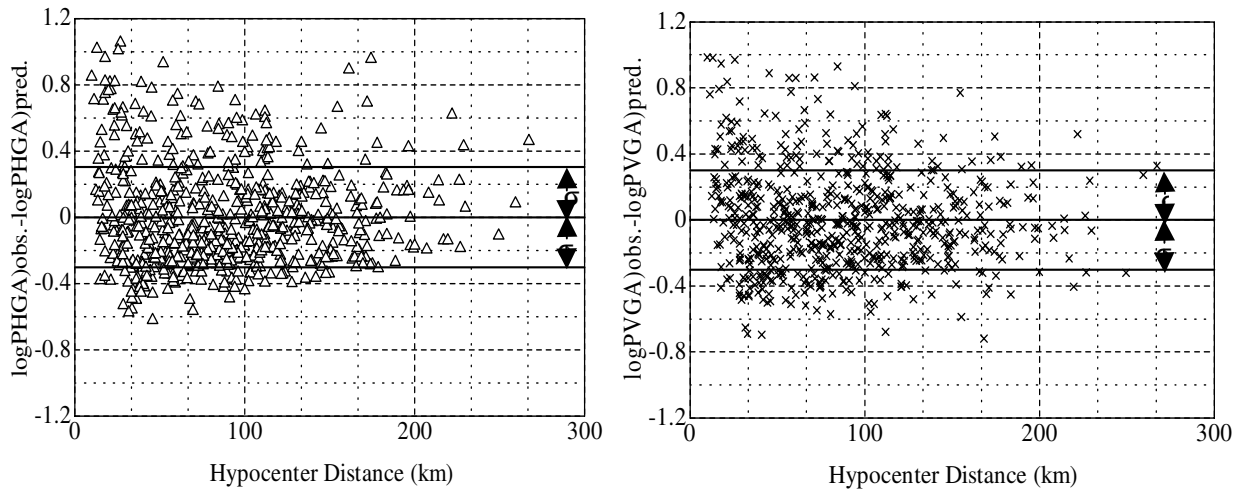
$$\log(PVGA) = 1.0681+0.3103M_J-0.0072D-\log(R)+0.0013R \qquad \sigma = 0.311 \qquad (6)$$

The resulting attenuation relationships of equations (3) and (4) are shown in Fig. 3(a) for horizontal component and in Fig 3(b) for vertical component of PGA. Equations (5) and (6) are also plotted to compare the result of stiff site including anelastic distance attenuation. It is interesting to observe that the PHGA is lower in the higher hypocentral distance when anelastic distance attenuation is considered but there is no change in the magnitude of PHGA in the case of near field records. The effect of considering stiff soil is not so obvious in this case as the PGA calculated for stiff soil in the near field is higher than that considering whole data. Figures 4(a) and 4 (b) show the dispersion of residual values (the differences between the observed and predicted values of logPHGA/PVGA) in the resulting regression analysis for PHGA and PVGA respectively. The mean of the residual values is zero in both cases. Some residual values have higher positive values representing some observed PHGA/PVGA values are higher with respect to predicted values from the result of regression analysis.



(a) (b)

Fig. 3. Attenuation Relations for (a) PHGA (b) PVGA



(a) (b)

Fig. 4. Residual Values for (a) PHGA (b) PVGA

Attenuation of Spectral Acceleration

Regression analysis is carried out for 19 structural periods to obtain the RSA attenuation relationship. Two step regression analysis described in the previous sub-section is carried out for each structural period separately. The result of the regression analysis for the spectral acceleration is shown in Table 2. The database contains the spectral acceleration up to 5 s period but the attenuation relationships worked out for 4s and 5s periods seemed unsatisfactory and hence not included here.

Figures 5 (a) and 5 (b) show the spectral shapes for the M_J = 5, 6 and 7 with hypocentral distance 30 km and focal depth 15 km. These spectra are obtained by replacing the coefficients of Table 2 in Eq. (1). Such spectra can be obtained for various hypocentral distances and focal depths to be compared with the design spectra. The spectral acceleration shows the trend of common spectrum of earthquake input motion with respect to the structural period.

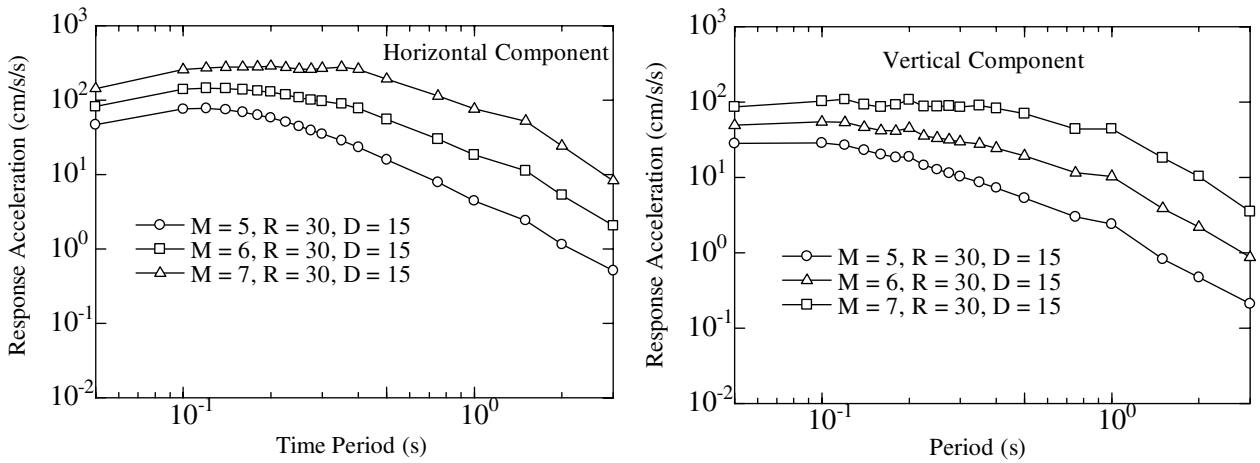
Table 2 Coefficients to use in Eq. (1) for Response Spectral Acceleration

T	Horizontal Component					Vertical Component				
(s)	b1	b2	b3	b4	σ	b1	b2	b3	b4	σ
0.05	1.6596	0.2421	0.0085	0.7257	0.321	1.7555	0.2433	0.0094	0.9361	0.388
0.10	1.7059	0.2649	0.0084	0.6929	0.340	1.2246	0.2789	0.0086	0.7010	0.339
0.12	1.5951	0.2720	0.0091	0.6293	0.349	0.9782	0.3033	0.0084	0.6375	0.337
0.14	1.4350	0.2847	0.0087	0.5794	0.352	0.8072	0.3012	0.0078	0.5648	0.337
0.16	1.2581	0.3033	0.0084	0.5479	0.357	0.6009	0.3154	0.0075	0.5150	0.344
0.18	1.0928	0.3236	0.0085	0.5302	0.361	0.3601	0.3494	0.0073	0.4969	0.346
0.20	0.9088	0.3478	0.0084	0.5136	0.375	0.1608	0.3782	0.0079	0.4473	0.350
0.225	0.6732	0.3661	0.0083	0.4548	0.386	-0.0648	0.3897	0.0070	0.4189	0.344
0.25	0.4453	0.3859	0.0081	0.4101	0.396	-0.3430	0.4179	0.0068	0.3667	0.350
0.275	0.2422	0.4111	0.0080	0.3961	0.398	-0.5615	0.4440	0.0068	0.3385	0.361
0.30	0.0252	0.4414	0.0083	0.3814	0.401	-0.7110	0.4598	0.0071	0.3180	0.359
0.35	-0.357	0.4930	0.0081	0.3583	0.408	-1.0624	0.5087	0.0073	0.2954	0.367
0.40	-0.646	0.5231	0.0079	0.3266	0.415	-1.2558	0.5267	0.0071	0.2782	0.383
0.50	-0.982	0.5423	0.0087	0.2704	0.432	-1.6032	0.5597	0.0075	0.2418	0.399
0.75	-1.512	0.5813	0.0100	0.2364	0.456	-1.9605	0.5818	0.0081	0.2370	0.419
1.00	-2.110	0.6190	0.0101	0.1269	0.457	-2.6456	0.6321	0.0081	0.0096	0.426
1.50	-2.796	0.6680	0.0102	0.0056	0.454	-3.3637	0.6726	0.0092	-0.0349	0.434
2.00	-3.093	0.6631	0.0102	0.0062	0.443	-3.7260	0.6711	0.0093	-0.1222	0.431
3.00	-3.348	0.6041	0.0094	-0.1202	0.428	-3.9335	0.6061	0.0085	-0.2457	0.434

COMPARISON WITH OTHER PUBLISHED ATTENUATION LAWS

There are several attenuation relationships of PGA and distance developed for the condition of Japan [3,4,5,7]. Figure 6(a) shows the comparison existing attenuation relations with the attenuation relation developed in this study. The comparison of the databases used in the attenuation studies are given in Table 3. The attenuation relation by Fukushima and Tanaka (1991) [4] and Molas and Yamazaki (1995) [5] are developed with the database of strong motions recorded by JMA. The attenuation relationship of Chang et al. (2001) [8] is developed for Taiwan. This attenuation relationship is considered here since it distinguishes the tectonic environments. Furthermore, it is the recent study concluded from the world's densest network of digital strong motion instruments [8]. The attenuation relationship for shallow crustal earthquakes is considered here for comparison. It is interesting to observe that the attenuation relationship from this study is nearest to the attenuation relationship by Lussou et al. (2001) [3]. Lussou et al. (2001) have used the data of K-NET in their study. They have included the anelastic attenuation in their relationship but excluded the effect of focal depth. K-NET uses the recent digital accelerometers with recording stations established in a uniform spacing of about 25 km. This must be the most reliable strong motion record arrays in Japan for which the record can be obtained for longer duration. The previous records did not have the precision of K-NET recorders and also the stations were scattered in various places. When the result of whole data is considered, it shows higher PHGA for far field records than all existing relationships. When stiff soil with anelastic distance attenuation is considered there is decrease in the PHGA in far field record but still it is among the highest of existing relationships. It is to be noted that the present attenuation relationship considers only the Okhotsk-Amur plates boundary. All other

relationships considered for comparison are developed using databases of strong motion records of all over Japan.



(a) (b)

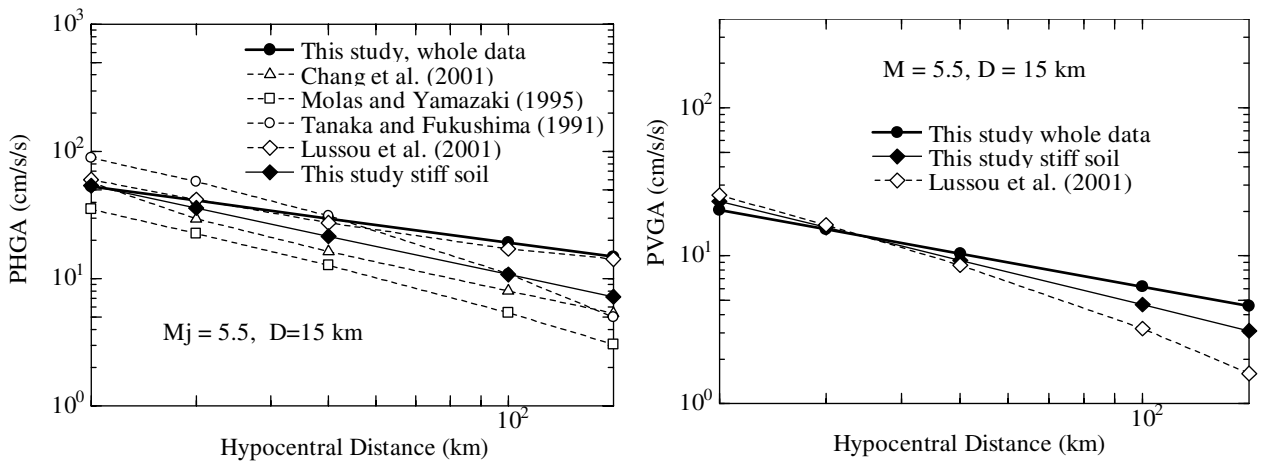
Fig. 5. Response Spectra for 5% damping (a) Horizontal Component (b) Vertical component

Table 3. Comparison of Databases of Attenuation Studies

Study	Fukushima and Tanaka (1991)	Molas and Yamazaki (1995, 1996)	Chang et al. (2001)	Lussou et al. (2001)	This study
Number of records	200 (USA) 486 (Japan)	2166	4720 Shallow 2524 Deep	3011	667
Number of earthquakes	15 (USA) 28 (Japan)	387	64	102	42
Magnitude range	$M_J \geq 5.0$	$M_J \geq 4.0$	Mw = 4.5-7.0	M_J = 3.5-6.3	M_J = 4.0-5.6
Depth	D≤20km(USA) D≤30km(Japan)	D≤200km		D≤20km	D = 8 – 43 km
Minimum acceleration	PGA≥10cm/s^2	PHGA≥1cm/s^2	PGA≥3.92 cm/s^2	-	PGA≥5cm/s^2
Definition of maximum	Mean of two horizontal components	Larger of two horizontal components	-	-	Larger of two horizontal components
Recording Instrument	Various including uncorrected SMAC	JMA 87-type-accelerometers	WMB, Taiwan Digital accelerometers	K-NET	K-NET
Data period	1965-1987	1988-1993	1994-1998	1996-1998	1996-2003
Spectral attenuation	Does not exist	Exist	Does not exist	Exist	Computed

There is no existing relationship to compare PVGA except the relationship by Lussou et al. (2001) [3]. They have considered the attenuation of 50 Hz frequency as the peak ground acceleration. The attenuation coefficients for 50 Hz frequency for vertical component of acceleration is taken as the attenuation of PVGA. The Lussou et al. (2001) relationship predicts PVGA higher than the equation of this study when T<0.2s and lower for T>0.2s. However, the difference is small.

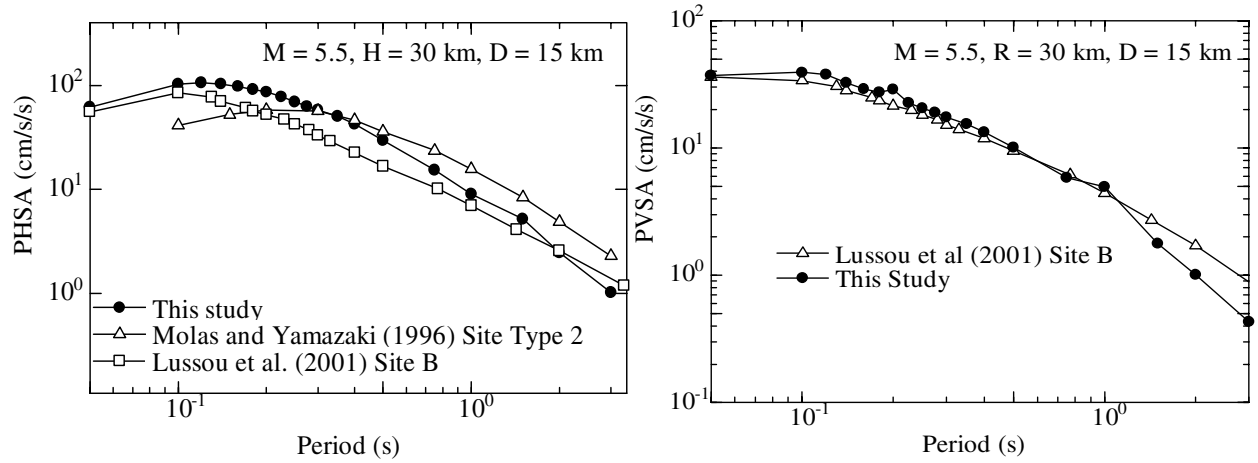
There are three attenuation relationships developed for Japan considering spectral acceleration [3,6,7]. The comparison of PHSA resulted from this study is shown in the Fig 7(a). Lussou et al (2001) have developed site specific spectral attenuation relationships for four site categories depending upon the V_s^{30}. In this case the comparison is made for the site category B (V_s^{30} = 360-760 m/s). Since the mean V_s^{30} of this study is 331 m/s it is representative of site category C. On the other hand, site type 2 of JMA is considered in case of Molas and Yamazaki (1996) representing fundamental ground period of 0.2-0.4 s. This corresponds to V_s^{30} of 300-600m/s. The response spectrum obtained in this study is higher than of Molas and Yamazaki (1996) for T < 0.3 s and lower for T>0.3 s.



(a) (b)

Fig. 6 Comparison of Attenuation Model developed with other Existing Models

There is no relation for vertical component of ground motion in Molas and Yamazki(1996) [6]. The spectrum obtained in this study is compared with the spectrum site category B given Lussou et al. (2001). As shown in the Fig. 7(b) the spectrum obtained in this study is nearer to the spectrum for site B of the Lussou et al (2001). The response acceleration is lower than of Lussou et al. for the structural periods more than 1.0 s.



(a) (b)

Fig. 7 Comparison of Spectrum obtained in this Study with the Existing Relationships (a) Horizontal component (b) Vertical component

CONCLUSIONS

Attenuation relationships for peak ground acceleration and peak response spectral acceleration is developed for the eastern margin of sea of Japan or Okhotsk-Amur plates boundary. The resulting attenuation relationships are compared with the existing attenuation relationships of Japan and Taiwan. Following observations are made in the developed attenuation relationships:

(1) The attenuation relationships depend upon the recording instruments of strong motion earthquakes. The resulting attenuation relationship from this study is quite similar to attenuation relation developed using K-NET records.

(2) The existing attenuation relationships of Japan derived by the JMA records underestimate the peak ground acceleration in far field records of Okhotsk-Amur plates boundary. The resulting attenuation relationship is near to the attenuation relationship of shallow crustal earthquakes of Taiwan.

(3) The resulting response horizontal spectral attenuation is lower than the existing relationship developed using JMA records in Japan for the period more than 0.3 s.

Further refinement of attenuation relationships considering site types is needed as sediments normally amplify the ground motion.

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