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ON SEISMIC MOTION NEAR ACTIVE FAULTS BASED ON SEISMIC RECORDS

H WANG[1] And A NISHIMURA[2]

SUMMARY

The reliability of assessment of seismic input motion is most important for aseismic design of structures. The disasters caused by Hyogoken-Nanbu Earthquake, 1995 and Northridge Earthquake, 1994 indicate that the seismic motion near active fault can be very strong, stronger than the seismic input motion used in present standard. Since this kind of ground motion is very rare during the life of it, the structure is designed to prevent collapse but to allow the damage. In the nonlinear response, the performance of structure becomes very sensitive to the accuracy of input seismic motion. In this paper, seismic motion straight above an inland fault has been examined based on strong seismic records observed in recent major earthquakes occurred in both Japan and the United States. A quantitative definition of seismic motion with a non-exceeded probability of 90 percent is worked out on the free surface of bedrock, the shear wave speed of which is over 400m/s. Besides, from the statistical results of analyses, no large difference was found between the records in the United States and Japan for the seismic motion in near-source field, although the geological condition may differ from country to country.

INTRODUCTION

The design seismic motion is very important for aseismic design of structures. After the disaster of Hyogoken-Nanbu Earthquake, the very strong seismic motion caused by inland active fault is taken into account in aseismic design in Japan. In principle, it is desirable to determine the design seismic motion for a specific site according to such risk factor as return period of earthquakes from recognized seismic faults. However, the potential earthquake related to an inland active fault has a great amount of uncertainty, the return period of earthquake of an inland active fault is not accurate enough at present, when compared with the service life of structure. In consequence, an extreme event associated with an inland active fault is taken into account in new standard for railway structures, unless it is evident that the fault will not move during the life of a structure.

According to the seismic environment in Japan, there are two types of earthquake, which are considered to determine the Level II ground motion for aseismic design in the standard [Wang and Nishimura, 1999]. One is the motion caused by interplate earthquakes near land with its magnitude around 8, named as Spectrum I. Another one is the motion caused by the earthquake associated with the inland active fault of magnitude more than 6.5, named as Spectrum II. In the following, the characteristics of Spectrum II are examined based on strong seismic records observed in near-source field in recently earthquakes.

There are many researches recently on the calculation of seismic motion for a given site using seismic source model of a fault and deep geological structure. While for the application of the method in aseismic design, there are still many problems to be solved, such as the distribution of the asperity on the fault plane, the start point of rupture, etc. Therefore, it is very useful to evaluate the seismic motion near inland fault from statistical analyses of near-source strong seismic records.

Because of the significant local effects on seismic motion due to soft surface soil as well as irregular topography of ground, the design seismic motion here is defined on a free surface of bedrock, of which the shear wave speed

[1] *Structure Technology Development Division, Railway Technical Research Institute, Tokyo, Japan Email ts_hwang@rtri.or.jp*
[2] *Structure Technology Development Division, Railway Technical Research Institute, Tokyo, Japan*

is over 400m/s. The local effects for specified site of structures can be evaluated through proper numerical analysis, where the design seismic motion is used as the incident motion. Furthermore, the response spectrum of acceleration is used to describe the characteristics of seismic motion here, and corresponding artificial seismic wave can be generated by adjusting Fourier amplitudes of the wave according to the expected response spectrum of design, with their phases reflecting the non-stationary property of the seismic motion.

Table 1 Near-source seismic records from recent earthquakes

No	Earthquake	Name of seismic record	Max. Acc. (gal)		Latitude	Longitude	EHD	CDF	Ground level	Property of soil at the position of seismometer
			NS	EW						
1	Hyogoken-Nanbu	Port Island	679.8	302.6	34.670	135.208	11.64	3.24	GL-83	Vs=450 (m/s)
2		Takasago Power Station	86.0	109.3	34.753	134.783	32.75	27.08	GL-100	Vs=460 (m/s)
3		SGK,Kansai Elec. Power Co.	293.9	319.8	34.743	135.442	34.57	24.65	GL-97.0	Vs=455 (m/s)
4		Roko (Kobe University)	272.0	306.5	34.725	135.240	14.99	6.90	GL-9.5	0.5m (240m/s) layer over Vs=590 (m/s)
5		Inagawa	185.3	200.4	34.836	135.427	38.03	25.03	GL-30	Vs=780m/s
6		Great Bridge of East Kobe	445.9	425.3	34.707	135.296	20.00	12.38	GL-33	Layer of N=18 above GL-45
7		Takaratuka	683.6	600.9	34.809	135.344	29.93	16.88	GL0.0	N over 63 1.5m surface layer with N=5
8		New Kobe substation	510.7	584.2	34.731	135.250	16.52	7.53	GL0.0	Vs=300m/s, 4m surface layer Vs=200m/s
9	Coyote Lake	San Ysidro	314.6	408.8	37.026	121.484		1.0	GL0.0	Rock
10	Loma Prieta	Santa Cruz UCSC	433.1	401.5	37.00	122.06	18.01	12.19	GL0.0	Limestone
11		Gilroy#1-Gavilan Coll.	426.6	433.6	36.973	121.572	26.56	12.21	GL0.0	Franciscan Sandstone
12	Landers	Joshua Tree fire station	268.3	278.4	34.131	116.314	16.90	10.79	GL0.0	Shallow alluvium over granite bedrock
13	Northridge	Tarzana Cedar Hill Nursery	970.7	1744.5	34.160	118.534	20.63	17.87	GL0.0	Thin alluvium over siltstone
14		Pacoima Kagel Canyon	424.2	295.2	34.288	118.375	18.73	8.98	GL0.0	Rock

NEAR-SOURCE SEISMIC MOTION OF INLAND FAULT

As mentioned above, extreme event associated with an inland active fault is to be taken into account in aseismic design, the strength of seismic motion straight above the fault is most interested. Because the average thickness of the Earth's crust ranges from 15 to 20km in Japan, it is reasonable to consider that the depth of an inland fault will not exceed 20km. Besides, for most of inland faults, their planes are almost vertical to the ground surface, so that the length of fault in horizontal will increase as the magnitude of earthquake increases. This results in that the maximum ground motion tends to a limit value in near-source field and almost independent to the magnitude, due to the fact that the energy of earthquake distributes in a wider area as the scale of it increases. Hence, we make a fundamental assumption that the maximum ground motion in near-source field is independent to the magnitude of earthquake associated with inland fault, if the magnitude is more than 6.5. The following will concentrate on the maximum ground motion in near-source field.

Seismic Records

Table 1 shows the list of records observed in recent earthquakes in the United States and Japan, Hyogoken-Nanbu (1995,M7.2), Coyote Lake (1979, M5.9), Loma Prieta (1989,M7.1), Landers (1992, M7.5) and Northrige (1994, M6.7). According to the purpose stated above in this study, all records are so chosen that they satisfy the requirements below.

(1) The soil condition at the station of seismometer meets the condition of the aforementioned bedrock.

(2) The maximum acceleration of the record is greater than 100gal.

(3) The Closest Distance to Fault is less than 30km.

It can be found from the table that most of records of Hyogoken-Nanbu Earthquake are in the ground. Theoretically, the motion in the ground includes both incident and reflected waves so that deconvolution shall be carried out to separate the incident wave from the record based on the soil condition where seismometer is installed, as we are examining the seismic motion on a free surface of bedrock. However, the original records are used here instead for two reasons followed. Firstly, it is difficult to get a result that is reasonably closer to incident wave than original record, as there are a number of unsolved problems in the deconvolution analysis for strong ground motion and strong nonlinear behavior of soil. Secondly, the influence of the surface soil would not be too strong since the shear wave speed of soil at all sites is higher than 450m/s, with only one exception at the Great Bridge of East Kobe.

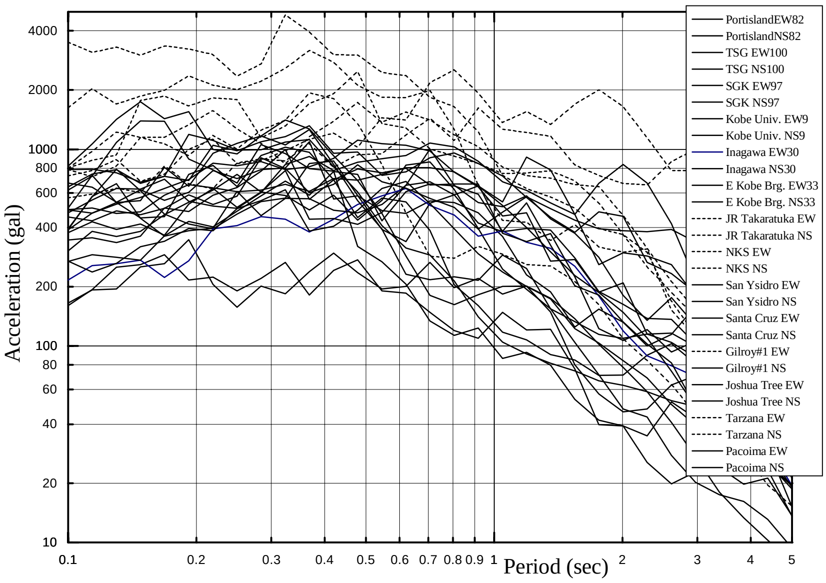

Figure 1: Acceleration response spectra of observed records at near field area of inland earthquakes

The acceleration response spectra of the selected records are illustrated in Fig.1. The accelerations of response vary from 200(gal) to 3000(gal) in the range of short period and from tens of gals to 1000(gal) in the range of long period. As the soil conditions at the observation stations have been chosen carefully, the wide variation may be attributed to the following reasons.

(1) Difference in the mechanism of seismic sources

(2) Difference in the propagation of seismic waves

(3) Influence of irregular topography

As to the influence of irregular topography, it can only be avoided by selecting records according to the geological condition if available. Through a careful investigation, it is found that the records at Tarzana, Northrige earthquake (1994, M6.7) [Gotou and Ejiri, 1994], New Kobe substation and Takaratuka, Hyogoken-Nanbu earthquake (1995, M7.2) [The Japanese Geotechnical Society, 1995], are influenced strongly by special topography, so that these records (dash lines in Fig.1) are excluded from statistical analyses.

Regarding the influence of the propagation of seismic waves, besides the distance from the sources, the profiles in deep ground in the range of several kilometers as well as the Q factor (quality factor) are considered to be very important, but they are out of the scope of this study. However, there are a number of attenuation functions of ground motion proposed, in which influences of propagation are considered in an average sense. By using the existed attenuation function, we can compensate the recorded seismic motions to a same distance from the seismic source so that the variation of ground motion due to propagation can be minimized. The rest variation of ground motion in statistics is attributed to the difference in the properties of seismic sources or other unclear reasons.

Compensation by Attenuation Function

To evaluate the seismic motion in near-source field, the extent of fault plane must be considered properly. Therefore, the measurement of the distance between the site and the seismic source in the attenuation function become very important to decide the near-source strong ground motion. To satisfy the above requirement, the Closest Distance to Fault has been widely used recently. The following is an attenuation function of response spectrum of ground motion based on the Closest Distance to Fault(CDF), which is proposed by Fukushima [Fukushima,1994].

$$\log S(T) = a_1(T)M_w^2 - a_2(T)M_w + b(T)\cdot R - \log(R + 0.025\times 10^{0.42M_w}) + \sum c_j(T)I_j \quad (1)$$

in which M_w, R and T are the moment magnitude, the Closest Distance to Fault and the period, respectively; a_1, a_2 and b are coefficients of regression; c_j is the coefficients related to site properties.

On the other hand, Ohno et al. [Ohno and Takahashi, 1994] proposed another type of attenuation relation based on Equivalent Hypocentral Distance (EHD), this is determined by the energy radiated from the finite fault plane.

$$\log S(T) = a(T)M_w - \log X_{eq} - b(T)X_{eq} + c(T) + \Delta s(T) \quad (2)$$

$$X_{eq}^{-2} = \sum_{i=1}^{N} d_i^2 X_i^{-2} \Big/ \sum_{i=1}^{N} d_i^2 \quad (3)$$

where X_{eq} denotes the Equivalent Hypocentral Distance; N, X_i, and d_i are the number of small areas used in the calculation, the distance between the site and the center of the area i, and the seismic moment on the area i, respectively. a, b and c are coefficients of regression.

Both attenuation functions give solely the average tendency of the ground motion in near-source field. They can not reflect the directivity of propagation of the rupture on fault plane. When the site gets far from the fault, the contour of ground motion gives a similar shape from Equ.1, but tends towards a circle for Equ.2.

The Closest Distance to Fault and Equivalent Hypocentral Distance given in Table 1 for every site of record are calculated according to the fault models published by USGS for earthquakes in USA and by Irekura for Hyogoken-Nanbu Earthquake, respectively.

As aforementioned, the ground motion in near-source field of an inland fault shows a tendency to saturate as the site is getting close to the fault, regardless of the length of the fault and so the magnitude of earthquake. Therefore, the influence of magnitude can be omitted here, because it is the ground motion at the place straight above the fault on ground surface to be evaluated. Only the influence due to the distance between the site and the fault is taken into account, and the compensation for the observed records is carried out by using the attenuation relation.

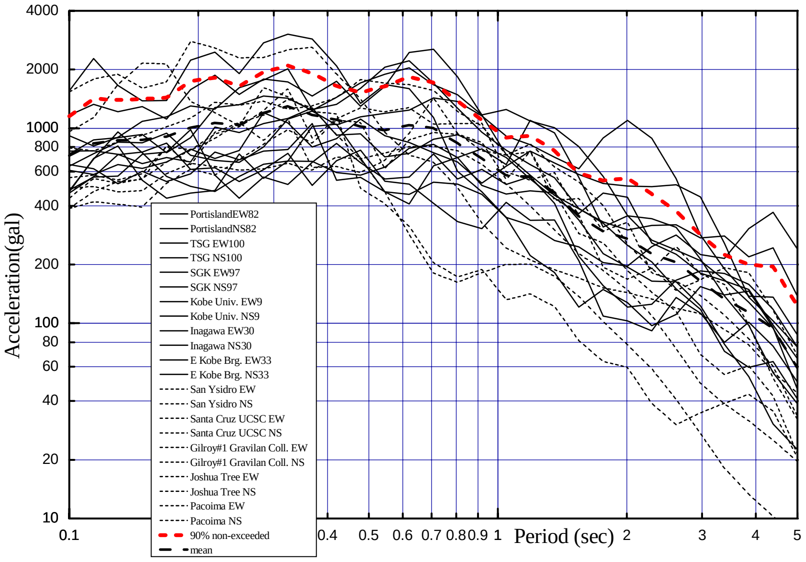

Figure 2: Acceleration response spectra of observed records after compensated by attenuation relation using Equivalent Hypocentral Distance

First we use the attenuation function of Equivalent Hypocentral Distance. After all fault models are examined, the Equivalent Hypocentral Distance of destination is taken as 12km in this study, although the smallest Equivalent Hypocentral Distance depends on the size of the fault. The compensated response spectra of acceleration by Equ.2 are shown in Fig.2.

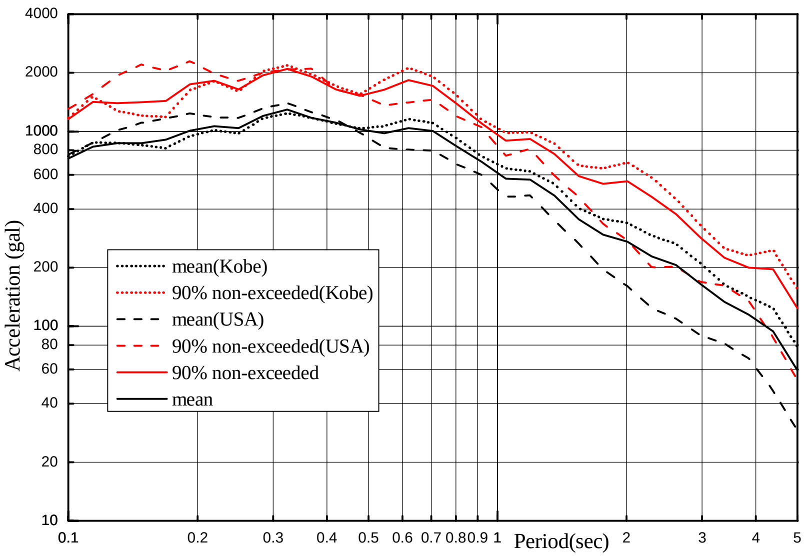

Figure 3: Comparison of the statistical results based on the seismic records in USA and Kobe, respectively

Because the compensation from the attenuation function gives a ground motion closer to the fault than original records, all spectra become larger from an overall point of view. The upper limit is about 2000gal in the range of short period, except those of SGK EW97 and Gilroy#1 Gravilan Coll.EW records. As expected, the deviation of ground motion from the statistical mean value becomes smaller for all period. When compared with those in the short period, the improvement in the long period is minor, implying the existence of dominating effects from the seismic source and the geological structure in deep ground.

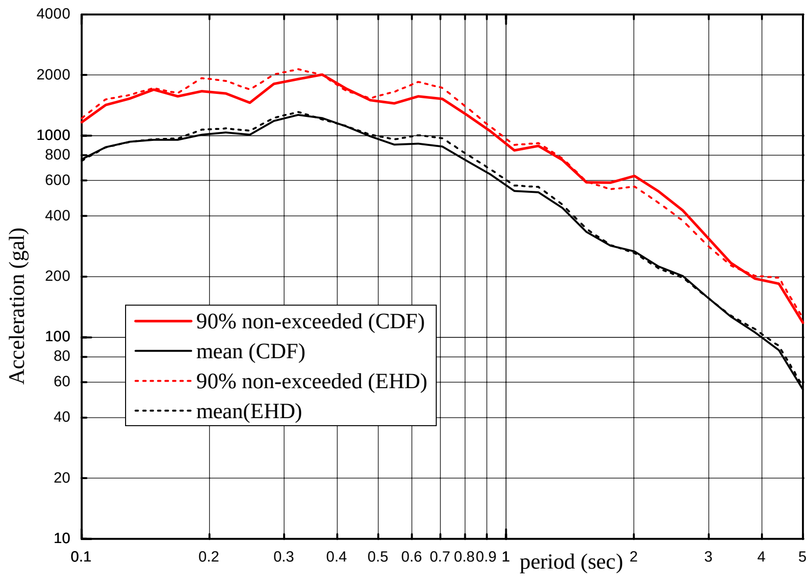

Figure 4: Comparison of the statistical results using Closest Distance to Fault and Equivalent Hypocentral Distance attenuation relations

Since the geological condition may differ from country to country, it is interesting to look at the difference of ground motion in different country. Fig.3 gives the comparison between the statistical results based on the seismic records in the United States and Kobe. They satisfactorily agree with each other for the period up to 1 second. For the period longer than 1 second, the records at Kobe give larger responses. This difference would be a major reason of larger deviation of total statistical results in the long period range. Meanwhile, it can also be found that the statistical results become smoother as the number of record increases.

The attenuation function based on the Closest Distance to Fault has also been used for comparison, where the distance of destination was taken as 2 kilometers. The point of 2 kilometers from fault is the place straight above it on the ground surface, because little portion of energy will be radiated from the area close to the surface within 2 kilometers, even though the rupture of the fault may reach and appear on the ground surface.

There is not much difference between the statistical mean values of response spectra after compensated based on the Closest Distance to Fault and that based on Equivalent Hypocentral Distance, but the values of 90% non-exceeded probability show a little difference (Fig. 4). This illustrates that the statistical results of ground motion straight above the fault is almost independent of the attenuation relation based on either the Closest Distance to Fault or Equivalent Hypocentral Distance.

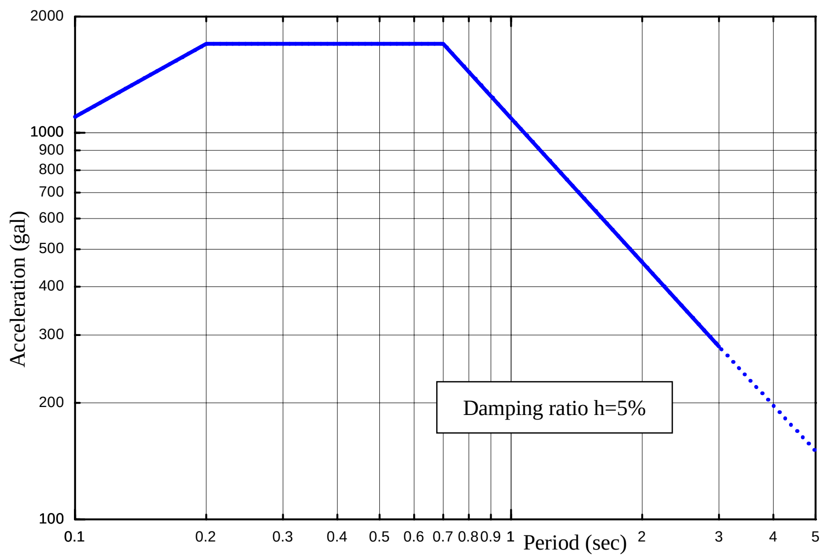

Figure 5: Acceleration Response spectrum for design seismic motion straight above an inland fault

Seismic Motion Straight above an Inland Fault

In view of the limited number of records adopted at present study as well as unknown properties of earthquakes in the future, it is wise and reasonable to determine the design seismic motion according to a certain non-exceeded probability, rather than by taking the envelope of the maximum values of records used.

To what degree the non-exceeded probability should be taken is very important but difficult to determine. It usually depends on a subjective judgement. For railway structures, the following three points are considered.

(1) Railways are a means of mass transportation and directly related to the safety of passenger.

(2) A failure at one point of a railway system will affect the whole route, and it is very costly and usually impossible to have a bypass for the same railway.

(3) The seismic records used are limited and many unknown factors are included.

In the light of above considerations, a high non-exceeded probability is strongly expected, but 90% non-exceeded probability is believed to be acceptable and adequate when the accuracy of the whole process of aseismic design is taken into consideration.

It is not difficult to get the value of a certain non-exceeded probability if we assume that the response spectrum at given period is normally distributed. The values of 90% non-exceeded probability are given in a thick dot line in Fig.2. Due to the influence of the records at SGK (Hyogoken-Nanbu earthquake) and Gilroy#1 Gavilan Coll. (Loma Prieta earthquake), the apparent value near 0.3s in period is over 2000gal, which may be attributed to some local effects of two sites. Finally, for the convenience of aseismic design we use three straight lines on the log-log plot to define the response spectrum of acceleration for the design seismic motion (Fig. 5), called Spectrum II. Its values are as following.

(1) 1100gal at 0.1s in period

(2) 1700gal between 0.2s and 0.7s in period

(3) 154gal at 5.0s in period.

Reduction of Ground Motion Near the Inland Fault

Spectrum II defines the motion straight above an inland fault. If the site is at other place, the ground motion can be reduced by the attenuation function according to the distance between the seismic fault and the site. Here the Equivalent Hypocentral Distance is recommended, since the distribution of ground motion from it is very close to that calculated by other analytical method. The reduction ratio depends on the shortest Equivalent Hypocentral Distance of given fault and the Equivalent Hypocentral Distance of the site to the fault. It can be easily derived from Equ. 2. However, as stated before, the attenuation function of Equ.2 can not reflect the effect of directivity of the propagation of the rupture on fault plane, the ground motion near the edges of the fault may be underestimated when a uniform distribution of energy on fault plane is assumed. To solve this problem, a modified length of fault in horizontal has been proposed to replace the real length of fault in the calculation of Equivalent Hypocentral Distance.

$$L' = L + 1.6\sqrt{L} \qquad (4)$$

where L is the real size of the fault, and L' is the modified size.

Fig.6 shows an example of the contour of reduction of ground motion near a fault, 60 kilometers in length and 20 kilometers in depth, by the method proposed above. The plane of the fault is vertical to ground surface with the energy uniformly distributed on it. It can be seen that the underestimation at the edge is well improved.

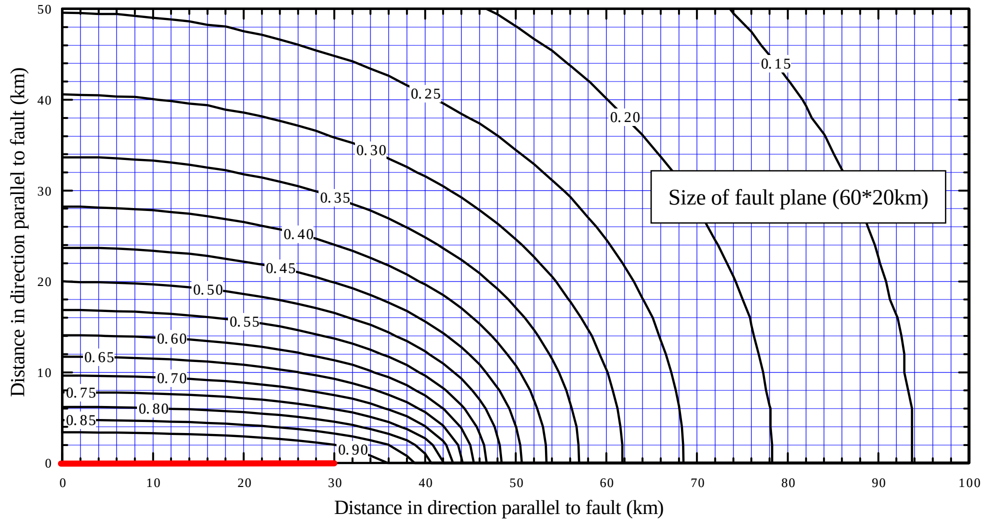

Figure 6: Contour of reduction of ground motion near a fault

CONCLUSIONS

In this paper, the ground motions due to earthquakes of inland fault have been examined based on the strong seismic records at near-source filed. A design seismic motion has been proposed, based on the values of 90 percent non-exceeded probability of statistical results. The seismic motion is defined on the free surface of a bedrock with shear wave speed over 400m/s. The proposed Spectrum II is used in new aseismic standard for railway structures in Japan. The maximum response acceleration between 0.2s to 0.7s in period is 1700gal.

The assumption that the ground motion tends to saturate as the site is getting closer to the fault has been used, and the ground motion straight above the inland fault was worked out by compensation of observed records with the attenuation function. Two kinds of attenuation function based on the Closest Distance to Fault or Equivalent Hypocentral Distance have been employed for compensation. No significant difference was found between two results.

Furthermore, the statistical results of records in the United States and Kobe have been compared, and the ground motions show almost same level before 1 second in period, but the records at Kobe gives larger result after 1 second.

For the ground motion at near-source field, the method of reduction based on Equivalent Hypocentral Distance has been proposed, in which modified length of the fault is used to avoid the underestimation of ground motion at the edges of the fault.

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