Soil Dynamics and Earthquake Engineering 57 (2014) 86–93

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Exploring the feasibility of earthquake early warning using records of the 2008 Wenchuan earthquake and its aftershocks

Chaoyong Peng [a,*], Jiansi Yang [a], Bing Xue [b], Xiaoyi Zhu [b], Yang Chen [b]

[a] Institute of Geophysics, China Earthquake Administration, Beijing 100081, China
[b] Institute of Earthquake Science, China Earthquake Administration, Beijing 100036, China

ARTICLE INFO

Article history:
Received 11 March 2013
Received in revised form
18 August 2013
Accepted 18 November 2013
Available online 6 December 2013

Keywords:
Earthquake early warning
Magnitude
Seismic hazard mitigation
Average period
Peak displacement

ABSTRACT

Earthquake early warning system (EEWS) is one of the effective ways to mitigate earthquake damage and can provide few seconds to tens of seconds of advanced warning time of impending ground motions, allowing for mitigation measures to be taken in the short term. After the devastating *Ms*8.0 Wenchuan earthquake, hundreds of M4-6 earthquakes occurred with depth range of 2–24 km. We explore a practical approach to earthquake early warning in Wenchuan area by determining a ground-motion period parameter τ_c and a high-pass filtered vertical displacement amplitude parameter *Pd* from the initial 3 s of the *P* waveforms of these aftershocks with $M \geq 4.0$. The empirical relationships both between τ_c and *M*, and between *Pd* and peak ground velocity PGV for the Wenchuan area are presented. The τ_c result shows that it is systematically greater for slow earthquakes, leading to a possible false alarm. The moment rate function is used to handle the fact that the *Pd* parameter alone miss the $M=8.0$ mainshock. These two relationships can be used to detect the occurrence of a major earthquake and provide onsite warning in the area around the station where onset of strong ground motions is expected within seconds after the arrival of the *P* wave. The robustness of onsite early warning can be increased by using multistation data when the station density is high or by combing τ_c and *Pd* as a single indicator.

1. Introduction

Earthquake early warning system (EEWS) is one of the most effective ways to mitigate earthquake damage, which is able to take full advantage of the existing seismic monitoring network resources. It is used to describe real-time earthquake information that has potential to provide warning prior to significant ground shaking. This is possible by rapidly detecting the energy radiating from an earthquake rupture and estimating the consequent ground shaking that will occur in later time either at the same location or some other locations. It can provide a few seconds to tens of seconds of advanced warning time of impending ground motions, allowing for mitigation measures to be taken in the short term.

The concept has been around for as long as we have had electric communications (Cooper, November 1868), but it is only in the past decades that substantial progress has been made to turn EEW into practical implementation [1–5]. EEW systems, already in operation in several countries around the world, have been using mainly two approaches: regional warning and on-site warning. In the first approach, the traditional seismological method is used to locate an earthquake, and determine the magnitude from stations at close epicentral distances, and estimate the ground motion at other distant sites. This approach has already been used in Japan [6,7], Mexico [2] and Taiwan [8]. In the second approach, the beginning of the ground motion (mainly *P* waves) observed at a site is used to predict the ensuing ground motion (mainly by *S*- and surface waves) at the same site. On-site warning is usually based on individual sensors, while regional warning requires seismic networks. Therefore the regional warning approach is more reliable but requires more time, and cannot be used for the sites at short distances, as is the case for Istanbul. In contrast, the second one is less reliable, but it is very fast and could provide early warning to sites even at very short distances, where an early warning is most necessary. In the second approach, it is necessary to make rapid estimation of the nature of the progressing earthquake or the ground motions at an early stage of its rupture process [9].

After the *Ms*8.0 Wenchuan earthquake on May 12, 2008, hundreds of aftershocks with magnitudes ranging from 4 to 6.5 occurred over a rupture length of about 300 km with focal depths from 2 to 24 km. By 30 September 2008, a total of 265 aftershocks with magnitudes larger than 4.0 occurred according to the Chinese National Seismic Network (CNSN); among them 43 aftershocks were larger than 5.0 and 8 aftershocks, larger than 6.0. The largest aftershock occurred on 5 August with a magnitude 6.5 at a depth of 13 km near the northeastern end of the rupture.

In this paper, we explore the use of the second approach, namely τ_c and *Pd* methods [9–13] for seismic early warning purposes in the Wenchuan Region using the accelerograms from

---

[*] Corresponding author. Tel.: +86 1060212219; fax: +86 1060212337.
E-mail addresses: pcy@geodevice.cn, john_pcyong@sina.com (C. Peng).

0267-7261/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.soildyn.2013.11.005

the strong motion networks operated by China Earthquake Administration. We will determine various regression relations between magnitude and τ_c, and *Pd* and PGV from the Wenchuan earthquake archived dataset, recorded by China Strong Motion Networks Center (CSMNC). The relationships determined in this paper can be used to guide the future implementation of early warning systems in real time.

2. τ_c and Pd method

For an earthquake early warning system, it is important to estimate the size of an earthquake. Wu and Kanamori [14] developed a method to estimate the magnitude of an earthquake from the first few seconds of strong motion records, by extending the method of Nakamura [1] and Allen and Kanamori [15]. In this method, the τ_c parameter, which characterizes the average period of ground motion during the initial t_0 second after the arrival of the *P* wave is calculated by using vertical component records to estimate earthquake magnitude, although the value of magnitude is not directly used for on-site early warning purposes. A high-pass filter is applied to remove the drift of the displacement records after double integration of the accelerograms [16]. Since the relationship involving these parameters depends on the specific filter used, it is important to use the same filter consistently [17]. For a complete presentation of the methods, see also Refs. [9,12]. The calculation of τ_c is given by the following equation:

$$\tau_c = 2\pi / \sqrt{\int_0^{t0} \dot{u}^2(t)dt \Big/ \int_0^{t0} u^2(t)dt} \tag{1}$$

where τ_c is in seconds, $u(t)$ is the high-pass filtered displacement of the vertical component ground motion, and $\dot{u}(t)$ is the velocity differentiated from the displacement $u(t)$.

Another element of EEW is to estimate the strength of shaking at a site from the first few seconds of the *P* wave. Wu and Kanamori [14] showed that the *Pd* parameter, which is the maximum displacement amplitude, can be used to estimate the PGV, and proposed that if *Pd* is equal to or greater than 0.5 cm, the event is most likely damaging. Thus, the magnitude and shaking intensity can be estimated for early warning purposes within 3 s after the *P* wave arrival is detected. If $\tau_c > 1$ s and $Pd > 0.5$ cm, then the potential of a damaging earthquake is quite high [12,18]. They also demonstrated that the combination of the τ_c and *Pd* methods can provide reliable threshold warnings within 10 s after the occurrence of a large earthquake [11,14], depending on the stations density of the seismic network.

Table 1
List of events studied in this paper.

Event date	Time	Long.	Lat.	Depth (km)	M	Number of records
2008/05/12	06:28:01	103.3	31.0	13.0	8.0	4
2008/05/12	07:34:42	103.8	31.3	13.0	5.8	4
2008/05/12	08:21:40	104.3	31.5	11.0	5.5	4
2008/05/12	08:26:12	104.1	31.4	12.0	5.1	3
2008/05/12	09:31:15	103.6	31.2	10.0	5.2	3
2008/05/12	09:42:24	104.1	31.5	14.0	5.3	3
2008/05/12	11:11:01	103.7	31.3	14.0	6.3	4
2008/05/12	17:54:32	103.6	31.3	17.0	5.1	3
2008/05/12	20:45:31	104.6	31.7	20.0	5.2	4
2008/05/12	23:46:18	103.6	31.3	13.0	5.4	3
2008/05/14	02:54:37	103.6	31.3	16.0	5.8	4
2008/05/16	05:25:47	103.4	31.3	14.0	5.9	7
2008/05/16	16:14:42	103.7	31.1	9.0	5.0	4
2008/05/22	07:18:43	103.8	31.2	11.0	4.8	7
2008/05/22	15:00:11	104.6	31.9	12.0	4.1	5
2008/05/23	00:05:05	103.8	31.2	12.0	4.7	5
2008/05/25	04:27:04	104.7	31.9	13.0	4.4	7
2008/05/25	08:21:47	105.5	32.5	14.0	6.4	3
2008/05/25	09:34:07	105.1	33.0	12.0	4.7	12
2008/05/27	08:03:21	105.7	32.8	15.0	5.3	4
2008/05/27	08:37:51	105.7	32.8	15.0	5.7	3
2008/05/27	13:59:33	105.3	32.5	15.0	4.7	3
2008/05/29	04:48:44	105.5	32.6	16.0	4.5	4
2008/05/29	07:10:20	103.7	31.2	13.0	4.4	6
2008/05/31	06:22:42	105.1	32.3	15.0	4.3	3
2008/05/31	07:34:23	105.5	32.7	16.0	4.3	5
2008/06/03	03:09:28	104.6	32.0	18.0	4.7	6
2008/06/05	04:41:05	105.1	32.4	16.0	4.8	6
2008/06/05	06:02:30	105.5	32.7	17.0	4.3	4
2008/06/06	11:03:50	104.0	31.2	19.0	4.4	6
2008/06/07	00:48:10	103.7	31.1	14.0	4.5	4
2008/06/07	06:28:31	105.5	32.5	15.0	4.2	5
2008/06/08	10:51:16	104.5	31.9	15.0	5.0	5
2008/06/09	07:28:36	103.9	31.3	13.0	4.7	9
2008/06/14	02:05:58	103.9	31.2	24.0	4.0	5
2008/06/15	00:11:22	103.8	31.2	15.0	4.7	8
2008/06/17	05:51:41	105.6	32.8	9.0	4.3	4
2008/06/19	02:55:29	103.6	31.2	9.0	4.3	6
2008/06/19	10:25:59	105.6	32.7	10.0	4.4	4
2008/06/19	20:27:45	103.7	31.1	10.0	4.6	6
2008/06/22	21:38:31	105.2	32.3	16.0	4.0	5
2008/06/27	18:20:54	103.5	31.4	13.0	4.5	3
2008/06/27	21:42:09	105.0	32.3	12.0	4.5	4
2008/07/15	09:26:21	104.3	31.5	15.0	4.6	3
2008/07/17	16:40:42	104.3	31.6	17.0	4.7	5
2008/07/23	19:54:42	105.6	32.7	10.0	5.7	7
2008/07/24	05:30:09	105.6	32.8	10.0	4.9	5
2008/07/24	07:09:27	105.6	32.8	10.0	6.0	6
2008/08/01	08:32:41	104.9	32.0	14.0	6.2	15
2008/08/01	18:12:16	105.3	32.4	14.0	5.0	7
2008/08/05	09:49:15	105.6	32.7	13.0	6.5	9
2008/08/07	08:15:34	104.7	32.1	15.0	5.0	10
2008/08/12	21:03:21	104.4	31.8	17.0	4.7	12
2008/09/11	02:53:45	105.2	32.4	12.0	4.7	10

3. Data and analysis

The τ_c and *Pd* methods have been investigated to determine linear relations for the Wenchuan Region between τ_c and *M*, and between *Pd* and PGV parameters [12,18].

We chose the mainshock and 53 aftershocks with magnitudes 4.0 and larger before October 1 for investigation. The sampling rates are 200 samples per second and only some of the portable stations are 250 samples per second. Magnitudes of the selected events were obtained from the network catalogs provided by the China Earthquake Networks Center (CENC). We use the local magnitude M_L [19] in our analysis. For events with M_L larger than 6, however, we replace the magnitude values by their surface wave magnitude, *Ms*, in consideration of the saturation problem of M_L. Both types of magnitudes are simply denoted by *M* in this study.

The key criteria for selecting events were: (a) events of $M \geq 4.0$, (b) focal depth less than 25 km, (c) availability of at least three stations records for each event, (d) within the epicentral distances of less than 50 km, and (e) the PGA values of vertical component record greater than 5 gal. Earthquakes with less than 3 records, including 3 aftershocks with magnitude greater than 6.0, are not included in this analysis. These criteria considerably limited our data, and we had to deal with a small number of events. In total, we used 296 waveforms with good quality for the mainshock and aftershocks in this study (Table 1). The spatial distribution of the events and stations are shown in Fig. 1.

The automatic *P* first arrival picking method described by Allen [20] is used to detect the *P* wave arrival from the vertical record. Since accurate τ_c estimation depends highly on the correct detection of *P* wave arrival [9], we double check the arrival time by visual inspection of the waveforms. For most records automatic timing is precise, but we make manual picks on several records where *P* first arrival cannot be detected by the automatic method