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IS THERE A LOGICAL SHORTCOMING IN GROUND MOTION ATTENUATION STUDY

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Abstract

Attenuation relations, also known as ground motion prediction equations, have been developed and adopted to assess seismic hazard. In almost every attenuation relation, a distance term is used to describe the attenuation effect, and a magnitude term is used to describe the source effect. Although there are various definitions for earthquake magnitude (e.g., local magnitude, surface magnitude and moment magnitude etc.), they are estimated based on the amplitudes of ground motions recorded by monitoring networks. To estimate the magnitude, a calibration function taking into account the attenuation effect of motion is adopted to convert the observed amplitude to the value at a point with distance 100 km from the source. To predict ground motion, geometric and inelastic attenuation terms are adopted with different formula forms. The result of this inconsistency is that the ground motion measure (such as peak ground acceleration and spectral acceleration) predicted by the attenuation relationship may be different with that observed for the given distance and magnitude. This is a logical shortcoming in the attenuation relationship studies. Why the shortcoming exists for so long a time? First, the exchange of information between the people who determine the earthquake magnitude (mostly seismologists) and the people who develop attenuation relationships (mostly civil engineers) is limited. Second, and more importantly, the data used to determine the magnitude and to predict ground motion are often different. Effect of this inconsistency on the seismic hazard assessment is examined in this study; some preliminary results are presented to show the problem and a potential solution to overcome this problem is suggested.

Keywords: strong ground motion, attenuation relationship, distance, magnitude

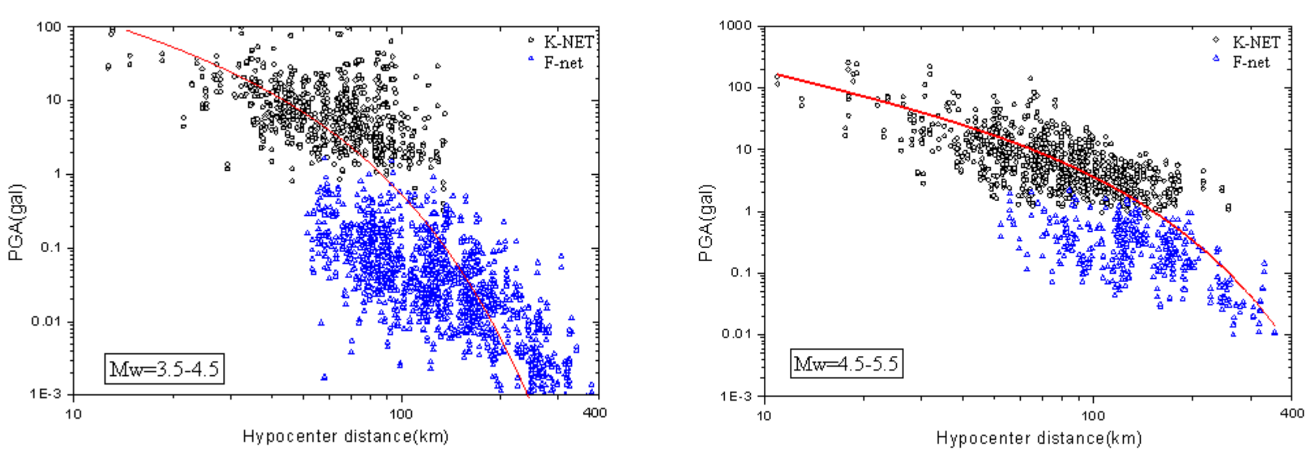
1. Introduction

The ground motion attenuation relationship has been developed mainly from regional strong ground motion data. However, in most regions of the world, observed data is not enough up to now. Meanwhile, there are many data recorded by the monitoring networks in these regions. Traditionally, those data was considered as very different with strong ground motion data, since they were recorded for different purposes, with different parameters and by different observing instruments in the initial stages [1]. Nowadays, the difference between seismographic data and strong ground motion data is getting much smaller than before, digital broadband monitoring network records velocity time history of the motion, the frequency bandwidth of the instrument system is up to 80 Hz, dynamic range reaches 140dB, and sampling rate can reach 50 sps (http:// data.earthquake.cn/datashare/network/csn48_stations.jsp), even 100sps (http://www.fnet.bosai.go.jp/notice/ Notice.20041206.php? LANG=en). On the website of the broadband seismograph network of Japan (F-net), it is declared that the seismographic data is available to predict ground motion (http://www.fnet.bosai.go.jp/top.php? LANG=en). Therefore, the possibility to develop ground motion attenuation relations by small earthquake records from monitoring network is dealt with in this paper. Firstly, the attenuation characteristics showed by the two kinds of data are compared to see if there is any barrier to analyze the data jointly, or to predict the strong motion by F-net data. One issue is pointed out by comparing the attenuation terms in current procedures of ground motion prediction and magnitude determination. The authors believe that it is a logical shortcoming in attenuation study of ground motion. Two ways to coordinate the inconsistency are discussed preliminarily by a case study in Lanzhou region of China.

2. Comparison of attenuation characteristics showed in the two kinds of data

In nature, the two kinds of data consist of two datasets. One is from mainly small events, at far distance and with low amplitude, and the other is from strong quakes, at near distance and high amplitude. So the problem is if the attenuation characteristics of ground motion may be obvious different, governed by earthquake size, distance and motion intensity. In this paper, the term "attenuation characteristics" is considered as one dataset could be extrapolated of the curve fitted by the other dataset, or both datasets can be fitted by the same curve.

An area in Northeastern Japan (E138°-143°, N36°-40°) is selected since both two types of records are available. Totally 1382 records (M_W=3.5-4.5) and 540 records (M_W≥4.5) from F-net [2], and 706 records (M_W=3.5-4.5) and 1496 records (M_W≥4.5) from K-NET [3] in the period of January of 1998 to December of 2010, are collected. These data are grouped with magnitude in 3.5-4.5, 4.5-5.5, 5.5-6.5 and 6.5-7.5. The attenuation characteristics of peak ground accelerations (PGAs), peak ground velocities (PGVs) and peak ground displacements (PGDs) are shown in Fig.1-Fig.3, respectively. PGAs of F-net data are from numerical differentiations of their velocity time histories, PGVs of K-NET data are from numerical integrations of their acceleration time histories, and PGD of the two data sets are from double and one integration(s), respectively. In the figures, the small black circles are for the K-NET data, blue triangles for F-net data, and the curves are fitted by the two datasets jointly.



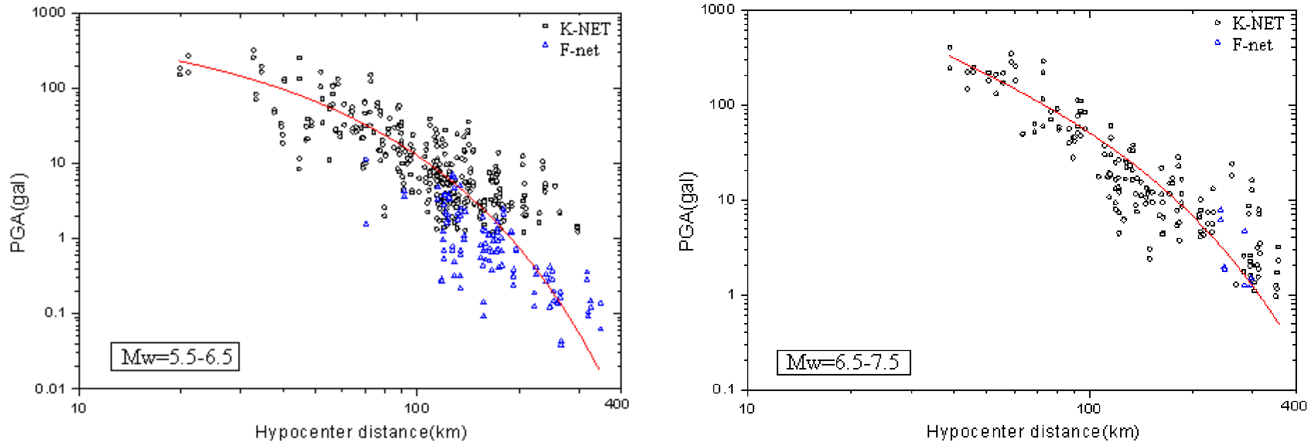


Fig. 1 – Attenuation characteristic of PGAs from F-net and K-NET data

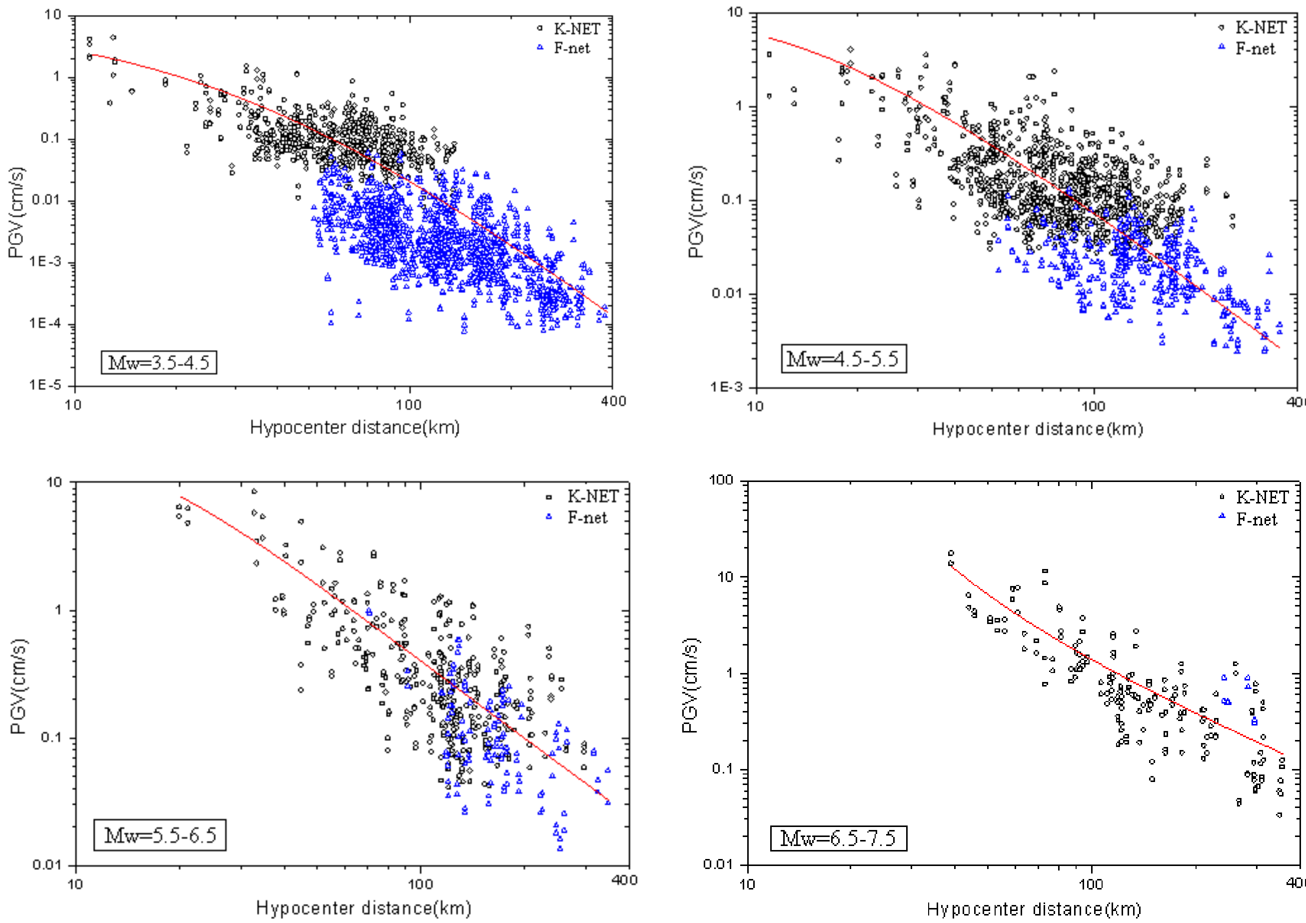


Fig. 2 – Attenuation characteristic of PGVs from F-net and K-NET data

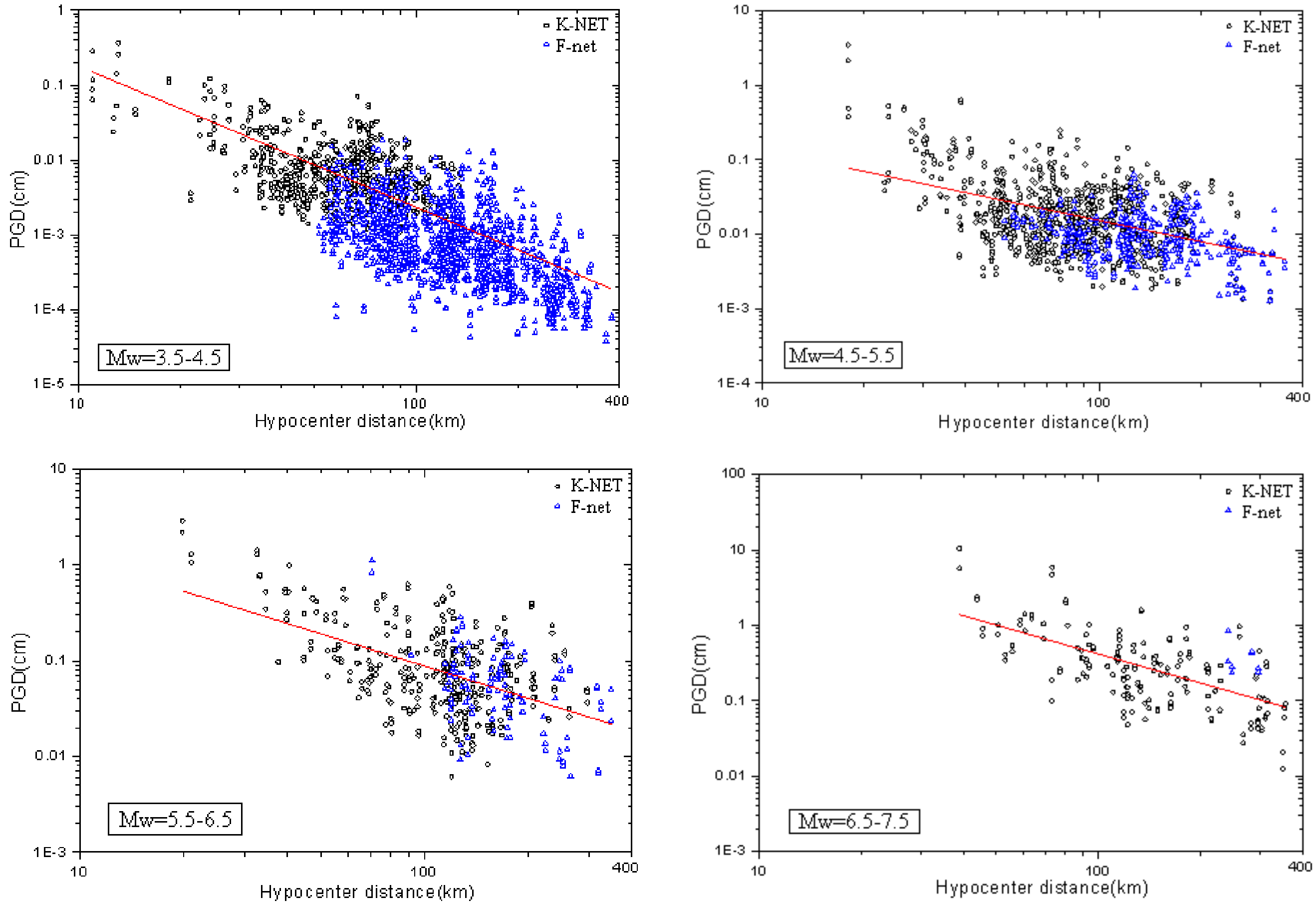


Fig. 3 – Attenuation characteristic of PGDs from F-net and K-NET data

One can find from the figures, the attenuation characteristics of F-net data are as a whole consistent with those of K-NET, not only of displacement, but also of velocity and acceleration, not only of small quakes, but also of larger shocks. There is certainly an inconsistency between the PGA attenuation characteristics of the two datasets in magnitude group 3.5 to 4.5, it needs further study to see the reason, but the more important thing is the consistency of PGAs in group of magnitude greater than 6.5. The comparison shows that F-net data can be added to K-NET data to fit the attenuation curve, they are helpful especially in far distance range, no matter for which ground motion parameter, or in which magnitude range, even though magnitudes are generally calculated from ground motions at much longer periods, theoretically infinite period in the case of moment magnitude, than those adopted in GMPE studies. This result is worth studying and probing for seismologists and earthquake engineers, who always emphasize the fact that the periods considered for magnitudes and for GMPEs are quite different, meanwhile adopt the same magnitude values in GMPE studies without any modification.

3. Attenuation terms in ground motion prediction

Fourier amplitude spectrum of strong ground motion from a point source can be predicted by the following equation [4]

$$Y(M_0, R, f) = E(M_0, f)P(R, f)G(f)I(f)$$

(1)

where, M_0 is the moment of an earthquake that can be estimated from the magnitude; R is distance; f is frequency; $E(\cdot)$ is source spectrum; $P(\cdot)$ is path effect, i. e. attenuation term; $G(\cdot)$ is site effect; $I(\cdot)$ is the effect of instrument or motion parameters. The path effect $P(\cdot)$ can be expressed by multiplication of geometrical spreading and inelastic energy dissipation as

$$P(R,f)=Z(R)\exp\left[-\pi f R/Q(f)c_Q\right]$$

(2)
where, c_Q is the seismic velocity used in determination of inelastic attenuation term $Q(f)$, $Z(R)$ is geometrical spreading term. $Z(R)$ can be expressed as

$$Z(R)=\begin{cases}\dfrac{R_0}{R} & R\leqslant R_1\\ Z(R_1)\left(\dfrac{R_1}{R}\right)^{p_1} & R_1\leqslant R\leqslant R_2\\ Z(R_n)\left(\dfrac{R_n}{R}\right)^{p_n} & R_n\leqslant R\end{cases}$$

(3)
where, R is the closest distance to the rupture surface.

In attenuation relationship of single parameter of ground motion, the equation is generally simplified as following form [5].

$$Y=b_1 e^{b_2 M} R^{-b_3}$$

(4)
where, Y is a motion amplitude, such as PGA, PGV or PGD; b_1, b_2 and b_3 are constants to be fitted; R and M are distance and magnitude, respectively. The attenuation term R^{-b_3} may be much more complicated with different distance definitions. For example, among the five horizontal attenuation relationships of NGA-West2, four adopted the closest distance to the rupture plane, R_{RUP}, [ASK (Abrahamson, Silva and Kamai), CB (Campbell and Bozorgnia), CY (Chiou and Youngs) and IM (Idriss)], one adopted the closest distance to the horizontal projection of the rupture plane, R_{JB} (Boore, Stewart, Seyhan and Atkinson). To model the attenuation of hanging wall effects, the horizontal distance from the top edge of the rupture, measured perpendicular to the fault strike, R_X, the value of R_X at the bottom edge of the rupture R_1, and the horizontal distance off the end of the rupture measured parallel to strike R_{Y0} are added [6].

In the CB equation [7], the geometric attenuation term and the inelastic attenuation term are:

$$f_{dis}=(c_5+c_6 M)\ln\left(\sqrt{R_{RUP}^2+c_7^2}\right)$$

(5)

$$f_{atn}=\begin{cases}(c_{20}+\Delta c_{20})(R_{RUP}-80), & R_{RUP}>80km\\ 0, & R_{RUP}\leq 80km\end{cases}$$

(6)
where, c_5 includes the geometrical attenuation effect; c_6 is magnitude-dependent apparent geometric attenuation; c_7 is an empirical model coefficient; c_{20} and Δc_{20} are the inelastic attenuation coefficients, the latter captures the regional differences in anelastic attenuation.

In the CY equation [8, 9], magnitude and period independent near-source geometric spreading coefficient c_4, combined with a magnitude dependent of extended ruptures on distance scaling $c_5\cosh\{c_6\max(M-c_{HM},0)\}$, is used for near-source geometric spreading. Then, body wave geometric spreading near the source to surface/Lg wave geometric spreading at larger distances is scaled proportional to $R^{-1/2}$. The far source distance scaling is coupled with an inelastic attenuation and scattering term $\gamma(M,T)R_{RUP}$.

4. Attenuation terms in magnitude determination

Different definitions of magnitude are from different wave signals recorded in earthquakes, like M_S[10,11], m_B[12], m_b[11], M_{JMA}[2,11]. This work starts with [13]. To establish empirically a relation between the maximum seismographic amplitudes at various distances from a shock, the ratio of the maximum amplitudes recorded at the same distance from two shocks, as registered by similar instruments, is assumed as a constant [10]. The local magnitude (M_L) is defined as logarithm of the maximum trace amplitude A (mm), with which the standard short-period torsion seismometer (T_0=0.8s, V=2800, h=0.8) would register that shock at epicenter distance 100 km, where the calculated amplitude is 0.001mm [13].

$$M = \log_{10} A - \log_{10} A_0 \tag{7}$$

where, $-\log_{10}A_0$ is the calibration function, an empirical correction of amplitude attenuation curve as a function of distance. It reflects geometrical spreading, inelastic and scattering attenuation and the tectonic setting of the region [14]. It is the attenuation term we mentioned above.

Horizontal-component seismographs in the U.S. Geological Surcey's (USGS) central California seismic network (CALNET) are used to synthesize the W-A seismograms. Both synthesized amplitude A and the real A from W-A seismograms were adopted to regress the parameters [15-17].

$$M_L = \log_{10} A + n\log_{10}\left(\frac{R}{100}\right) + k(R-100) + 3.0 \tag{8}$$

where, R is the hypocentral distance (km); n is the geometrical spreading coefficient and k is the attenuation coefficient, which are the regressed parameters. The calibration function involves the second and the third terms at the right side of Eq. (8). For central California, they got n=1.000, k=0.00301km^{-1}, $0 \leq R \leq 400$km. The same expression is used for southern California, n=1.110, k=0.00189km^{-1}, $10 \leq R \leq 700$km, and other values of n and k for Great Basin, Western US, Greece, Western Australia and Japan are listed as well in references.

M_S scale and calibration function is developed, which is reported in International Seismological Center (ISC) and US National Earthquake Information Center (NEIC) bulletins and estimated using amplitudes and respective periods of Rayleigh waves with periods between 10s and 60s at epicentral distances $20° \leq \Delta \leq 160°$ and focal depth≤60km [11,12,18].

$$M_S = \log_{10}\left(\frac{A}{T}\right)_{\max} + 1.66\log_{10}\Delta + 3.3 \tag{9}$$

where, $\left(\frac{A}{T}\right)_{\max}$ is the maximum of $\left(\frac{A}{T}\right)$, A is the amplitude; T is corresponding period (18s-22s); Δ is the epicentral distance (degree). The second term at the right side of the equation is the calibration function.

A new magnitude scale, namely moment magnitude M_W, is proposed in 1970s. It is considered as the most reliable magnitude accurately describing the size of earthquakes[12] and is adopted by NEIC and the Global Centroid Moment Tensor (GCMT) Project [19].

$$M_W = \frac{2}{3}\left(\log_{10} M_0 - 16.1\right) \tag{10}$$

where, M_0 is seismic moment (dyn·cm), automatic regional moment tensor inversed by long-period body waves, surface waves, et al.; on a global basis for moderate to large events, moment tensors are routinely assessed by the Global Centroid Moment Tensor Project using global waveform modeling techniques. In the absence of such data, it is derived via estimation of the area and slip of surface rupturing events and/or inferred from the 100s magnitudes [19].

5. Is there a logical shortcoming?

From the above discussion, one can see that the attenuation terms in magnitude determination and ground motion prediction are quite different in forms with different parameters. Many scientists think that the fact is reasonable, since the former is to determine the size of an earthquake from amplitude of displacement mainly in long period range, the latter is to estimate the amplitude of ground motion mostly in short period range. The question we should answer is that what is the meaning implied in adopting the same magnitude. It must be made sure if the difference is just in form, with considering the fact that the parameters in the calibration function are regional and can be fitted from the regional observed data.

It was pointed out that the calibration function, $-\log_{10}A_0$, has significantly beyond its use in estimating local magnitudes, which gives the dependence of strong motion parameters on the distance [16]. It was assumed that A_0 can be modeled by a geometrical spreading factor R^{-n} and an attenuation factor $e^{-\gamma R}$, γ can be related to the inelastic attenuation coefficient Q as $\gamma=\pi f/Qc_Q$. The attenuation coefficient k equals to $\gamma/ln10$. Following the Richter's definition, magnitude M_L can be expressed as Eq. (8).

In the work of local-magnitude scales derived for Khorasan province in northeastern Iran [20], Taheri et al. considered a parametric and a nonparametric description of $\log A_0$ while performing the inversions for geometrical spreading and inelastic attenuation parameters n and k, similar with Eq.(8). They adopted the strong ground-motion data from the Bam Earthquake on December 26 of 2003 to evaluate the frequency dependent intrinsic attenuation factors of $Q(f)$, which is related to the parameter k. They compare the $\log A_0$-distance curves from the linear and tri-linear parametric inversion, nonparametric inversion and the result from strong motion data. The differences are caused in different magnitude and distance ranges from the recorded strong-motion and the broadband datasets, and they believed that the attenuation functions derived from the broadband data and from the strong-motion data are both equally valid for determining the local magnitudes of the events in the region by means of their related datasets.

Therefore, the authors of this paper believe that there must be a logical shortcoming if the calibration function in magnitude determination is really quite different from the attenuation term in motion prediction. Let us think about a very simple case that firstly to determine magnitude from motion amplitude recorded at a station, and then to predict the amplitude of motion at the same station with the determined magnitude. One cannot obtain the same value of the amplitude just from the difference between the attenuation terms in the two procedures, while the two amplitude values should be consistent according to the logic in nature. This shortcoming exists in all ground motion attenuation relationships in general. In order to coordinate this inconsistency, there may be two ways from the authors' personal point of view. One is to try the possibility to replace the attenuation term in prediction equation by the calibration function, the other is to improve the magnitude determine procedure.

Trifunac adopted the magnitude calibration function of Richter to derive GMPEs for PGA, PGV and PGD [21]. The result showed that the calibration function may represent a satisfactory first-order approximation for all peaks of strong ground motion for the distance range from about 20 to 200 km, from the limited number of data available at that time, although it is believed to be clearly needed to have different attenuation curves for acceleration (high-frequency waves), velocity (intermediate-frequency waves), and displacement (low-frequency waves) peaks, especially at short distances which are less than about 20 km. The reason was explained as that the function incorporates empirically the regional average amplitude attenuation with distance and thus experimentally includes the average properties of the Earth's crust in the region. It was pointed out that the calibration curve would have a tendency to flatten out at short distances for large earthquakes characterized by long ruptures and large peak amplitudes; while this curve would probably have a larger negative slope at short distances for small quakes, compared with the available observed ground motion data.

Ottemöller and Havskov presented a method to automatically determine the moment magnitude for local and regional distances from the source spectrum of P, S, or Lg waves [22]. After removal of the instrument response, the displacement amplitude spectrum *A*(*f*) from a point source could be

$$\mathrm{A}(f) = S(f)D(f)G(R)$$

(11)

where, *S*(*f*) is the source spectrum, $\mathrm{S}(f) = \frac{M_0}{4\pi k \rho v^3}\left[1+\frac{f^2}{f_c^2}\right]^{-1}$, M_0 is the seismic moment, *k*=0.83, *ρ* is density of the crust medium, *v* is the wave velocity at the source, f_c is the corner frequency; *D*(*f*) is the attenuation term, $\mathrm{D}(f) = \exp\left[\frac{-\pi T f}{Q(f)}\right]\cdot \exp(-\pi\kappa f)$, *T* is the travel time, *Q*(*f*) is the frequency-dependent quality factor; *G*(*R*) is the geometrical spreading terms for the respective wave types, $\mathrm{G}(R) = \frac{1}{R}$ for P wave, $\mathrm{G}(R) = \begin{cases} R^{-1} & R \le 100km \\ (100\times R)^{-1/2} & R \ge 100km \end{cases}$ for S/Lg waves. This equation is very similar with Eq. (1) without consideration on site condition and the type of motion parameter. In which, the shape of the source spectrum depends on M_0 and f_c. These two parameters can be fitted by minimizing the difference between the observed and synthetic source spectral amplitudes. M_w then can be determined from M_0, as average if more than one records are available. Of course, *G*(*R*) can be taken as a tri-section curve for wave guide effect in the crust, as in Eq. (2). This way is quite ideal, but must to be explored by seismologists since there are a lot of data should be analyzed, magnitudes of huge amounts of data should be modified by means of a relation developed from the new magnitudes and the traditional ones for each earthquake.

6. A preliminary case study

In this paper, the authors would like to try to replace the attenuation terms in prediction equation with the calibration function in magnitude determination. Lanzhou region in Western China (N33°-39°, E100°-108°) is chosen for the case study. Five regional source and crustal medium parameters, stress drop $\Delta\sigma$, quality factor parameters Q_0 and η, geometrical spreading parameters R_1 and R_2, are inversed by micro-Genetic Algorithm (μGA) from 592 records of 33 small earthquakes (M_w=3.5-4.5), which are taken in the seismology based method [4] to predict strong ground motion in [23]. The searching ranges in the inversion are preselected from the regional seismological studies, and are listed in Table 1. In this paper, the geometrical spreading term for Western China [23] is replaced by a regional calibration function [24], as follows

$$\mathrm{R}(\Delta) = \begin{cases} 1.284 + 1.167\log_{10}\Delta, & \Delta \le 120km \\ 2.867 + 0.077\sqrt{\Delta}, & \Delta \ge 120km \end{cases}$$

(12)

It is clear that no inelastic attenuation term included in the regional calibration function, so the regional parameters to be inversed are three, $\Delta\sigma$, Q_0 and η, and the result is listed in Table 1. The attenuation curves from these parameters (solid line), are compared with those from [23] (dot line), as shown in Fig.4.

Table 1 – The searching ranges and results of inversed parameters

Inversed parameters	**$\Delta\sigma$ (bars)**	**Q_0**	**η**	**R_1 (km)**	**R_2 (km)**
Ranges	1-200	40-700	0.2-0.6	50-100	100-150
Result in this paper	76	121	0.34	-	-

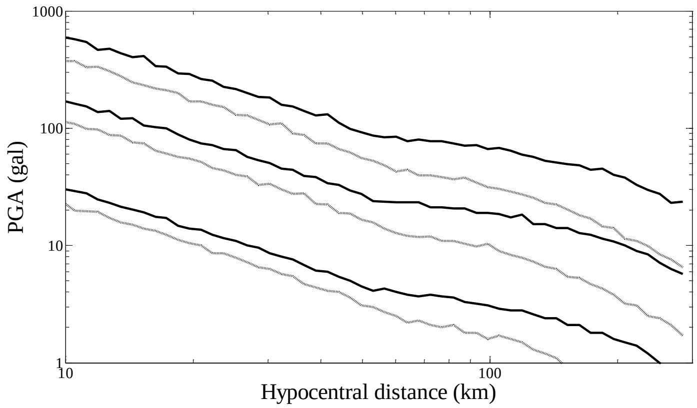


Fig. 4 – Comparison of attenuation curves

Since the values of inversed parameters $\Delta\sigma$ and Q_0 are higher than the values in [23], the curves are higher than our previous results in parallel at the distance less than R_1, the effect of this replacement is more obvious in distance range further than 60 km, and shows slower attenuation. The result suggests that we should look for a better way to adopt the calibration function in the attenuation relationships.

7. Conclusions

In order to see the possibility to adopt data from digital broadband monitoring network in developing strong ground motion attenuation relationships, two datasets in Northeastern Japan from F-net and K-NET is compared. The attenuation characteristics of PGAs, PGVs and PGDs from the two sets show a consistency as a whole, not only of displacement but also velocity and acceleration, not only of small quakes but also strong shocks. The attenuation terms in ground motion prediction and magnitude determination are illustrated respectively. A logical shortcoming is pointed out, motion amplitude at a station cannot be predicted as same as observed amplitude adopted in determining the magnitude, if the attenuation term in motion prediction is really quite different from the calibration function in magnitude determination. Two ways to coordinate the inconsistency in the two procedures are discussed briefly. One is to modify the procedure of magnitude determination by seismologists. The other is to try to replace the attenuation term in prediction equation by the calibration function in determining magnitude. A preliminary result of a case study in Lanzhou region of Western China is presented, which suggests that we should study for a better way to adopt the calibration function in the attenuation relationships rather than a direct replacement.

8. Acknowledgements

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