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Early estimate of epicenter seismic intensities according to co-seismic deformation

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Resumen

Para un sismo, el desplazamiento cosísmico absoluto de la falla puede calcularse con base de la localización, la profundidad focal, el mecanismo focal y la magnitud. Así, en base a informaciones provenientes de estaciones remotas, es posible estimar el desplazamiento cosísmico e inferir la correspondiente distribución de intensidades sísmicas. Se presenta el ejemplo del sismo de Wenchuan de 2008, M8.0, y se determina exitosamente la distribución de intensidades utilizando los desplazamientos cosísmicos más un modelo de velocidades. Una evaluación preliminar de intensidades es indispensable para efectos de un diagnóstico temprano del desastre y de una respuesta emergente efectiva en caso de un sismo destructor como el de 2008 en Wenchuan, China.

Palabras clave: Sismo de Wenchuan M8.0, deformación cosísmica, desplazamiento absoluto, intensidad sísmica.

Abstract

The absolute fault displacement in co-seismic deformation is derived assuming that location, depth, faulting mechanism and magnitude of the earthquake are known. The 2008 Wenchuan earthquake (M8.0) is used as an example to determine the distribution of seismic intensities using absolute displacement and a crustal model. We find that an early prediction of the distribution of seismic intensities after a large earthquake may be performed from the estimated absolute co-seismic displacements using known information from distant stations. Early information on intensities may be vital in disaster evaluation and emergency response after a disastrous event, such as the 2008 Wenchuan earthquake in China.

Key words: Wenchuan M8.0 earthquake, co-seismic deformation, absolute displacement, seismic intensity.

Introduction

On 12 May 2008 at 14:28 local time, an earthquake of magnitude 8.0 struck Wenchuan County in Sichuan province, China. It was one of the most severely damaging and most disastrous earthquakes in the history of the People's Republic of China (Mei, 1982), and the most challenging one in terms of rescue operations and severity of nationwide effects. It was felt over the entire country except in Heilongjiang, Jilin and Xinjiang provinces. Damage extended over six provinces. Casualities included 69,227 dead and 17,923 missing, and the direct economic losses in Sichuan Province exceeded 845.1 billion RMB or about 66% of the GDP of Sichuan Province in 2007 (Scientific research report of Wenchuan 8.0 earthquake, see Monitoring and Prediction division, 2009).

Early emergency response following huge seismic disasters such as the Wenchuan earthquake requires a first estimation of the rupture geometry in the hypocentral area. This is the primary responsibility of the seismologist, and it represents an important part of his functions in society. Muramatsu (1969) proposed the concept of maximum amplitudes of displacements, velocities and accelerations at a set of stations directly expressed in terms of intensities. This constitutes the earliest 'ShakeMap' concept. Because of high density seismological network in Japan, the distribution map of intensities can be produced directly. The regions with strongest ground shaking are reported directly to the government and the public within two or three minutes after an earthquake, even faster than the location, the magnitude or the origin time.

In the 1990's the U.S. ShakeMap system was developed and used in seismic networks. Computer simulation was adapted to obtain improved results of ShakeMap by inserting virtual seismic stations between the actual network stations. ShakeMap has played an important role in early reporting of seismic information and helping to pinpoint the rescue efforts and the emergency response of local and nationwide authorities. The ShakeMap System is being adapted and tested in some regional areas

of China. However, when the stations are far from the epicenter some difficulties may arise in producing an early estimate of the shake area when a point source is assumed in computing the ground shaking. This is largely due to the sparse distribution of seismic stations and the complexity of the geological structure. Here we examine the problem of early estimation of seismic intensity in the case of the Wenchuan, M 8.0 earthquake. Assuming that early information on the location, the depth, and the magnitude of the earthquake is available, and that the crustal model and the fault-plane parameters can be inferred from the known seismicity in the epicenter region and from historical as well as geological information, we compute the absolute co-seismic displacement theoretically (Wang *et al*., 2006). In a second step, we estimate the approximate distribution of seismic intensities from the absolute displacements. This procedure provides a rough first damage estimate which is helpful in making an initial disaster evaluation and establishing a basis for emergency response after a major disaster such as the Wenchuan earthquake.

Location and fault parameters

The parameters of earthquake location are latitude, longitude, depth, magnitude, and origin time. These parameters are rapidly provided by the agency in charge of earthquake location. For the Wenchuan earthquake, the information was as follows: origin time 2008-05-12, 14:28:00.0 (Beijing local time); 31.0°N, 103.4°E, depth 13 km; magnitude Ms=8.0.

The length of the fault rupture was obtained by means at an empirical expression widely used for shallow earthquakes in the Chinese mainland (Wu and Liang, 1983).

$$\log L\,(\mathrm{km}) = 0.51M - (1.78 \pm 0.09) \qquad (1)$$

where L is the rupture length in km and $5.0 \leq M \leq 7.9$ is the Richter surface-wave magnitude. For the Wenchuan earthquake, we obtained $L \approx 250$ km though our magnitude is barely beyond the range of validity of the formula.

The width of the fault rupture may be estimated by several methods. For a preliminary estimate we may use

$$W = h / \sin(dip) \qquad (2)$$

where W is the width of the fault rupture, h is the focal depth and dip is the dip angle of the rupture. For the Wenchuan earthquake we have h = 13 km and assume a dip of about 60 degrees which yields W = 15 km. This agrees with the emergency practice of assuming a width of 15 to 20 km in shallow ruptures with surface breakage. Thus the estimated rupture area is $S = L \times W = 3750$ km^2 for a rectangular rupture plane.

As for the orientation of the fault plane we consider the available tectonic and geological information available for the epicenter area. As an initial guess we use dip = 60° and rake between 30° and 45°. The strike is obtained from regional geological data. The general North-South strike is common in various regions of China. We might also use CMT fault-plane results but this catalogue is not yet available for rapid access after a large earthquake.

For the Longmenshan Fault, on which the Wenchuan earthquake was located (Wang and Meng, 2009), the general strike of the rupture is about N40°E. The dip direction is NW and the dip is generally between 50° to 80°. Thrust faults developed in this area since early Quaternary (An *et al*., 2004). Finally we adopt the following set of fault rupture parameters: strike N40°E, dip 60°NW, and rake 120°. The width of the fault is 15 km and the length of the fault is 250 km.

Crustal model

An estimated model for velocities in the crust may be obtained in several ways. We may adopt the velocity model used by regional seismic networks for routine earthquake location, or we may adopt the global average crust model from IASPEI'91, or from the CRUST 2.0 program, or from recent results of seismic imaging, or from historical seismicity in the general epicenter region, or from recent seismic surveys. The required precision depends on the purpose of the research. For purposes of early emergency response a rapid evaluation is prioritary as long as the error falls within a reasonable range.

In the present case we used the Crust 2.0 model, which yields V_p=3.47km/s; V_s=3.76km/s; ρ = 2950kg/m^3. In calculation, we used such a uniform half-infinite space model.

Fault slip dislocation

The fault slip dislocation, or fault slip distance, is related to moment, magnitude, fault rupture area, and rigidity as:

$$M_0 = \mu S\bar{D} = 10^{(1.5*\mathrm{Ms}+9.1)} \qquad (3)$$

where M_0 is the seismic moment, $\bar{D}$ is the average slip location, μ is the rigidity and S is the rupture area (Bormann, 2002). For calculating μ, the formula may be used as below:

$$\mu = \rho V_s^2 \qquad (4)$$

where V_s is the shear-wave velocity and ρ is the rock density. In the present example we find $\mu \approx 42$ GPa.

Using the expression (3) and (4), the average slip location of the Wenchuan earthquake is $\bar{D} \approx 6.0$ m.

Co-seismic deformation and intensity transform

Calculations tend to agree with field data in suggesting that the distribution of surface co-seismic displacements is consistent with the seismic intensities of the earthquake (Zhang *et al*., 2008). Therefore it is reasonable to estimate seismic intensities by the co-seismic displacements. Here we adopt a code to compute co-seismic deformations developed by Wang *et al*. (2006); (see Zhang *et al*., 2007). We build a fault slip model using the above parameters for the Longmenshan Fault (An *et al*., 2004). Bassed on this model (Table 1), the vectorial co-seismic displacement of Wenchuan M 8.0 earthquake can be estimated as already mentioned.

The absolute values of the synthetic displacements *Ux, Uy, Uz* are designated as "absolute co-seismic displacements". We take the modulus of the co-seismic displacements as the factors to be used for transforming co-seismic displacements to seismic intensity. Fig. 1 shows the results for the absolute co-seismic displacements. These values were obtained from Eq. (4) as a function of the length of rupture *L*. We now introduce a relationship between Richter-magnitude and Mercalli intensity (http://en.wikipedia.org/wiki/Richter_magnitude_scale). Thus we transform the modulus of co-seismic displacement to seismic intensity at the epicenter (Table 2). According to Table 2, Fig. 1 may be transformed into a map of intensity distribution (Fig. 2).

Table 1

The parameters of the slip model

Length /km	Width /km	Strike /deg	Dip /deg	Rake /deg	Location of epicenter $\phi(N)$ $\lambda(E)$ h(km)	Average slip /m
250	15	220	60	120	30.4° 103.6° 12 (CENC)	6.0

Table 2

The comparison of magnitude, fault slip, absolute co-seismic displacement and Mercalli intensity scale

M	Displacement/m	Intensity/°
>8.5	≥15	XII
8.5~7.9	(15~5.5]	XI+~XI
7.8~7.2	(5.5~1.3]	X+~X
7.1~6.5	(1.3~0.30]	IX+~IX
6.4~5.9	(0.30~0.065]	VIII+~VIII
5.8~5.2	(0.065~0.011]	VII+~VII
5.1~4.5	(0.011~0.0015]	VI+~VI
4.4~3.9	(0.0015~0.0003]	V+~V
3.9~3.2	(0.0003~5.0e-5]	IV+~IV
3.2~2.5	(5.0e-5~1.0e-5]	III+~III
2.4~1.9	(1.0e-5~1.3e-6]	II+~II
<1.8	<1.3e-6	I

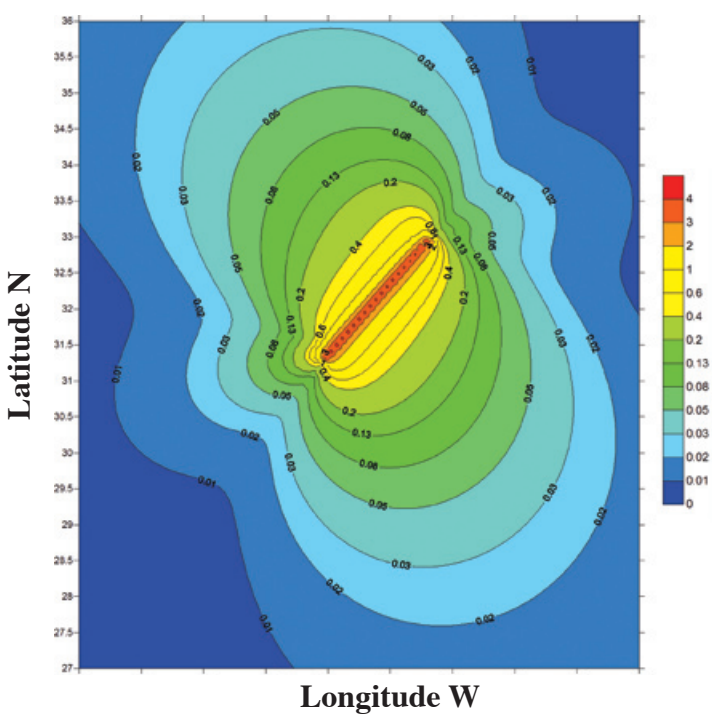

Fig. 1. The distribution of the absolute co-seismic displacement, in meters, calculated according to the assumed slip model.

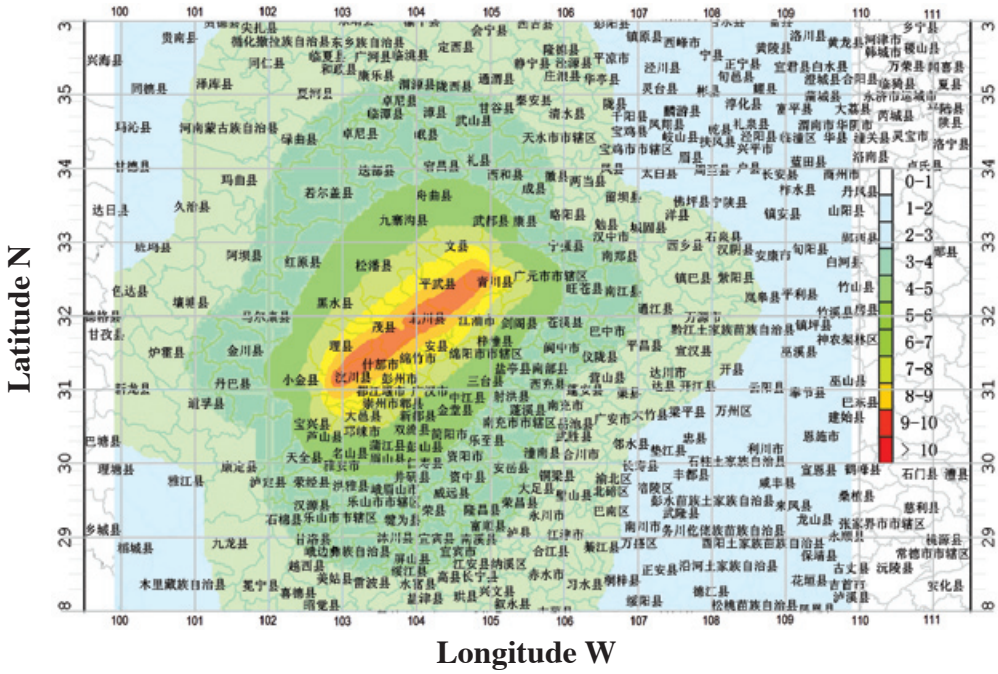

Fig.2 Distribution of intensities obtained from by absolute co-seismic displacement. The background map comprises GIS data of county-level cities and towns.

Here we summarize the methodology followed and the results obtained for our case study.

After an earthquake occurrs, the location and the magnitude M are soon determined and calculated respectively. Thus, the fault length L, width W, the rigidity coefficient μ and the moment M_0 can be inferred according to the formulas (1), (2), (3) and (4). The average slip $\overline{D}$ is calculated by formula (4).

Once the average slip location $\overline{D}$ we obtained, str_$\overline{D}$ (slip along strike) and dip_ $\overline{D}$ (along dip direction) can be calculated because strike, dip and rake angle are can be obtained from information of an earthquake that already occurred, by means of historical geological investigation or CMT results. Then, we can use Wang's Code for calculating co-seismic deformation to obtain the deformation field of Ux, Uy, Uz at different point. The absolute displacement is the modulus of $\sqrt{U_x^2+U_y^2+U_z^2}$. That is,

$$|\overline{D}| = \sqrt{U_x^2+U_y^2+U_z^2} \qquad (5)$$

Figure 1 shows the distribution of $|\overline{D}|$. Although fault slip seems to be a 2 dimension problem when we transform average slip $\overline{D}$ into strike_$\overline{D}$ and dip_$\overline{D}$, the deformation field caused by fault slip assumes 3 dimensions.

The relationship among magnitude M, the fault length L, and absolute displacement $|\overline{D}|$ is based in the following empiric relationship between magnitude M and Intensity I_0,

$$I_0 = 1.5M - 3.5\log h + 3.0 \qquad \text{(Shebalin, 1978)} \qquad (6)$$

where, h is depth of seismic focus. I_0 is epicenter intensity.

For example, when we say that intensity is between X and X$^+$, it is meant that the ranges on the intensity map represent all values of I_0 up to I_0+1. For instance a value of 10 (or X) on the map represents everything equal to or greater to 10 and less than 11.

At I_0=10 (M_1=7.58) the average slip $\overline{D}$ is $\overline{D}_1$, corresponds to an absolute displacement $|\overline{D}| = \sqrt{U_{x1}^2+U_{y1}^2+U_{z1}^2}$;

At I_0=XI (M_2=8.18) the average slip $\overline{D}$ is $\overline{D}_2$, corresponds to an absolute displacement $|\overline{D}| = \sqrt{U_{x2}^2+U_{y2}^2+U_{z2}^2}$;

When $\overline{D}_1 \le \overline{D} \le \overline{D}_2$, intensity X corresponds to an absolute displacement[$\overline{D}_1$, $\overline{D}_2$]. According to this calculation, we obtained Table 2.

When plotting Fig. 2, we interpolated the data into a grid in the range of 100°E—109°E and 27°N—36°N with a curved surface technique such as Kriging. There are a few points with intensities greater that X according to the method of interpolation. The distribution of these points, however, was covered up when plotting the Fig. 2.

According to the Table 2, transforming the displacements in different interval range into different intensity with different color, then we can plot intensity contour by surfer software. With the help of MapInfo software we made a superposition of the geographic information data and intensity contour data. Superposition area should be consistent with that from fig. 1.

Comparing Fig. 2 with the actual intensity map of Wenchuan M8.0 earthquake (Fig. 3), we find that the calculated intensity map is consistent, especially in the epicenter region which is critical. This result suggests that the proposed method provides a good estimate and could be useful in emergency response and estimation of earthquake hazard. For example, we may produce estimates of casualties and losses in the epicentral region with the help of a Geographical Information System. In addition, we may obtain approximate values for the distribution of rupture sizes and we may provide a reasonable theoretical basis for future government and administrative policies of emergency response for the first time.

Discussion

(a) In many cases, for example, in western China, with few seismic stations, it is hard to assess how big the hazard is. In places where there are a few seismometers it may be more effective to use the proposed methodology. The theoretical displacement intensity can provide a measure of the seismic intensity. Field investigations provide an essential check of theoretical co-seismic displacement intensity. A combination of both theoretical and field data will be essential as a basis for seismic intensity zoning, and to improve seismic hazard assessment. A well-conducted evaluation of earthquake hazard in the epicenter area of a disastrous earthquake takes time.

(b) Our proposed co-seismic displacements based method depends on the accuracy of crustal velocity model, fault parameters (strike, dip, rake of fault) and other parameters that involve a great deal of earlier work that can be based in investigations such as of historical seismicity of different faults, CMT data, geological survey information, measurements of fault rupture, distribution of aftershocks, and so on. Thus an early emergency response involves much prior investigation. The use of centroid moment tensor solutions depends on faster access to CMT data. This depends on improving the present methodology.

The co-seismic displacement data in this study is based on the assumption that the same displacement values can be generated by earthquakes of different sizes generated on a 250 km long fault that is 15 km wide. However, the actual fault break of a magnitude 7 earthquake might be only a few dozen kilometers long, yet it could produce a significant displacement in the epicenter area.

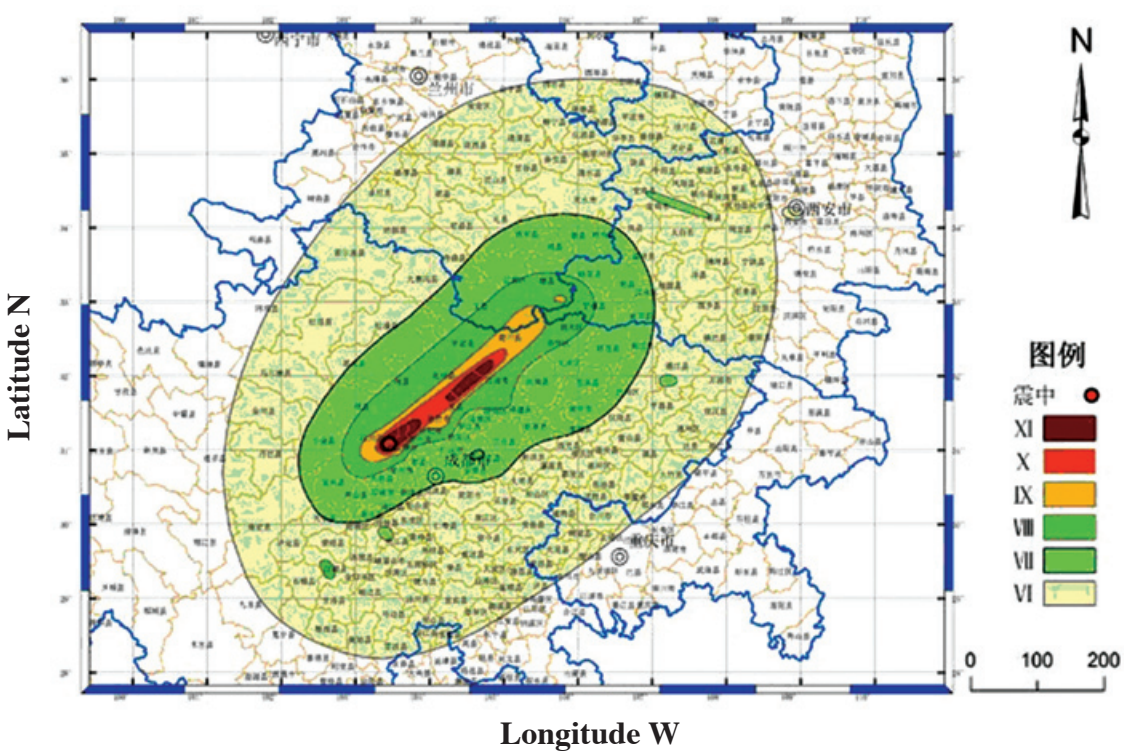

Fig. 3. Seismic Mercalli intensities map of Wenchuan M8 earthquake. WebGIS techniques were used . (see: http://www.cea.gov.cn/manage/html/).

Thus, displacements and intensities should be estimated from the actual fault parameters. The results should be used in a statistical analysis.

Conclusion

We show that the seismic intensity distribution map calculated from absolute co-seismic displacements is consistent with the real seismic intensity map. Consistency is especially good in the epicentral region. The main point of this paper is that the absolute co-seismic displacement can be quickly and automatically calculated with the help of available information: the focal parameters of the earthquake, the crustal model and the fault parameters. The distribution of seismic intensities may be calculated rapidly using the tables reported in this paper based on empirical relationships between the absolute co-seismic displacement and the Mercalli intensity. It is hoped that this contribution will play an important role in early disaster evaluation and formulating policies of emergency response after a disastrous earthquake such as the Wenchuan Earthquake.

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