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EMPIRICAL LONG-PERIOD RESPONSE SPECTRAL ATTENUATION RELATIONS BASED ON SOUTHERN CALIFORNIA DIGITAL BROAD-BAND RECORDINGS

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SUMMARY

The reliability of digital broad-band data in long-period range is particularly inspected. This is done by verifying the instrument response characteristics, examining the signal-to-noise ratio, comparing the recovered ground motions and response spectra from different digital broad-band recordings. The result shows that the digital broad-band recordings are reliable even the period is as long as 20s. The empirical attenuation relationship of horizontal acceleration response spectrum is developed by regression. The short-period (*T*=0.04-3s) and long-period (*T*=1-20s) response spectral attenuation relations are derived from analog recordings and digital broad-band recordings, respectively. By connecting the short-period and the long-period attenuation relationships together, the wide period (*T*=0.04-20s) attenuation relationships of horizontal acceleration response spectrum of western North America are obtained.

INTRODUCTION

The seismic design of large-scale structures with long natural period needs the knowledge of characteristics of long-period ground motions. Due to the limitation of instrument response and processing procedures, the analog strong motion records are not suitable for studying the characteristics of long-period ground motion. Compared with the analog accelerometer, the frequency response of the digital accelerometer improved a lot, and the long-period errors introduced by digitization of analog record are avoided. So the digital data are generally considered reliable to study the long-period ground motion and some researchers hereby have calculated the long-period response spectra [1]. Nevertheless, some recent researches show that when the period is longer than 10 second, the record of digital accelerometer is unreliable due to background noise [2, 3]. Therefor, if we want to study the ground motions which the period is longer than 10 second, the existing strong motion data can't meet the demand. Besides the empirical method, it is also feasible to study the long-period ground motion by seismic method from the earthquake source and propagation path [4, 5, 6]. Nevertheless, the results should be checked by reliable

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observation data. At present there are some limitations to understand the characteristics of long-period ground motion and the lack of reliable long-period ground motion observation data is the key problem.

The digital broad-band seismometers which designed for seismological study have some excellent properties such as high dynamic range, broad-band and low noise level. These properties are also needed by earthquake engineering study, and under some conditions the records of digital broad-band seismometer can be used in earthquake engineering study. Therefor, we demonstrate the applicability of such records in long-period ground motion research from instrument response, comparison of recovered ground motions, data correction and signal-to-noise ratio. The TriNet digital broad-band records of BH and HL channels are used to regress the attenuation laws of long-period acceleration response spectra.

TRINET DIGITAL BROAD-BAND RECORDS

TriNet is a cooperative project between the US Geological Survey, California Institute of Technology and California Geological Survey. TriNet involves the following partner seismic networks: California Strong Motion Instrumentation Program (CSMIP), Southern California Seismic Network (SCSN) and USGS National Strong Motion Program (NSMP). There are about 200 TriNet stations in Southern California. Some stations began operation in late 1980's. The TriNet system includes two types of sensors: a strong-motion accelerometer, which records strong ground motion, and a broad-band seismometer.

The data used in this study are the TriNet BH and HL channel recordings. The BH channel is the broad-band high gain channel and the HL channel is the high broad-band low gain channel. The seismometer of BH channel is the STS-1 or STS-2, and most of the seismometers of HL channel are FBA-23. The instrument frequency response of BH channel and HL channel is shown in Figure 1. The amplitude response of STS-1 and STS-2 is flat relative to velocity, whereas that of FBA-23 is flat relative to acceleration and is low-gain so it is similar to the accelerometer.

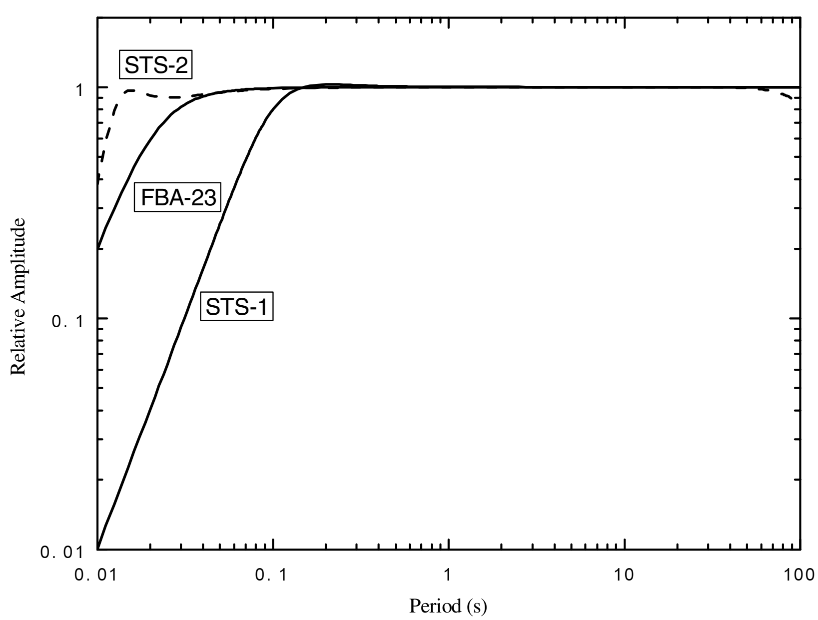

Figure 1 The frequency response of TriNet digital broad-band systems.
The HL is relative to acceleration and the others are relative to velocity.

We can see from Figure 1 that if from the point of view of the frequency response only, these seismometers can record the long-period ground motions.

DATA PROCESSING

Recovery of ground motions

In order to recover the ground motions, the instrument correction must be made. The instrument response can be expressed as transfer function. After converted by the transfer function of the instrument system, the digital counts can be transformed into the ground displacement $x(t)$, velocity $\dot{x}(t)$ and acceleration $\ddot{x}(t)$, respectively, where t is time [7].

Corrections

Before calculation of response spectrum, the baseline correction, rotation correction and high-pass filtering are necessary. Unfortunately, after these correction procedures the long-period information is lost simultaneously. The cut-off frequency of the high-pass filter is the key factor. If the cut-off frequency is low there will be a large baseline deviation in integrated displacement; if the cut-off frequency is high the long-period ground motion information may be filtered also. So when we are interested in the long-period ground motion, an appropriate cut-off frequency is very important for the baseline correction.

We first eliminate the DC offset for each record. Another correction procedure we take is the high-pass filtering. When the data are corrected for the instrument response a high-pass filter with the cut-off period of 40s is applied. Besides of above procedures, no other correction is applied.

Figure 2 is the recovered ground acceleration, velocity and displacement of E-W component of BH and HL of station SVD for the M_L5.1 earthquake of February 10, 2001. When drawing the figure the sampling rate of the HL channel is resampled to 20 sps in order to consistent with that of the BH channel. We can see from Figure 2 that the ground displacement and velocity recovered from HL record are acceptable and no significant baseline errors. And also, the ground motions recovered from BH and HL are coincident. This consistency may indicate that the two seismometers are reliable and the true ground motion can be recorded and recovered.

APPLICABILITY OF THE RECORDINGS

We use the following procedures to inspect the applicability of the digital broad-band recordings in studying long-period ground motion.

Instrument response characteristic

Both the BH and HL channel have a good instrument response characteristic in long-period range (Figure 1).

Fourier amplitude analysis of signal and noise

In order to verify if the digital broad-band record can be used to study the long-period ground motion, the signal-to-noise ratio is checked. The record of a M_L5.1 earthquake, Feb. 10, 2001, recorded by station PAS is also as an example to analyze the Fourier spectra of the signal and noise.

The records of E-W component of BH and HL are recovered to ground acceleration. We extract 40 second of pre-event data as noise (including the instrument noise and background noise) and the following 125 second of data as seismic signal. The longer the noise we take the more objectively reflecting the level of noise.

We calculate the Fourier amplitudes of the noise and signal, respectively. They are shown in Figure 3.

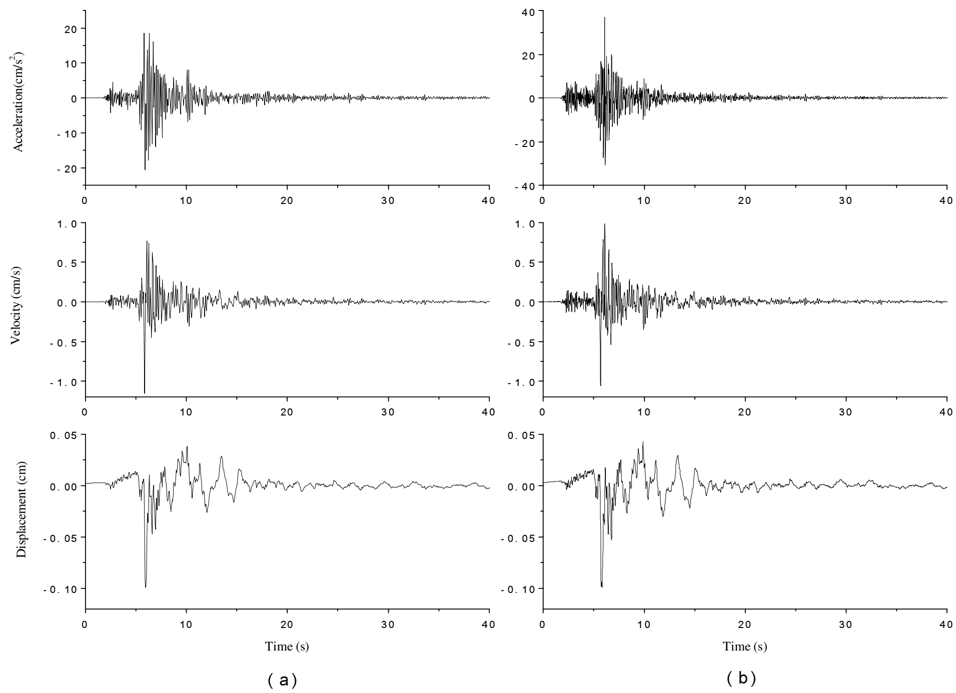

Figure 2 Recovered ground acceleration, velocity and displacement (from top to bottom, respectively) from BH and HL channels of SVD station (a) BH (b) HL

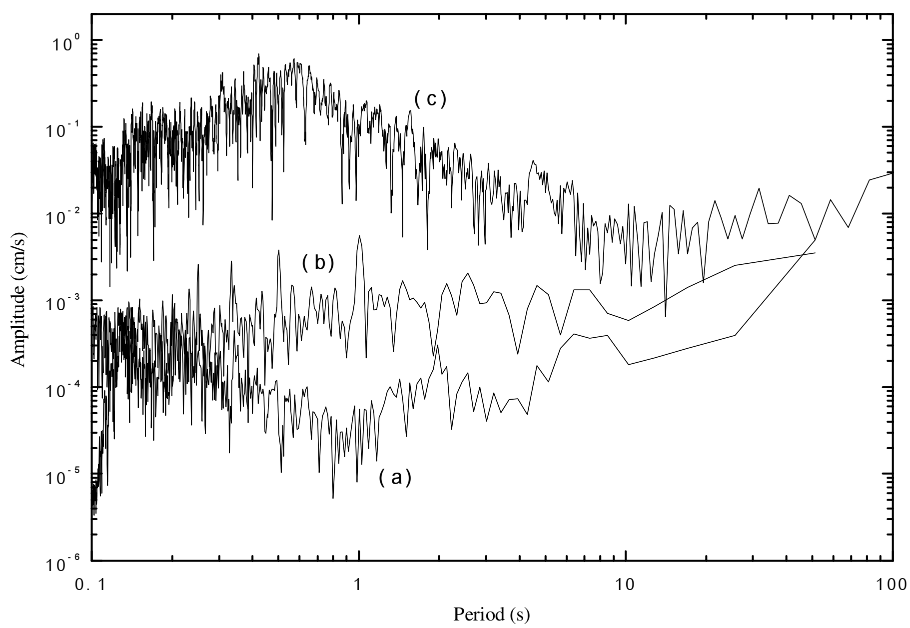

Figure 3 Fourier amplitude of noise and seismic signals for BH and HL channels. (a) BH noise (b) HL noise (c) Seismic signals

We can see from Figure 3 that the level of noise of BH channel is the lowest, about in the order of 10-4cm/s. The noise level of HL channel is higher than the BH channel. At the period of 20 second the level of seismic signal is higher than the noise level of both channels. We must note that the record used here is a weak ground motion, because the magnitude is only ML5.1 and the epicentral distance is about 115km. The result shows that for the study of long-period ground motion the signal-to-noise ratio of both BH and HL channels is satisfactory. The BH channel has higher signal-to-noise ratio and is more applicable for long-period ground motion study.

Comparison of recovered ground motions

Figure 2 is the recovered ground acceleration, velocity and displacement of E-W component of BH and HL of station SVD for the M_L5.1 earthquake of February 10, 2001. We can see from Figure 2 that the recovered ground acceleration, velocity and displacement from both BH and HL channels are coincident. This consistency indicates that the two seismometers are reliable and the true ground motion can be recorded and recovered.

Comparison of calculated response spectra

The comparison of calculated response spectra from BH and HL recordings can also be used to verify the validity of the recordings. Figure 4 is the comparison of acceleration and displacement response spectra from N-S and E-W components of BH and HL recordings of station SVD for the M_L5.1 earthquake of February 10, 2001. The solid line denotes the response spectra calculated from BH recording and the dotted line denotes the response spectra calculated from HL recording. The upper is the absolute acceleration response spectra and the lower is the relative displacement response spectra.

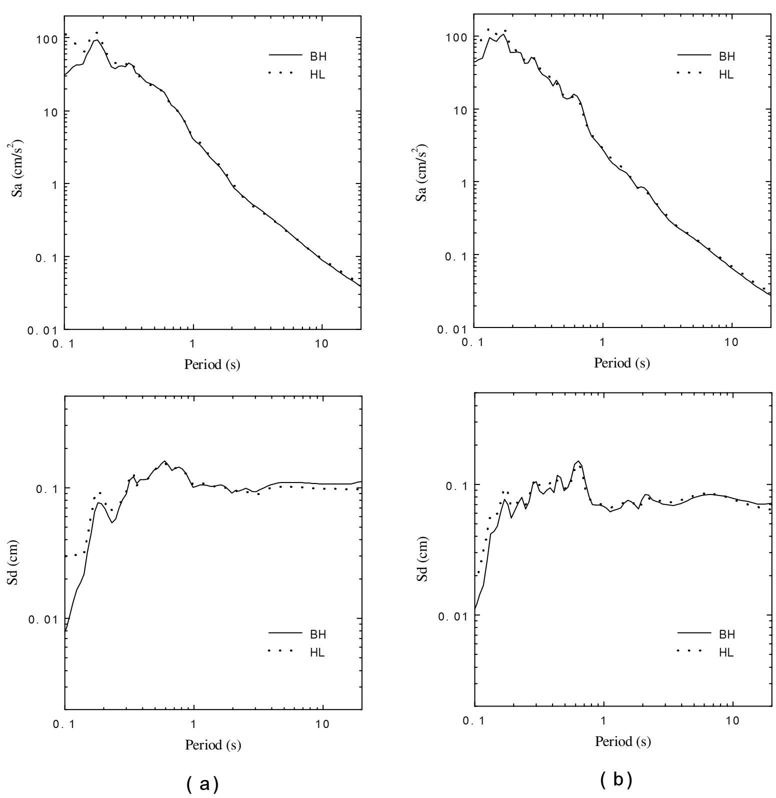

Figure 4 Comparison of response spectra calculated from BH and HL records.
Top is the acceleration response spectra and bottom is the displacement response spectra.
(a) E-W component (b) N-S component

We can see from Figure 4 that when the period greater than 0.3s, the response spectra from both BH and HL channels are very close. Because of the low sampling rate for BH channel (20sps), the BH channel cannot record ground motions of high frequency, so the lower response spectra from BH channel can be expected. On the contrary the HL channel has a high sampling rate (80sps or 100sps), so the response spectra at short period range is also reliable for the HL recordings.

From above analysis we can conclude that the digital broad-band recordings have high quality long-period characteristics and the records are suitable for studying long-period ground motions. We find that the noise level of the record is very low. Even in weak ground motion condition the digital broad-band record has high signal-to-noise ratio when the period is as long as 20s. The signal-to-noise ratio of the BH channel is higher than that of the HL channel. From both BH and HL records in one station, the same ground motions can be recovered, and the calculated response spectra are the same in a specific period range. This indirectly proves the reliability of the two types of records. When in the weak ground motion conditions, the BH channel digital broad-band recordings are more suitable for long-period ground motion study compared with the HL channel recordings. The processing of the digital broad-band records is rather simple, and there are less correction procedures are needed. This reserves the vital long-period components and ensures the base for long-period ground motion study.

METHOD

The ground motion estimation equation is:

$$\log Y = c_1 + c_2 M + c_3 \log\left(R + c_4 e^{c_5 M}\right) \qquad (1)$$

where Y is the ground motion parameter (peak horizontal acceleration or acceleration response in cm/s). M is the surface-wave magnitude and R is the epicentral distance. Coefficients to be determined are c_1, c_2, c_3, c_4, c_5.

The coefficients in the equation (1) for predicting ground motion are determined using a two-stage regression procedure [8]. In the first stage, the coefficients c_4 and c_5 are determined. In the second stage, other coefficients are then determined.

We only use the data recorded in the stations with the site shear wave velocity in the upper 30m more than 500m/s.

DATA

The long-period and short-period attenuation laws are developed separately using different data sets. The long-period response spectra attenuation equations are regressed by the TriNet digital broad-band records. The short-period response spectra attenuation equations are regressed by the analog instrument data in Western North America.

Table 1 is the earthquake catalog and the corresponding number of TriNet stations which are used in this study. Most of the data are from BH channel records. The HL channel records are used only when the BH channel records in the same station are clipped. The total number of stations is 377. Each horizontal component record is used as an independent data. There are 522 data in total. Figure 5 is the distribution of the digital broad-band data in magnitude and distance.

Table 1 Earthquake Catalog

No.	Date	Lon.	Lat.	M	No. Sta.
1	91/06/28	-117.99	34.27	5.8	4
2	92/04/23	-116.32	33.96	6.1	5
3	92/05/18	-116.34	33.95	5.0	6
4	92/06/28	-116.44	34.20	7.5	5
5	92/06/28	-116.92	34.18	5.1	3
6	92/06/28	-116.43	34.13	5.3	4
7	92/07/05	-116.32	34.58	5.4	6
8	92/07/11	-118.07	35.21	5.7	6
9	92/07/24	-116.29	33.90	5.0	6
10	92/08/17	-116.86	34.19	5.0	5
11	92/09/15	-116.36	34.06	5.1	6
12	92/11/27	-116.90	34.34	5.4	7
13	92/12/04	-116.90	34.37	5.2	6
14	93/05/17	-117.77	37.16	6.2	6
15	93/05/28	-119.10	35.15	5.2	6
16	93/08/21	-116.32	34.03	5.0	8
17	94/01/17	-118.54	34.21	6.7	6
18	94/01/17	-118.70	34.33	5.6	6
19	94/01/19	-118.71	34.38	5.1	8
20	94/01/29	-118.58	34.31	5.1	8
21	94/03/20	-118.47	34.23	5.2	7
22	94/06/16	-116.40	34.27	5.0	8
23	95/06/26	-118.67	34.39	5.0	8
24	95/08/17	-117.66	35.78	5.4	9
25	95/09/20	-117.63	35.76	5.5	9
26	96/01/07	-117.65	35.77	5.2	9
27	96/11/27	-117.65	36.08	5.3	14
28	97/03/18	-116.82	34.97	5.0	11
29	97/04/26	-118.67	34.37	5.1	17
30	97/11/30	-118.93	37.72	5.2	16
31	98/03/06	-117.64	36.07	5.2	23
32	98/03/07	-117.62	36.08	5.0	20
33	98/06/09	-118.79	37.59	5.2	18
34	99/08/01	-116.97	37.53	6.0	13
35	99/08/02	-117.09	37.38	5.0	7
36	99/10/16	-116.27	34.59	7.2	17
37	99/10/21	-116.39	34.87	5.1	21
38	01/02/10	-116.94	34.29	5.1	33

Figure 6 is the distribution of the analog data in magnitude and distance. The number of data is 187 in total.

RESULTS

The attenuation relations of long-period (T=0.04-3s) and short-period (T=1-20s) acceleration response spectra are obtained respectively using regression analysis method described above. By connecting the two attenuation curves together in the period T=1.5s, the wide period (T=0.04-20s) attenuation relations for horizontal acceleration response spectra in rock sites for Western North America are developed. Figure 7 is the response spectra in different distances. The smooth continuity of the long-period attenuation relationships obtained from digital broad-band records and the short-period attenuation relationships obtained from analog strong motion records implies that the two databases are both reliable in the period of about 1.5s.

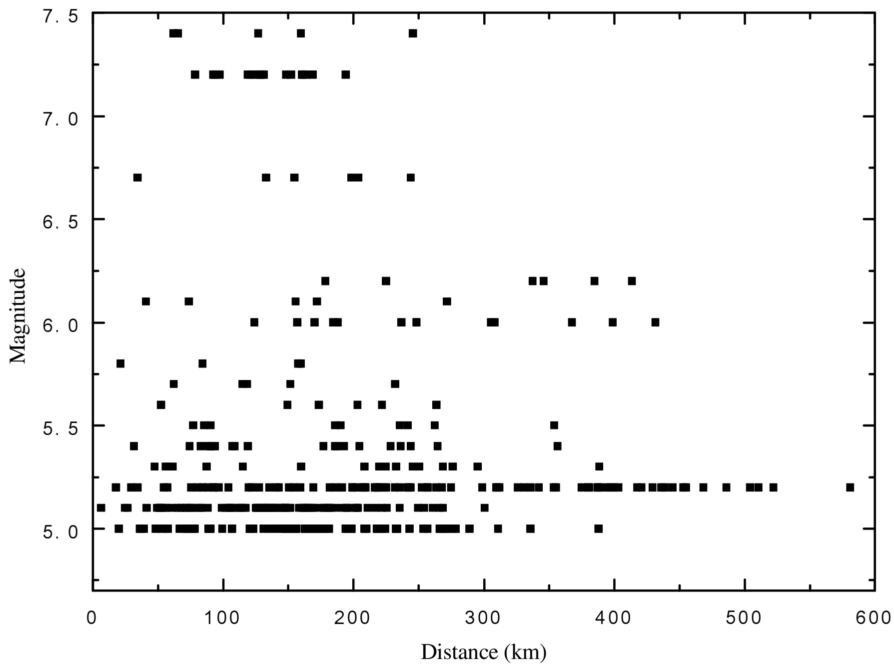

Figure 5 The distribution of the digital broad-band data in magnitude and distance

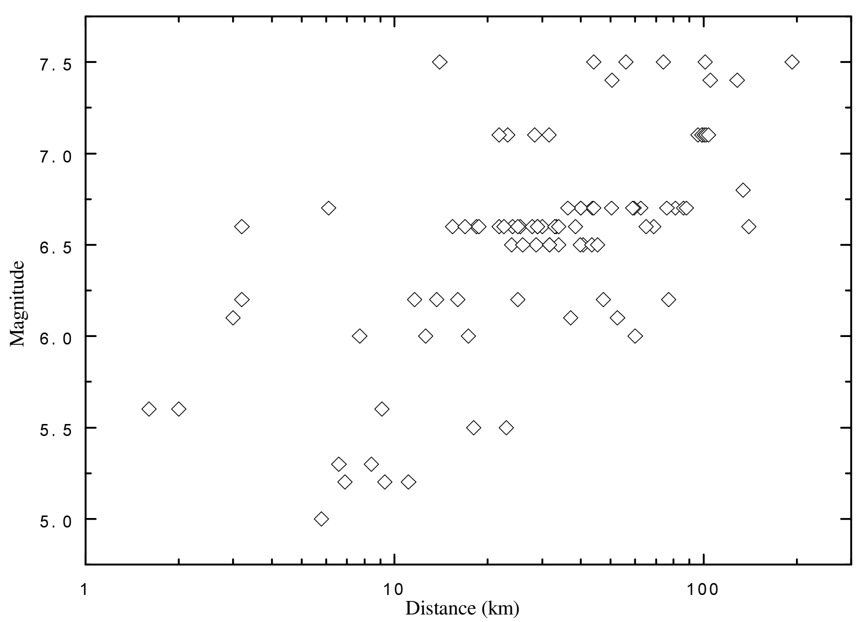

Figure 6 The distribution of the analog data in magnitude and distance

CONCLUSIONS

1. The digital broad-band seismographs used by seismologists have high quality long-period characteristics and the records are suitable for studying long-period ground motions. We find that the noise level of the broad-band record is very low. Even in weak ground motion conditions the digital broad-band record has high signal-to-noise ratio when the period is as long as 20s. The signal-to-noise ratio of the BH channel is higher than that of the HL channel. From the BH channel records and the HL channel records in one station the same ground motions can be recovered, and the calculated response spectra are the same in a specific period range. This indirectly proves the reliability of the two types of records. When in the weak ground motion condition, the BH channel digital broad-band records are more suitable for long period ground motion study compared with the HL channel records. The processing of the digital broad-band records is rather simple, and not too many correction procedures are needed. This reserves the vital long period components and ensures the basis for long period ground motion study.

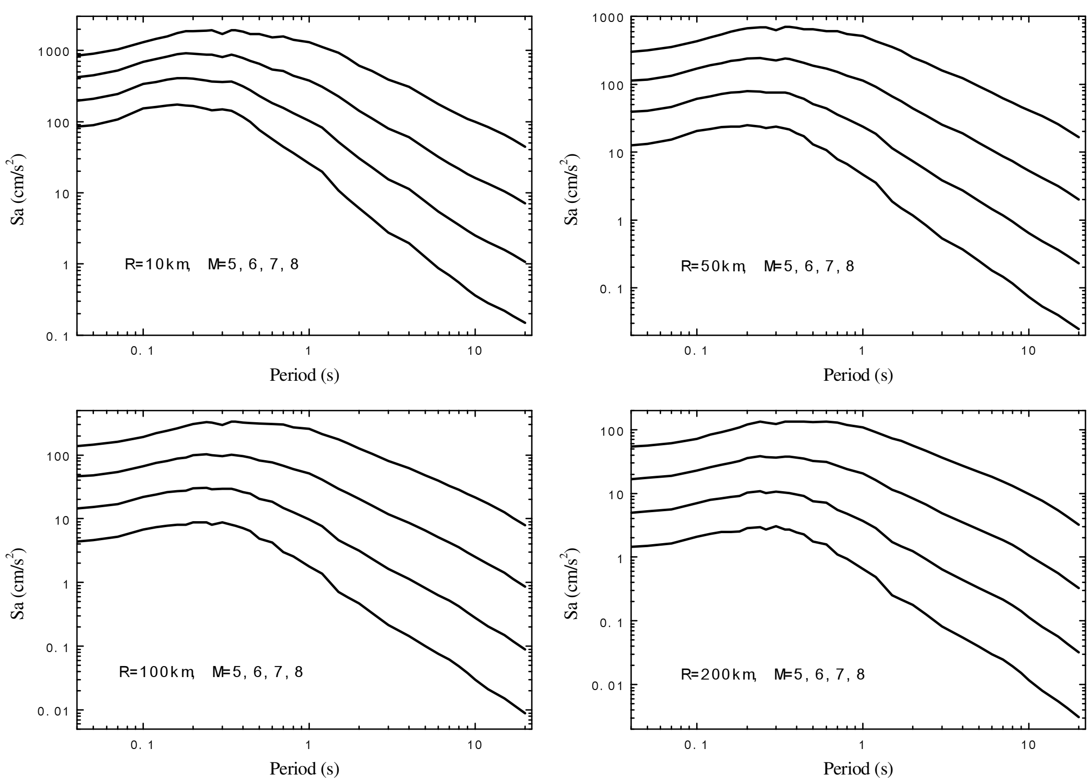

Figure 7 Acceleration response spectra in different distances.

2. The smooth continuity of the long-period attenuation relationships obtained from digital broad-band records and the short-period attenuation relationships obtained from analog strong motion records implies that the two databases are both reliable in the period of about 1.5s. By connecting together the two attenuation relationships of long-period and short-period response spectra, a wide period (T=0.04-20s) attenuation relationship for horizontal acceleration response spectra in rock sites for Western North America is developed.

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