

Modifying the intensity distribution by assessing the reliability

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Abstract This article presents an application of a procedure to modify the intensity distribution by assessing the reliability. There are two potential possibilities that may influence the intensity distribution: (1) For the interpolation error, we generate a measured grid across the calculation region. When the point to station spacing is <5 km, we consider the results precise; however, some points have less precision because these are farther from the corresponding stations. When the spacing is between 5 and 50 km, we consider the results imprecise and define a reliability factor that correlates with the distance. (2) Some records may have errors that result from local site conditions, equipment problems, or some disturbance such as lightning stroke, which will lead to some grid points having an incorrect intensity. We regress the attenuation relation for sites with abnormal intensities and consider the results to be accurate when the standard deviation (STD) is $<\sigma$ and inaccurate when the STD is $> 2\sigma$. We then define a reliability factor to correlate with STD between σ and 2σ , such that the intensity distribution is in accord with both wave propagation theory and the investigation intensity.

Keywords Reliability · Intensity distribution · Interpolation error · Station error · Wenchuan earthquake · Chi–Chi earthquake

1 Introduction

For rapid emergency response, such as resource dispatch management, information regarding the spatial distribution of seismic intensity is particularly useful, and a near real-time or quick damage assessment in terms of seismic intensity is greatly in demand. One practical way to fulfill this demand is to correlate seismic intensity with peak ground motions because they can be acquired in near real time via a rapid reporting system (Lind et al. 1996; Yamazaki et al. 1997; David et al. 1999; Kanamori 1993; Ma et al. 2003; Jin et al. 2008; Wei et al. 2010).

On May 12, 2008, the large magnitude Wenchuan earthquake struck the densely populated Sichuan Province of China (31.0°N, 103.4°E). More than 80,000 people were killed, ~370,000 people were injured, and economic losses have been estimated to be in excess of 800 billion RMB. The large moment magnitude (M_w 7.9) (Hao et al. 2009; Shen Sun et al. 2009; Xu et al. 2009; Zhang et al. 2009) of the event attests to it being a great intercontinental earthquake. The Wenchuan earthquake occurred on the Longmen Shan fault zone, which delineates the eastern margin of the Tibet Plateau. Located on the western circum-Pacific seismic belt, Taiwan is situated in the collision zone between the Philippine Sea plate (PSP) and the Eurasian plate (EP). As a result, seismicity in Taiwan is considerably high, as demonstrated by the catastrophic 1999 Jiji (Chi–Chi) earthquake. For rapid reporting of felt earthquakes within Taiwan, a real-time strong motion network, the Taiwan Rapid Earthquake Information Release System (TREIRS), has been operated by the Central Weather Bureau (CWB) since 1997 (Shin and Teng 2001; Wang et al. 2005). In addition to routine magnitude and hypocenter determinations following a felt earthquake, peak ground motions recorded by the TREIRS system are used to generate seismic intensity.

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In this paper, we use the records from the Wenchuan and Jiji (Chi–Chi) earthquakes to simulate the progress of rapid reporting of seismic intensity. After mesh generation in the calculation region, we apply the interpolation method to calculate the peak ground acceleration (PGA) for each grid. In accordance with the intensity scale, we transform the PGA to intensity. However, owing to some problems, following the analysis of the intensity distribution, we present a reliability index to modify the intensity distribution.

2 PGA and intensity

In general, PGA is calculated in the reporting system of seismic intensity; however, estimating the intensity from PGA is a complex academic problem. Therefore, in this paper, we analyze the relation between intensity and PGA, which are given on the Chinese seismic intensity scale (GB/T 17742-2008). The relation can be written as

$$I = a \ln A_m + b, \tag{1}$$

where A_m is the PGA, I is the intensity, and a and b are the regressed coefficients.

Figure 1 shows the relation between A_m and I . In the areas below $I = IV$, PGAs corresponding to intensity are not given, and the regression is shown as a dash–dot line. Based on this result, we can directly calculate the intensity from PGA.

3 The intensity distribution

In this study, we divide the calculated regions into 16,416 grids with a grid spacing of 0.02° and 21,091 grids with a grid spacing of 0.05° for the Jiji (Chi–Chi) and Wenchuan earthquakes, respectively. From the catalog, 379 records distributed across the whole of Taiwan have been selected for the Chi–Chi earthquake (Fig. 2b), and 87 records have been selected from the Wenchuan earthquake, including all stations in Sichuan Province and additional stations in Gansu and Shanxi provinces (Fig. 2a).

Peak ground acceleration and peak ground velocity (PGV) grid points are calculated by an interpolation methodology as shown in Fig. 3 (Wei et al. 2010; Zhang 2008). In this interpolation methodology, the weighted is refined as the inverse square of the distance, as follows:

$$\begin{cases} W_a = \frac{\left(\frac{1}{\Delta_{ad}}\right)^2}{\left(\frac{1}{\Delta_{ad}}\right)^2 + \left(\frac{1}{\Delta_{bd}}\right)^2 + \left(\frac{1}{\Delta_{cd}}\right)^2} \\ W_b = \frac{\left(\frac{1}{\Delta_{bd}}\right)^2}{\left(\frac{1}{\Delta_{ad}}\right)^2 + \left(\frac{1}{\Delta_{bd}}\right)^2 + \left(\frac{1}{\Delta_{cd}}\right)^2} \\ W_c = \frac{\left(\frac{1}{\Delta_{cd}}\right)^2}{\left(\frac{1}{\Delta_{ad}}\right)^2 + \left(\frac{1}{\Delta_{bd}}\right)^2 + \left(\frac{1}{\Delta_{cd}}\right)^2} \end{cases} \tag{2}$$

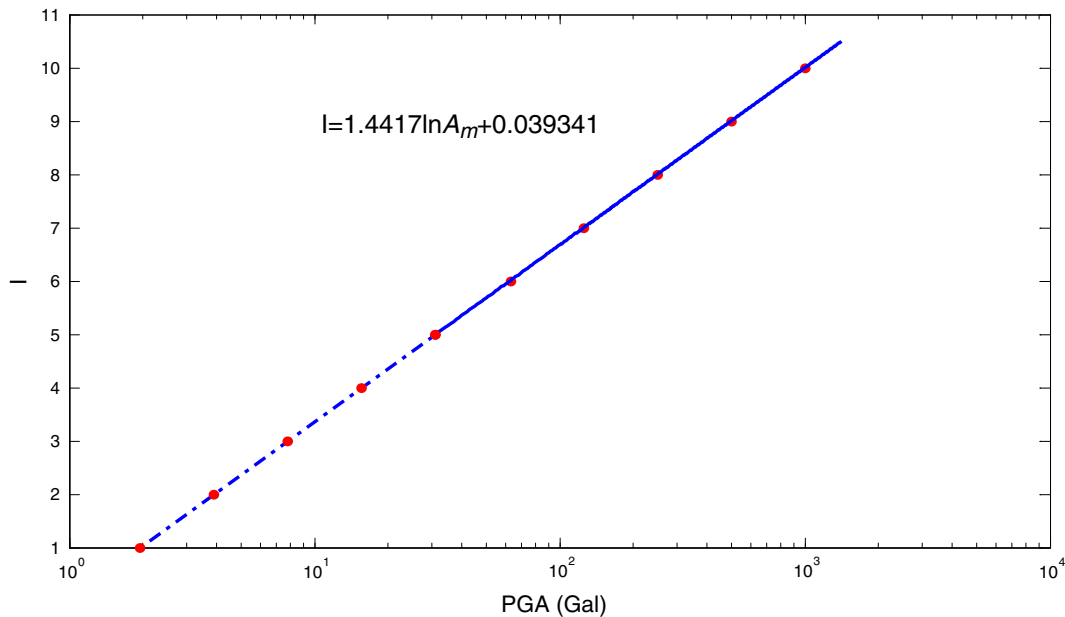


Fig. 1 The relation between A_m and I . The PGA corresponding to intensity could be calculated by the relation if $I < IV$

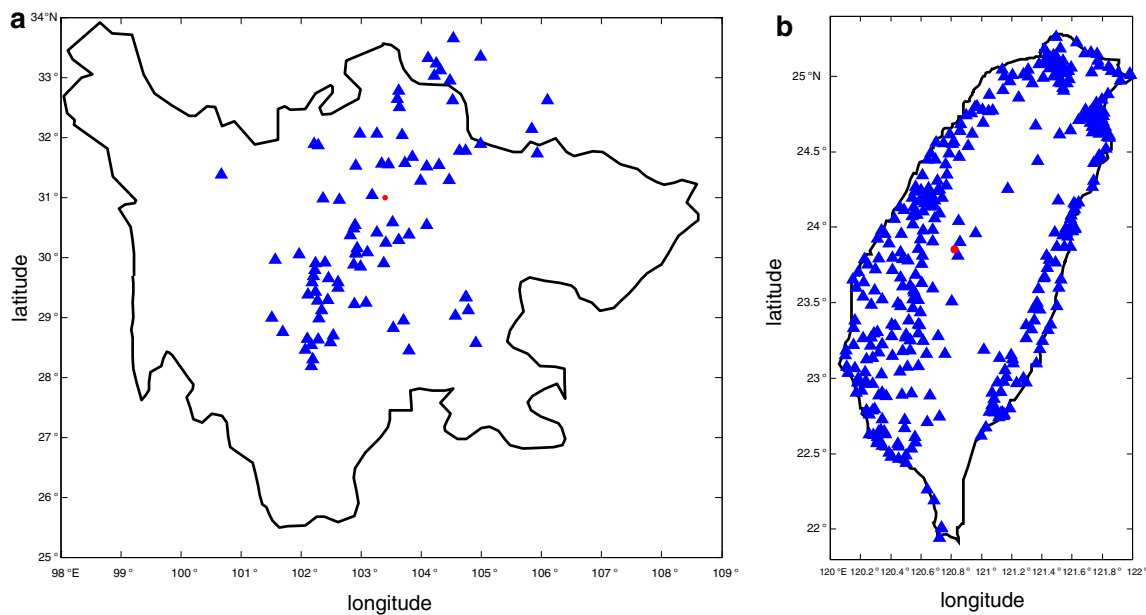


Fig. 2 Distributions of epicenters (circle) and recording stations (triangle) for Wenchuan (a) and Jiji (Chi-Chi) (b) earthquake

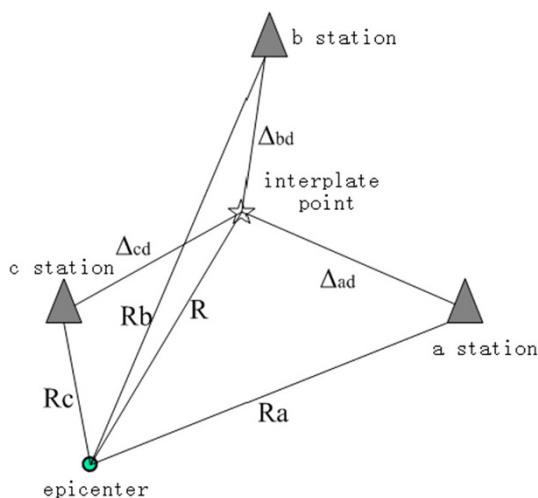


Fig. 3 Sketch of relation between station, interpolate points, and epicenter

The methodology can be written as follows:

$$A(R) = W_a A_a f(R, R_a) + W_b A_b f(R, R_b) + W_c A_c f(R, R_c) \tag{3}$$

where W_a, W_b, W_c is the weighted, A_a, A_b, A_c is the PGA of $a, b,$ and c stations, and $f(R, R_a), f(R, R_b), f(R, R_c)$ is the coefficient of attenuation relations.

By transforming PGA or PGV at each grid point into intensity, we can generate an intensity contour (Fig. 4).

Figure 4 depicts the spatial distribution of intensity for the calculated region. In general, the spatial distribution of intensity is closely related to station distribution, the

quality of the records, or site conditions. Two notable abnormal regions are observed in the intensity distribution. This may be due to a limited distribution of stations in these regions, so we could interpret that the interpolation precision is related to the distance from the stations to the grid points. Alternatively, local site conditions may influence PGA. Some grid points are controlled by abnormal PGA, for example, Fig. 5 showing three records, where the PGAs are higher contrast to some records with a closer epicentral distance; therefore, the region must be showing abnormal intensities. These two reasons lead to abnormal intensity estimates; therefore, we present a methodology to modify the intensity distribution by assessing the reliability.

4 Reliability assessments

4.1 Reliability of the attenuation relation of PGA

The most commonly used attenuation model in China that is recommended for *Evaluation of Seismic Safety for Engineering Sites* (GB17741-2005) is

$$\log Y = C_1 + C_2 M + C_3 M^2 + C_4 \log(R + R_0(M)) + C_7 R + \sigma, \tag{4}$$

where Y is the peak ground motion or response spectrum at a variable period; C_i ($i = 1, 2, \dots, 7$) is the regression coefficient; M is the local magnitude; R is the fault distance, which can be written as D ; $R_0(M) = C_5 \exp(C_6 M)$ is a

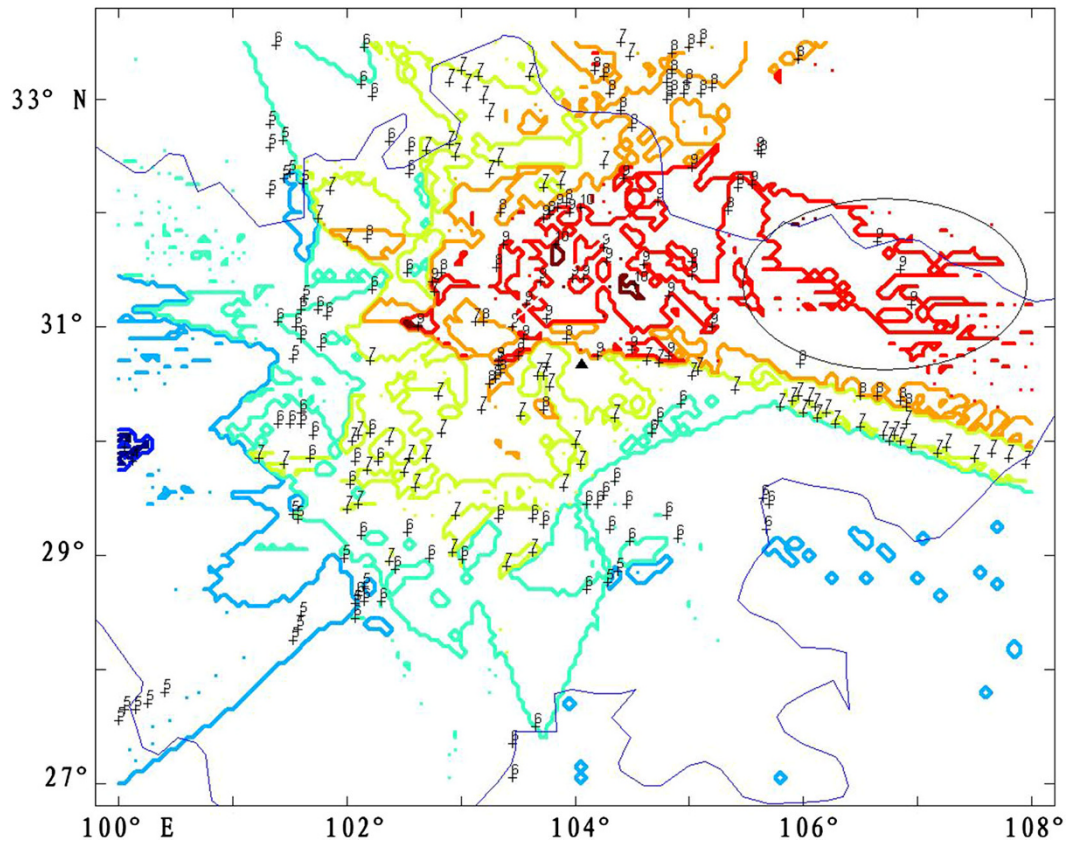


Fig. 4 Intensity distribution map. The notable abnormal regions are observed in the intensity distribution. This may be due to station distribution, the quality of the records, or site conditions

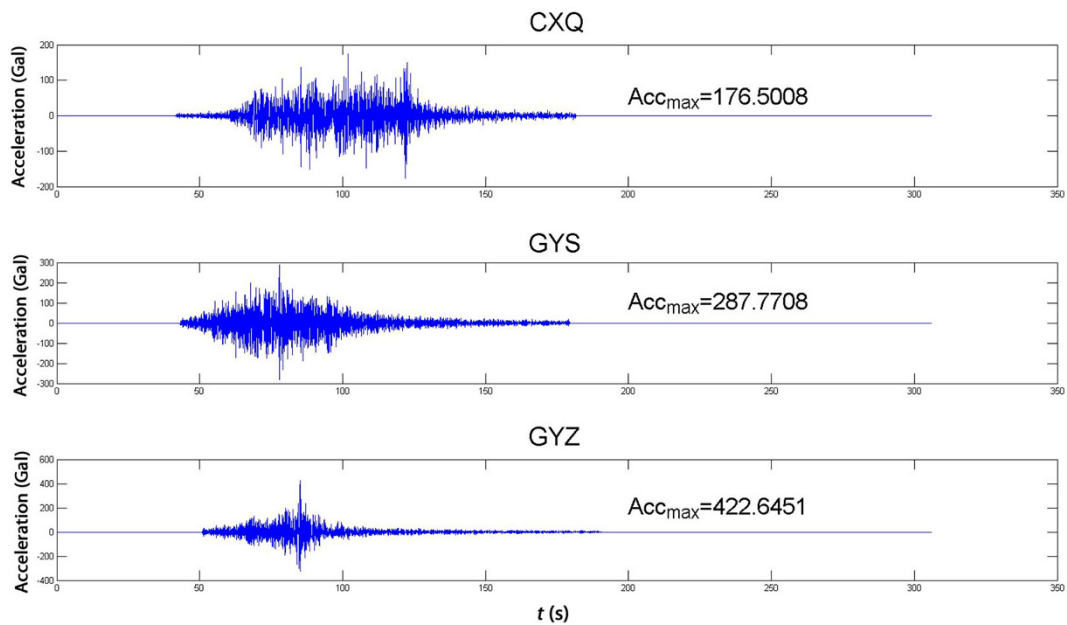


Fig. 5 Stations with abnormal PGA. The PGAs are higher contrast to some records with a closer epicentral distance; therefore, the region must be showing abnormal intensities

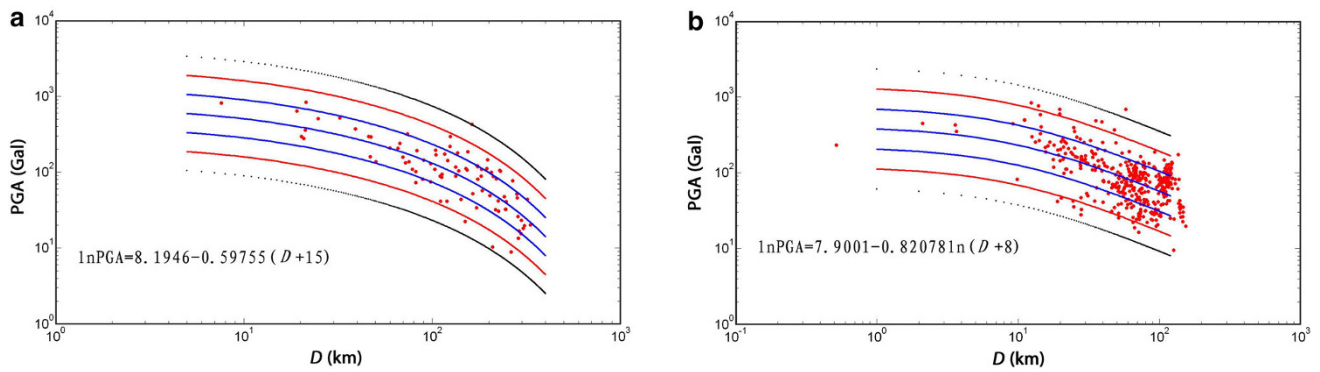


Fig. 6 PGA regression results. **a** Wenchuan earthquake; **b** Jiji (Chi–Chi) earthquake. The area between black lines is defined as 3σ ; the area between red lines is defined as 2σ ; the area between blue lines is defined as σ

saturation factor that has a correlation with the earthquake intensity. In general, $R_0(M)$ is the hypocentral depth and σ is the random variable. The $C_2M + C_3M^2$ is a constant if the attenuation is response to particular earthquake. In general, the coefficient C_7R is very small, which shows that the coefficient C_7 has less relation to Y ; therefore, we remove C_7R , so that Eq. (3) can be written as

$$\log Y = C_1 + C_2 \log(D + 10) + \sigma \tag{5}$$

Table 1 Attenuation relation

Earthquake		C_1	C_2	σ
Wenchuan	PGA	8.1946	-0.59755	0.51101
Jiji (Chi–Chi)	PGA	7.9001	-0.82078	0.60696

Figure 6 and Table 1 shows the regression results and the standard deviation (STD) of PGA. We generally accept the PGA when the $STD < \sigma$ and assume that stations with $STD > 2\sigma$ are not valid; thus, the PGA reliability can be refined as

$$P(A_m) = \begin{cases} 0 & \eta_A \geq 2\sigma_A \\ \frac{2\sigma_A - \eta_A}{\sigma_A} & \sigma_A \leq \eta_A < 2\sigma_A \\ 1 & \eta_A < \sigma_A \end{cases} \tag{6}$$

where η is residuals between observation and the attenuation relation, σ is the STD, $P(A_m)$ is the PGA reliability, and the modifying methodology can be written as:

$$A'_m(x, y|A_m) = P(A_m)A_m + [1 - P(A_m)]\bar{A} \tag{7}$$

where A_m is the observation PGA, \bar{A} is the calculated PGA by the attenuation relation.

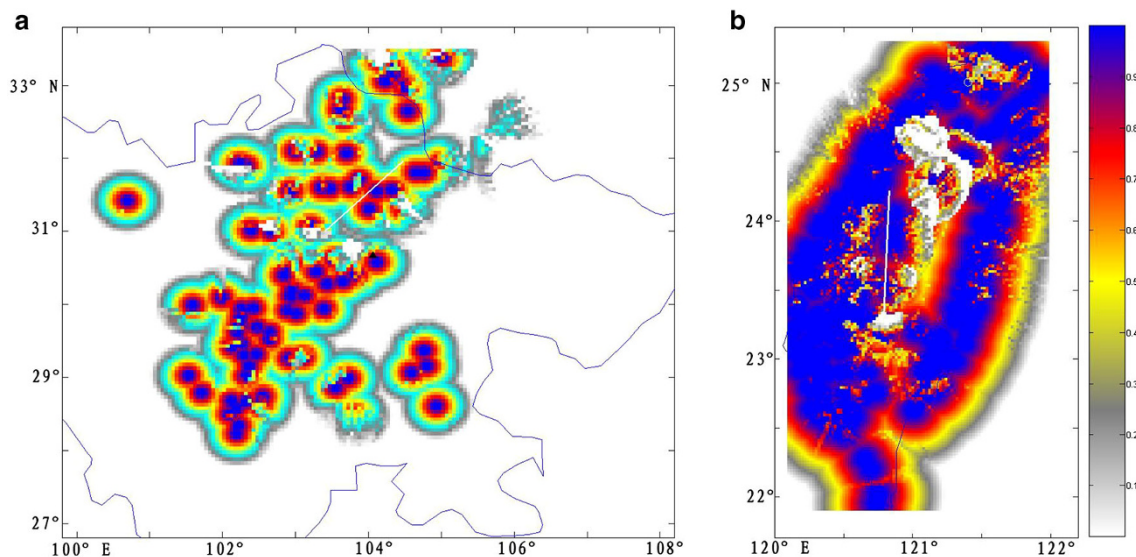


Fig. 7 Distribution of synthetic reliability. **a** Wenchuan earthquake; **b** Jiji (Chi–Chi) earthquake. The error regions of previous intensity distribution have a very low reliability, so these errors could be modified

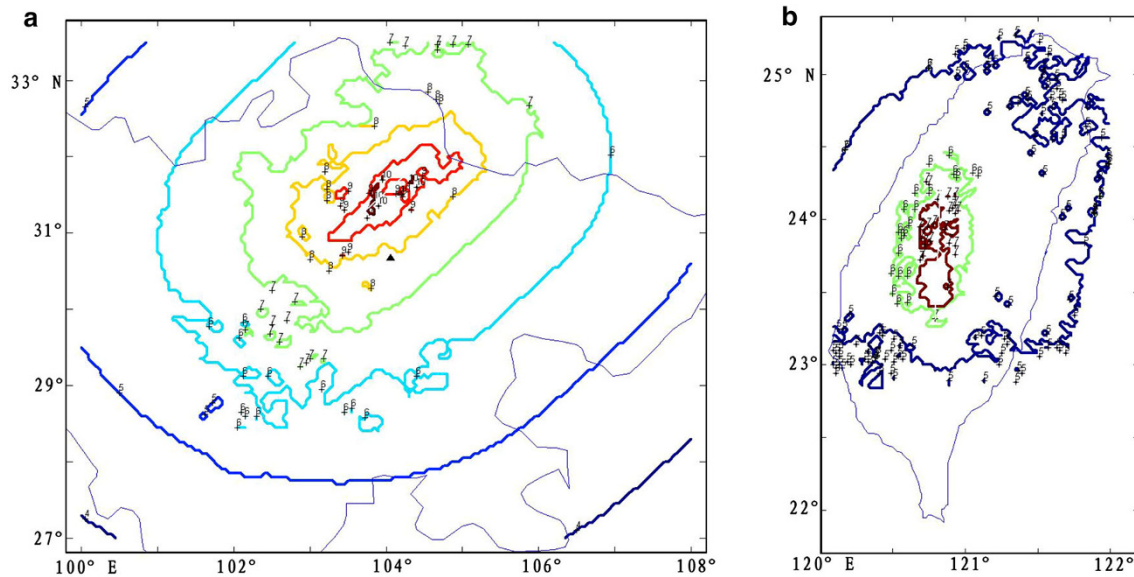


Fig. 8 Modified intensity distribution for the study areas. **a** Wenchuan earthquake; **b** Jiji (Chi-Chi) earthquake. There are some differences between Figs. 3 and 8, and some grid points with greater separation are modified

4.2 Reliability of the interpolation distance

We use an interpolation method of inverse weighted square distance, presented by Jin and Zhang, where the interpolation precision is related to the interpolation distance. This method is very accurate when the distance from point to the station is <5 km (R_{\min}). However, if the distance from point to the station is >50 km (R_{\max}), the method is inaccurate and these grid points will be calculated by the attenuation relation, and we define a reliability index with which the distance correlates, when the distance is between 5 and 50 km. The reliability $P(R)$ of interpolation distance can be refined as:

$$P(R) = \begin{cases} 1 & R \leq R_{\min} \\ 1 - \frac{R - R_{\min}}{R_{\max} - R_{\min}} & R_{\min} < R \leq R_{\max} \\ 0 & R > R_{\max} \end{cases} \quad (8)$$

The modifying intensity distribution can be written as:

$$A'_m = P(R)A_m + [1 - P(R)]\bar{A}, \quad (9)$$

where A'_m is the modified PGA, A_m is the unmodified PGA, and \bar{A} is calculated by the attenuation.

4.3 Modifying method of the synthetic reliability

The synthetical reliability can be refined as:

$$P_s = P(R) * P(A_m). \quad (10)$$

Figure 7 depicts the spatial distributions of the synthetic reliability; we find that the error regions of previous intensity distribution have a very low reliability, so we confirm that this method could be used to

modify the errors. The modifying method can be written as:

$$A'_m = P_s A_m + (1 - P_s) \bar{A} \quad (11)$$

where A'_m is the modified PGA, A_m is the unmodified PGA, and \bar{A} is calculated by the attenuation P_s is the synthetic reliability.

5 Results

Figure 8 shows the modified intensity distribution, which can be differentiated from Fig. 3 by the absence of regions with abnormal intensities, and the grid points in these regions are calculated by the attenuation relation. This methodology mainly modifies the points with greater separation between station and points, with the aid of which the results accord not only with the theory of the wave propagation, but also with the investigation intensity.

6 Discussion and conclusions

We analyze the intensity distribution of the Wenchuan and Jiji (Chi-Chi) earthquakes. We found that some interpolation errors and abnormal stations influence the intensity distribution. First, we find that some stations with an abnormal PGA have affects on the intensity distribution and introduce the reliability of PGA, refining the PGA reliability as STD, which are calculated by the attenuation relation. We then introduce the interpolation reliability; however, some researchers suggest that the interpolation

methodology has only high precision if the distance is less than 5 km, but gives large errors when the distances are greater than 50 km. So we adopt the PGA attenuation relation to modify some error grid points in the intensity distribution. The modified results are in accord with wave propagation theory and also meet the investigation intensity. All of these tasks can be completed in 2 min; thus, this methodology can be applied to the rapidly reporting system of seismic intensity.

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