Characteristics of Strong Motion Duration from the Wenchuan M_w 7.9 Earthquake

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SUMMARY:
A great number of free-field strong motion records were obtained during the Wenchuan M_w 7.9 earthquake, which provided valuable data for our study. In this work, we analyze and discuss characteristics of the significant, bracketed and uniform duration of strong motions, records from 120 free-field strong motion stations within 500km to the causative fault are used as database. The regression equations for significant duration D_s, bracketed duration D_b and uniform duration D_u were obtained based on regression analysis and compared with previous empirical relations. It was shown that the observed durations were unusually long compared with other earthquake of similar magnitude. Significant durations D_s (5~75%) and D_s (5~95%) increase with fault distance and can be 2~3 times of former empirical predictions. Significant durations near Qionglai and Liangshan in the backward can be 1.5 times as large as the forward, and durations in the Weihe basin are substantially larger than other region with similar fault distance. Both bracketed duration and uniform duration decrease with fault distance, larger absolute durations (D_b, D_u) are located near along the Beichuan-Yingxiu fault, and durations in the forward near Wenxian and Longnan and in Weihe basin are much larger than backward durations with similar fault distance. Our study showed that the distribution of durations during Wenchuan earthquake exhibited complexity and was influenced under the combined effects of rupture directivity, basin effects and site conditions.

Keywords: strong motion; duration; fault distance; Wenchuan earthquake

1. INTRODUCTION

The M_w 7.9 Wenchuan earthquake struck the western part of Sichuan province in China, on May 12, 2008, with the epicenter close to Yingxiu Town (31.0° N, 103.4° E). The energy radiated by the Wenchuan earthquake was so tremendous that shaking could be felt in most parts of China and was felt as far as Pakistan and Thailand, with the most violent shaking being felt in Sichuan, Gansu and Shanxi Provinces, resulting in unprecedented human casualties and infrastructural damage. High ground motion and serious damage are observed within a narrow belt of the Beichuan-Yingxiu fault (Li *et al*., 2008; Yuan, 2008; Lekkas, 2010; Li *et al*., 2010).

The duration of ground motion play an important role in the response of foundation materials and structures, and it has been shown that the duration can have a significant effect on the inelastic deformation and energy dissipation demands, particularly for short period structures when stiffness and strength degradation is encountered (Mahin, 1980; Bommer et al., 2004). The importance of ground motion duration in geotechnical engineering is universally recognized, and the number of cycles of duration of strong motion is a very important parameter in the assessment of liquefaction potential (Seed and Idriss, 1982; Liu et al., 2001; Hancock and Bommer, 2005). Recorded durations in the M_w 7.9 Wenchuan earthquake are unusually long as shown by previous studies (Wen *et al*., 2010), and this might be one of the important factors that lead to serious damage in the rupture fault region (Li *et al*., 2008; Lu *et al*., 2010; Lekkas, 2010).

The purpose of this paper is to investigate the duration characteristics of strong motions from the M_w7.9 Wenchuan earthquake. The Wenchuan earthquake left behind the first comprehensive set of strong ground motion records from an intra-plate large earthquake in China, which provides us with unusual opportunity to investigate the duration characteristics of strong motions. This paper focused on the following three indicators of duration: bracketed duration D_b, uniform duration D_u, and significant duration D_s. A total of 120 free-field strong ground motion records in terms of acceleration are used to examine the duration characteristics of strong motions during the Wenchuan earthquake. All 120 strong ground motion stations are located within 500km from the ruptured Beichuan-Yingxiu fault and Guanxian-Jiangyou fault. These records are examined and compared to former empirical relationships. The duration characteristics of vertical ground motions are compared with the horizontal motions, and the effects of site condition and rupture directivity on the bracketed, uniform and significant duration are also studied.

2. DEFINITION OF DURATIONS

A large number of definitions of strong-motion duration have been put forward in the literature, although these can generally be grouped into three generic categories (bracketed, uniform, and significant) and then classified by whether the amplitude or energy thresholds used for their measurement are absolute or relative to the peak value in the recording (Bommer and Martínez-Pereira, 1999; Bommer et al., 2009).

The focus of the present work is on the characteristics of bracketed, uniform, and significant duration of the Wenchuan M_w 7.9 earthquake. Records from 120 free-field stations in terms of acceleration are used as database, with three orthogonal components (EW, NS and UD) at each station, and each component is considered individually and are taken in their 'as-recorded' orientations. We examine the duration characteristics of Wenchuan earthquake in three different definitions.

The first is the significant duration D_s, which is defined as the interval between the times at which different specified values of Arias intensity are reached. The integral of ground acceleration is related to the Arias intensity which is defined using the integral (Arias 1970; Dobry et al., 1978; Trifunac and Brady, 1975)

$$I_A = \frac{\pi}{2g}\int_0^T a^2(t)dt \tag{5.1}$$

where $a(t)$ is the acceleration time history, g is the gravity acceleration and T represents total duration of the time history. Two common measures of significant duration are defined as the time interval between 5~75% and 5~95% of I_A (denoted as D_s(5~75%) and D_s(5~95%), respectively), the former is intended to capture the energy from the body wave whereas the latter includes the full wave train.

The second definition of duration employed is the bracketed duration D_b, which is defined as the interval between the first and the last excursion of a specified threshold (typically 0.05g or 0.1g).

The final definition is the uniform duration D_u, which is defined as the sum of the time intervals during which the acceleration is greater than the threshold (Bommer and Martínez-Pereira, 1999). For the definitions of bracketed and uniform duration, three absolute threshold accelerations 0.100, 0.050 and 0.025 g are used, whence in total six durations D_b(0.100g), D_b(0.050g), D_b(0.025g), D_u(0.100g), D_u(0.050g) and D_u(0.025g) are employed.

3. STRONG MOTION DATA

The Wenchuan earthquake was well recorded by the National Strong Motion Observation Network System in China. The network system obtained the records from 460 stations in 17 province, municipalities and autonomous regions. Over 1,400 components of strong motion records were obtained from the main shock of the Wenchuan earthquake (China Earthquake Administration, 2008; Yu *et al*., 2009; Li *et al*., 2010). Near fault strong ground motions were recorded by the stations in the fault surrounding area including a part of Sichuan, Shanxi and Gansu province.

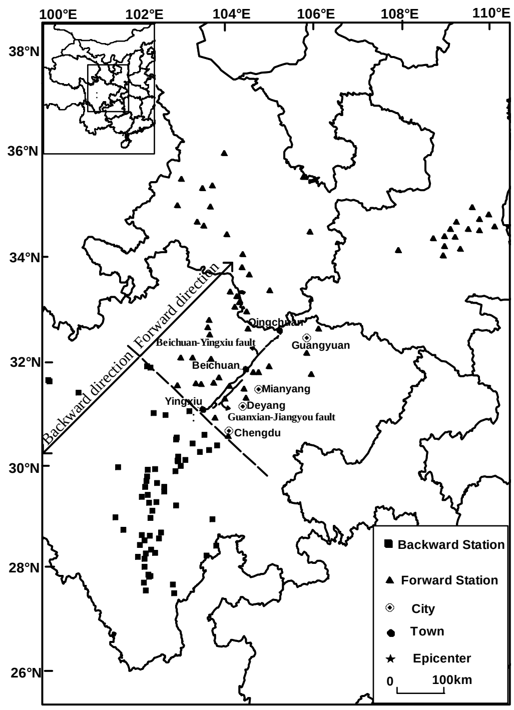


Figure 3.1. Locations of 120 free-field strong motion stations

Within 500 km to the ruptured Beichuan-Yingxiu fault and Guanxian-Jiangyou fault, a large number of strong ground motion observation stations successfully recorded the acceleration time histories during the Wenchuan earthquake. According to the quality of records, these data are classified before the analysis. The incomplete records, those with low signal-to-noise ratio, those with one of three components missing were discarded, and in all, 360 accelerograms from 120 free-field stations are used for analyzing the duration characteristics of strong ground motion. Figure 3.1 shows locations of all 120 strong motion stations together with the two surface ruptures of the Beichuan-Yingxiu fault and Guanxian-Jiangyou fault, and the locations of Yingxiu Town, Beichuan Town, Qingchuan Town, and Chengdu City. Ground motions in the near fault zone are significantly influenced by the rupture mechanism and slip direction relative to the site (Somerville et al. 1997). Forward directivity occurs when a site is located at one end of the fault and the rupture initiates at the other end of the fault and travels towards the site. In order to investigate the effects of forward directivity on duration characteristics, these stations are divided into two groups according to the rupture mechanism of the causative fault: (i) forward station (solid triangles); (ii) backward stations (solid squares).

All strong motion stations were equipped with a three-component, force-balance accelerometer. Most of the digital accelerometers were either an ETNA or a MR2002 with a 18-bit resolution and a 108-db dynamic range. The full scale of the recording system is ± 2g, and the sampling rate was 200 or 500 data per sec. Each recording system was operated in trigger mode with a 20-sec pre-event memory (China Earthquake Administration, 2008). In this study, we generally follow the site classification system adopted in the Chinese code (China Ministry of Construction, 2001). In general, Class I corresponds to rock site or site with less than a few meters of soil, whereas the classification of Classes II, III and IV depends on both shear wave velocity as well as thickness of the soil. Among the selected 120 stations , the station numbers (percentage) are 22 (18.3%), 91 (75.8%), 7 (5.9%) for site class I, II, and III respectively, and none are from site class IV.

4. DISTRIBUTION CHARACTERISTICS OF DURATIONS

The strong motion data recorded in this event make it possible to investigate the distribution of durations in space. Figure 4.1 shows the spatial distribution of significant duration D_s(5~95%) and D_s(5~75%) of strong motions in EW component. It is shown that shorter duration D_s(5~95%) of 20~60s mainly locate near along the narrow rupture fault belt and in the forward directivity region near Wenxian and Longnan, while durations larger than 80s locate in the backward region from Qionglai to Liangshan and Wenhe basin in Shanxi province. It is noted that observed duration D_s(5~95%) near Qionglai in southwest Sichuan basin are 100~120s and are much larger than other region with similar fault distance. The significant duration D_s(5-95%) can be as large as 120s, which is unusually long compared with the 1999 Kocaeli earthquake (between 30 to 40s) with a magnitude of

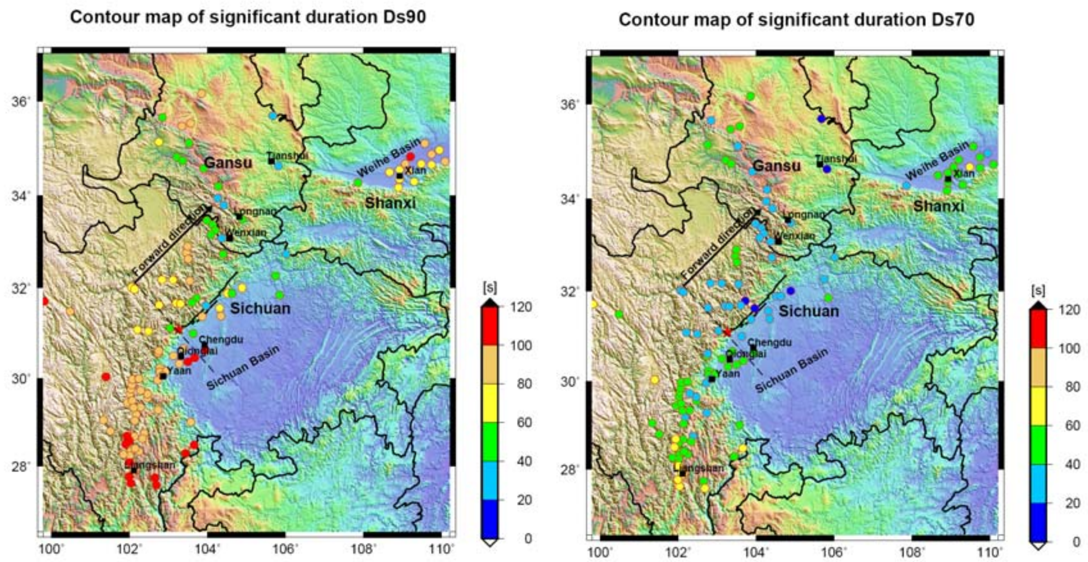


Figure 4.1. Spatial distribution of significant duration D_s(5~95%) and D_s(5~75%) recorded from the M_w7.9 Wenchuan earthquake. The length of significant duration is shown by the colors (scale from 0 to 120s).

M_w=7.4 (Rathje et al., 2000).The largest significant duration D_s(5~75%) is about 80s. Recorded D_s(5~75%) shorter than 40s mainly locate near along the narrow rupture fault belt and in the forward region in Gansu province, and durations larger than 40s mainly locate in the backward region from Qionglai to Liangshan and Wenhe basin in Shanxi province. On the whole, the observed significant duration D_s(5~95%) and D_s(5~75%) are short when close to the causative fault and increase with fault distance. The significant duration is strongly affected by the rupture directivity, recorded durations near Wenxian and Longnan in Gansu province are much smaller than the backward region, this can be explained by energy concentration of ground motion due to forward directivity effect. Recorded durations in Weihe basin are substantially larger than other region with similar fault distance, and this prolonged durations might be correlated with the basin margin effects as shown by Wang (2011), which leads to diffuse scattering and energy dispersing in S-wave.

Figure 4.2 shows the spatial distribution of bracketed duration D_b(0.025g), D_b(0.050g) and D_b(0.100g) of strong motions in EW component. The bracketed duration D_b(0.025g) can be as large as 240s, and most durations larger than 160s locate near along the narrow rupture fault region. It is noted that duration D_b(0.025g) larger than 20s can still be recorded in distant area near Tianshui in Gansu province and Weihe basin in Shanxi province. In Weihe basin, the prolonged bracketed duration may be a result of combined amplification effects of both soil sites and basin margin effects on ground motion as shown by Wang (2011). The bracketed durations decrease with the threshold, the largest

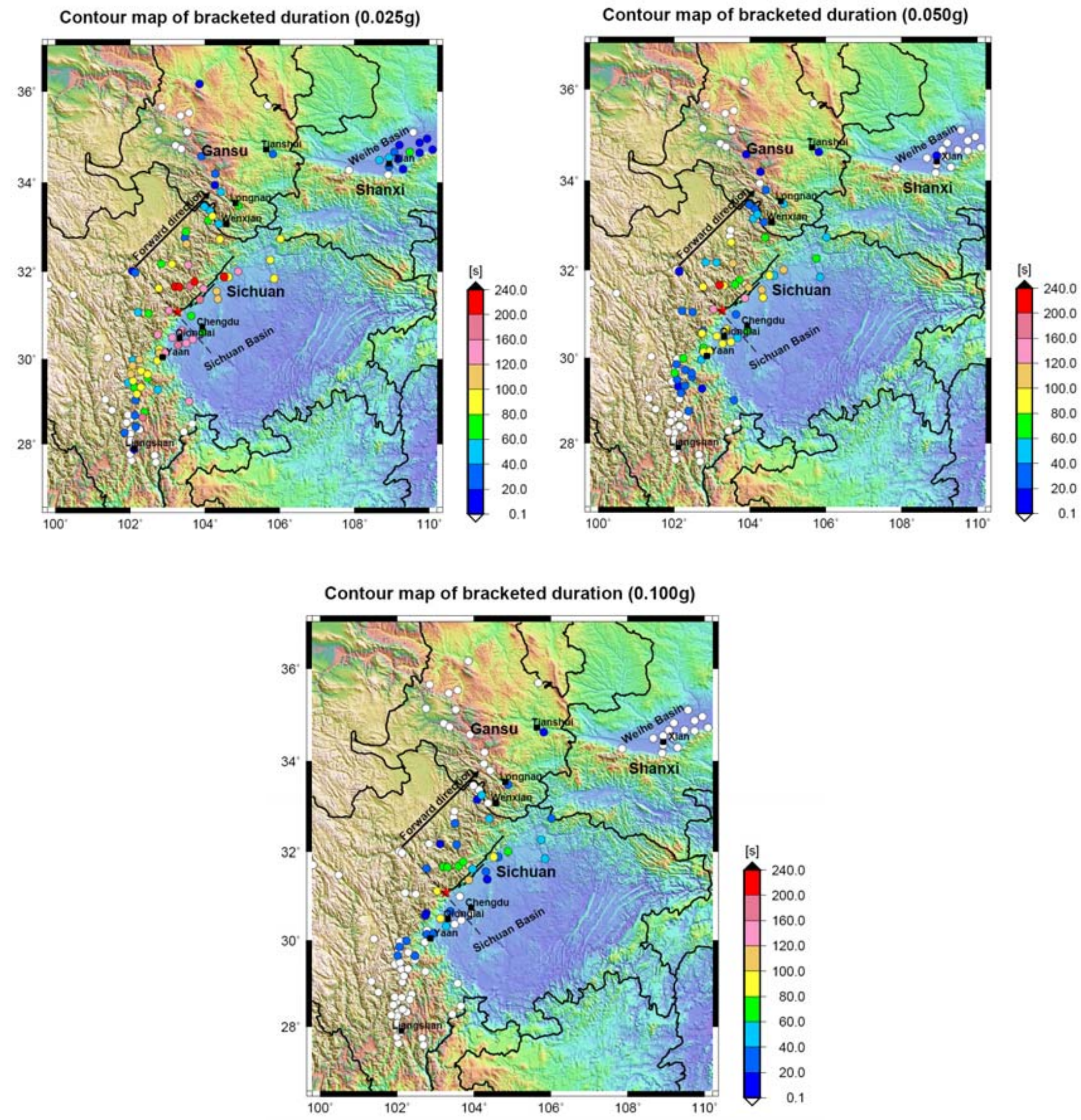


Figure 4.2. Spatial distribution of bracketed duration $D_b(0.025g)$, $D_b(0.050g)$ and $D_b(0.100g)$ recorded from the Mw 7.9 Wenchuan earthquake. The length of bracketed duration is shown by the colors (scale from 0.1 to 240s), durations smaller than 0.1s are considered as zero and are shown in colorless.

duration $D_b(0.050g)$ and $D_b(0.100g)$ are about 200s and 120s, respectively. On the whole, recorded bracketed duration decrease with fault distance and larger durations mainly locate near along the rupture fault, and the distribution of bracketed duration is strongly affected by the rupture directivity, soil sites and basin margin effects.

Figure 4.3 shows the spatial distribution of uniform duration $D_u(0.025g)$, $D_u(0.050g)$ and $D_u(0.100g)$ of strong motions in EW component. It can be seen that nonzero duration $D_u(0.025g)$ larger than 10s can still be recorded near Longnan and Tianshui in Gansu province and in Weihe basin in Shanxi province. For the uniform duration $D_u(0.100g)$, non-zero durations can only be recorded near along the narrow rupture fault region, and the non-zero region is much smaller compared with $D_u(0.025g)$ and $D_u(0.050g)$. The largest uniform duration $D_u(0.025g)$ is about 80s, and the largest uniform duration $D_u(0.050g)$ and $D_u(0.100g)$ are only 50s and 30s, respectively. On the whole, distribution of uniform duration is similar to the bracketed duration, but uniform durations are much smaller than the bracketed durations with same threshold when compared with figure 4.2. The uniform durations decrease with fault distance and larger durations mainly locate near along the Beichuan-Yingxiu fault. Recorded durations near Tianshui in Gansu province and Weihe basin in Shanxi province are larger than the backward with similar distance due to forward directivity and basin effects.

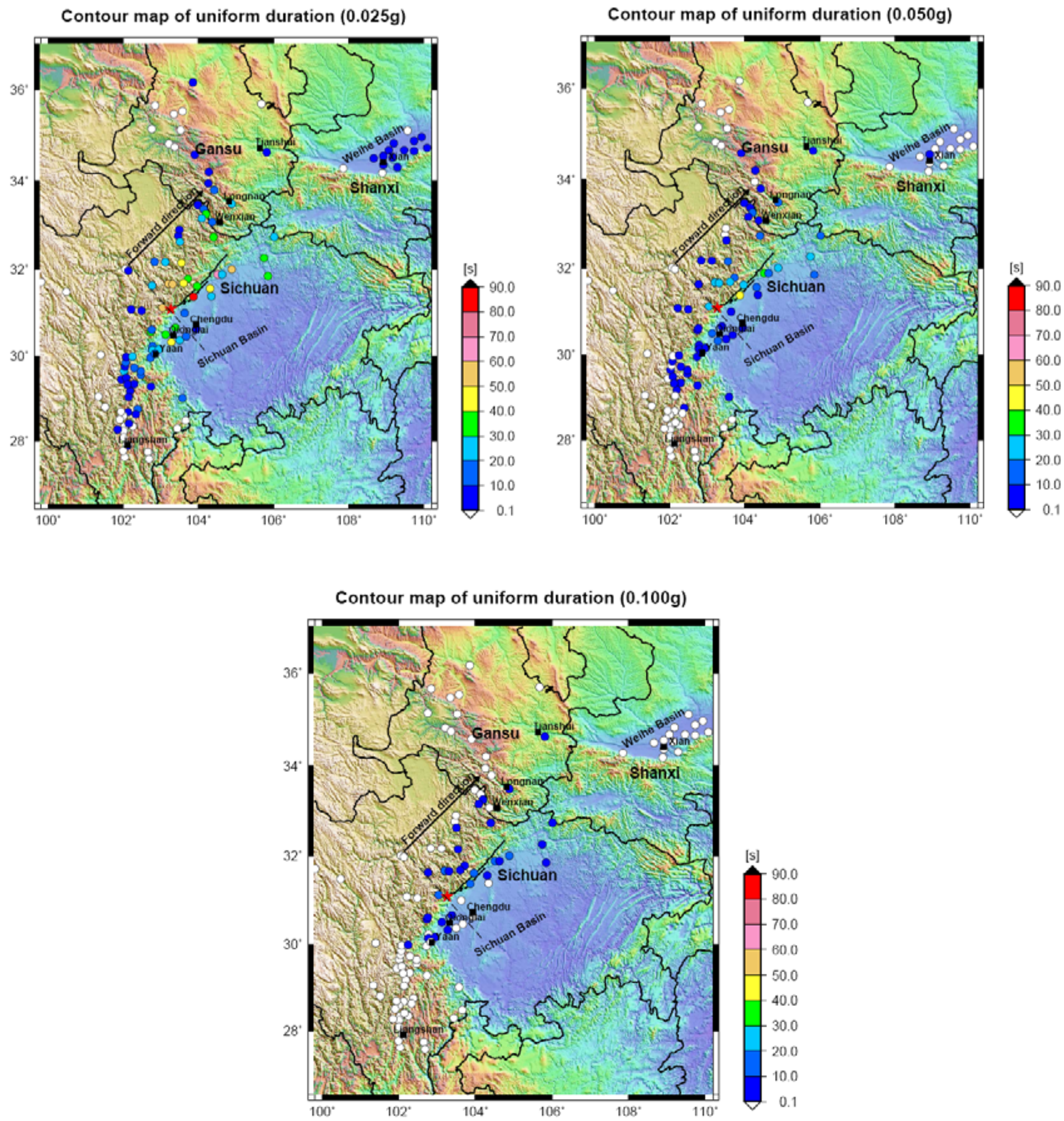


Figure 4.3. Spatial distribution of uniform duration D_u(0.025g), D_u(0.050g) and D_u(0.100g) recorded from the M_w 7.9 Wenchuan earthquake. The length of uniform duration is shown by the colors (scale from 0.1 to 90s), durations smaller than 0.1s are considered as zero and are shown in colorless.

5. VARIATION OF DURATIONS WITH FAULT DISTANCE AND COMPARED WITH PREVIOUS STUDIES

It is obvious from the previous discussions that the duration of ground shaking in the main causative fault area show high variability in space, depending on the distance of the observation station from the fault plane as well as its orientation from the rupture faults. In this section, duration characteristics of ground motion from this earthquake are examined in more details. Figure 5.1 shows the variation of 5~75% and 5~95% significant duration of EW component strong motions with fault distance. It can be seen that the significant duration shows a tendency of increasing with distance at all sites (site class I, II, III). Most of duration D_s(5~75%) fall between 30 and 60 seconds, and most of duration D_s (5~95%) fall between 60 and 120 seconds which is comparatively longer than other earthquakes of similar magnitude. The duration D_s(5~75%) is about 30s within10km to the rupture fault, and the D_s(5~95%) is about 70s. The average D_s(5~95%) can be about 1.5 times of D_s(5~75%) on the whole distance. In figure 5.1, we also compared recorded D_s(5~75%) and D_s(5~95%) at various sites with the predictions by the models of Bommer *et al.* (2009) and Kempton and Stewart (2006) for soil site with V_s = 250m/s. Figure 5.1 also showed the median curve and the median curves with plus one and minus one standard deviation. It was shown that recorded durations do not show any special trend for data either from different site class I, II, and III. Most D_s(5~75%) and D_s(5~95%) recorded during Wenchuan earthquake were much larger than the predictions by Bommer *et al.* (2009) and Kempton and Stewart (2006).

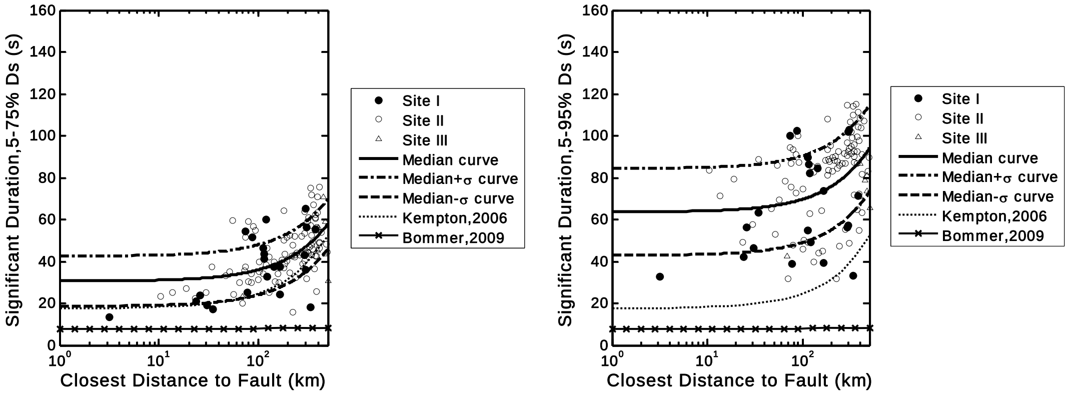
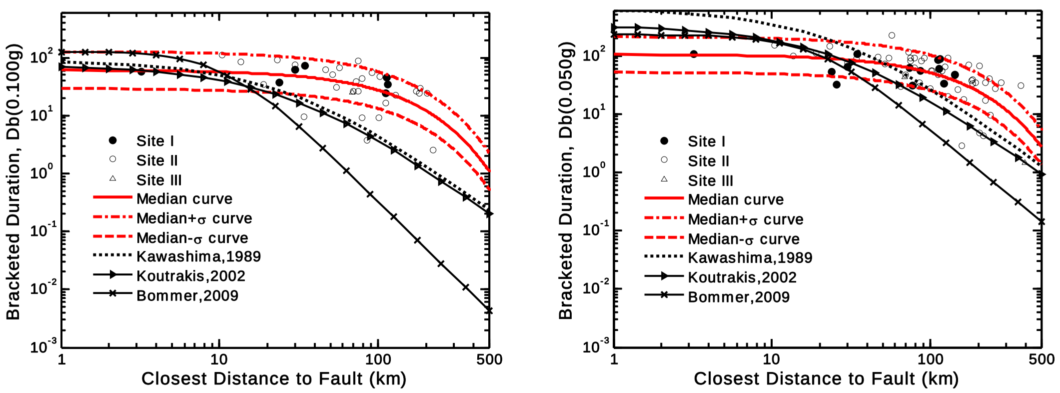


Figure 5.1. Recorded significant duration (D_s) of Wenchuan earthquake compared with former empirical formula by Kempton and Stewart (2006), Bommer et al. (2009). The solid circles represent recorded values on site class I, open circles represent recorded values on site class II and triangles represent recorded values on site class III.

Figure 5.2 shows the variation of recorded bracketed duration (D_b) of strong motions in EW component with fault distance, and durations at various sites are compared with the predictions of Kawashima and Aizawa (1989), Koutrakis *et al.* (2002) and Bommer et al. (2009). It can be seen that significant durations show a tendency of decreasing with fault distance at all sites. Recorded D_b(0.100g) and D_b(0.050g) decrease much slower than the empirical formula by Koutrakis *et al.* (2002) and Bommer et al. (2009), and the D_b(0.025g) durations decrease slower than the empirical formula by Kawashima and Aizawa (1989), Koutrakis *et al.* (2002) and Bommer et al. (2009). For the 0.100g bracketed duration, observed values are very close to the predictions of Kawashima and Aizawa (1989) and Koutrakis *et al.* (2002) within 10km of the causative fault, but can be twice more than the predicted values beyond 20km. The recorded durations D_b(0.100g) are about 1/2 of the prediction of Bommer et al. (2009) within 10km of the causative fault, but are much larger than the prediction beyond 30km. For the 0.050g bracketed duration, the recorded data are about 1/2 of the predicted values given by Bommer et al. (2009) and Koutrakis *et al.* (2002) within 20km, and are larger than the predicted values of Bommer et al. (2009) and Koutrakis *et al.* (2002) when beyond 30km. Recorded D_b(0.050g) are much smaller than the prediction of Kawashima and Aizawa (1989) within 50km, while larger than the prediction beyond 50km. For the 0.025g bracketed duration, the recorded D_b(0.025g) are smaller than the predicted values of Bommer *et al.* (2009) and Koutrakis *et al.* (2002) at minor distance, while larger than the predictions when the fault distance is greater than 30km.



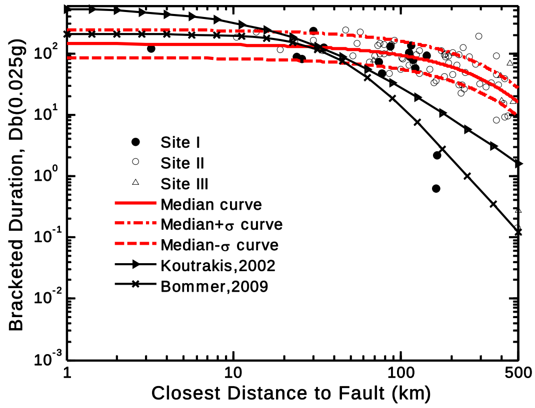


Figure 5.2. Recorded bracketed duration (D_b) of Wenchuan earthquake compared with former empirical formula by Kawashima and Aizawa (1989), Koutrakis et al. (2002), Bommer et al. (2009). The solid circles represent recorded values on site class I, open circles represent recorded values on site class II and triangles represent recorded values on site class III. (a)A=0.100g ;(b) A=0.050g; (c) A=0.025g.

Figure 5.3 showed the recorded uniform duration D_u and obtained regression formula with absolute thresholds of 0.100g, 0.050g and 0.025g. The obtained regression formulas were compared with former empirical formula by Bommer et al. (2009). It can be seen that recorded uniform durations are smaller than the predicted values of Bommer et al. (2009) at minor distance, while much larger than

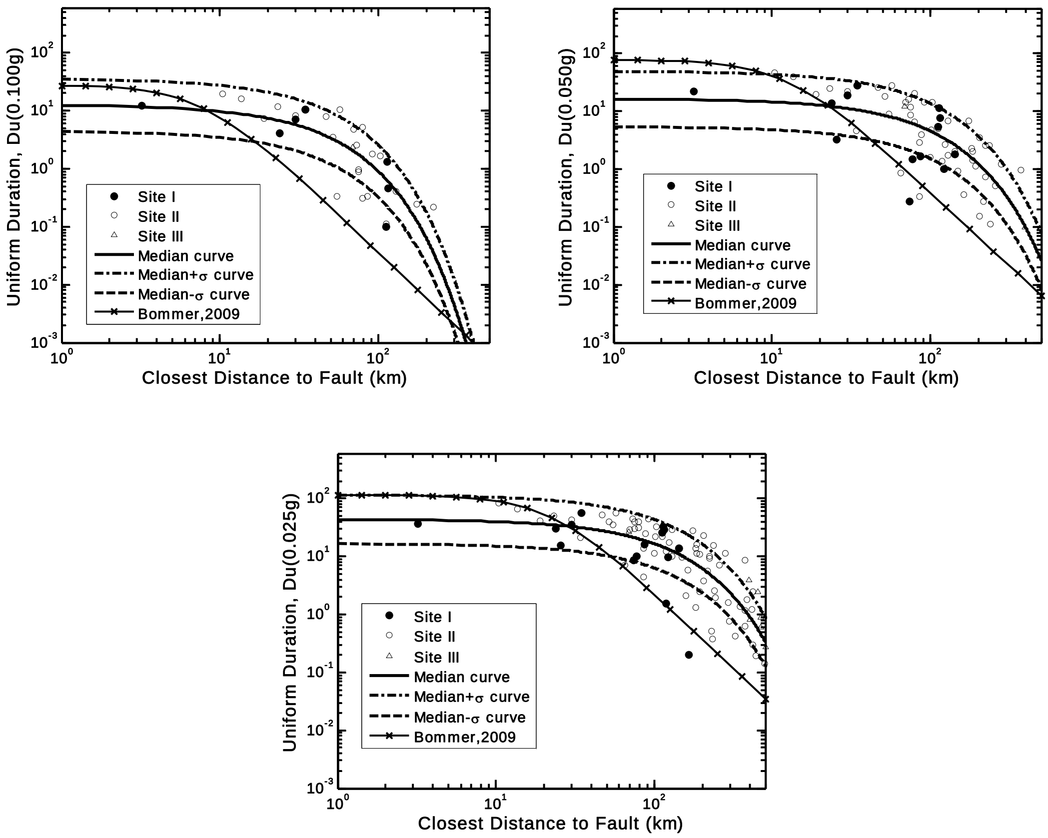


Figure 5.3. Recorded uniform duration (D_u) of Wenchuan earthquake compared with former empirical formula by Bommer et al. (2009). The solid circles represent recorded values on site class I, open circles represent recorded values on site class II and triangles represent recorded values on site class III. (a)A=0.100g ;(b) A=0.050g; (c) A=0.025g.

the prediction beyond 30km. No special trend is shown for duration data from site class I, II, and III.

On the whole, the uniform durations D_u with all thresholds (0.100g, 0.050g and 0.025g) decrease much slower than the empirical formula by Bommer et al. (2009).

6. CONCLUSIONS

Strong motion data of 120 free-field stations were used to investigate the duration characteristics of ground shaking during the Wenchuan M_w7.9 earthquake. The significant duration (D_s(5~75%), D_s(5~95%)), bracketed duration (D_b(0.025g), D_b(0.050g), D_b(0.100g)) and uniform duration (D_u(0.025g), D_u(0.050g), D_u(0.100g)) of strong motions were statically analyzed, empirical models for this earthquake were developed from strong motion data and compared with former empirical relations. The effects of forward directivity, basin effects and site condition on durations were also studied.

Smaller significant durations of 20~60s mainly locate near along the narrow rupture fault belt and in the forward directivity region, while durations larger than 80s locate in the backward region. The largest significant duration D_s(5~75%) and D_s(5~95%) are about 80s and 120s, which are comparatively longer than other earthquakes of similar magnitude. The significant durations of ground shaking are unusually long, which can be 2~3 times of former prediction given by Bommer et al. (2009). Our former knowledge on strong motion duration could not be applied to understand the unusual long ground shaking observed during the Wenchuan earthquake. For the bracketed and uniform durations, larger durations locate near along the narrow rupture fault region and decrease with fault distance. The distribution of absolute durations is strongly affected by the rupture directivity, and the recorded nonzero duration region in the forward is much larger than the backward direction. Observed bracketed duration D_b(0.025g) can be as large as 240s, and most durations larger than 160s locate near along the narrow rupture fault region. Recorded bracketed and uniform durations decrease much slower than the former empirical formula, absolute durations are smaller than the former predicted values of Bommer et al. (2009) at minor distance, while larger than the predictions beyond 30km.

In general, the distribution of durations during Wenchuan earthquake was influenced under the combined effects of rupture directivity, basin effects and site conditions. Azimuthal variation of strong motion shows consistently significant differences in the forward directivity region and the backward. Recorded durations in the M_w 7.9 Wenchuan earthquake are unusually long and the distribution of strong motion durations manifests high complexity as shown by our studies, this may be closely correlated with the complicated source rupture process involved in this event (Parsons et al., 2008; Wang et al., 2008; Koketsu et al., 2009； Zhang et al., 2009).

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