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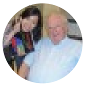

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ORIGINAL PAPER

An empirical equation of effective shaking duration for moderate to large earthquakes

Ya-Ting Lee · Kuo-Fong Ma · Yu-Ju Wang · Kuo-Liang Wen

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Abstract The duration of strong shaking is particularly important for assessing building performance, potential landslides and liquefaction hazards. The results of this investigation can potentially help reduce related fatalities and economic losses. In this study, we analyzed the acceleration seismograms of the Taiwan strong motion network to characterize the strong shaking duration associated with earthquake sources, propagation paths and site effects. This study proposes a new definition for the strong shaking duration called "effective shaking duration" (ESD), which considers the amplitude and radiation energy decays. We first consider the window of a time series during which the amplitude is $\geq$0.01 g, and we then defined the ESD as the length of the interval of the dissipated energy within 5–95 % of the total energy during this time frame. We calculated the strong shaking duration for 495 inter-plate events with magnitudes of $M_L > 5.0$ and focal depths <50 km in the Taiwan region from 1994 to 2012. Using a nonlinear regression procedure, we thus obtained an empirical equation for strong shaking durations. The equation is a function of earthquake magnitude, distance and site conditions, which are defined by the V_s30 value (the S-wave velocity structure of the top 30 m of the site). The results indicate that the shaking durations significantly increase with magnitude and also decrease with distance and V_s30. Compared with empirical equations from global datasets, our empirical equation is applicable to earthquakes in other regions and will produce smaller but more applicable duration values for smaller earthquakes. However, for larger events, our ESD values are comparable with those derived from other definitions (e.g., significant duration). Although the empirical relationship is mainly based on Taiwanese events, in view of the massive dataset, this empirical equation could provide important information to the global community regarding the ground shaking duration estimation in the ground motion prediction of future earthquakes.

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Keywords Effective shaking duration · Earthquake source · Propagation path · Site effect · Ground shaking duration estimation

1 Introduction

The duration of strong ground motion is critical to estimating seismic hazards, particularly for building performance, landslide triggering and liquefaction (Trifunac and Novikova 1995; Rauch and Martin 2000; Hancock and Bommer 2005; Bommer et al. 2006; Kempton and Stewart 2006). Lee et al. (1972) and Trifunac and Novikova (1995) calculated the correlations between the duration signal and magnitude and between the duration signal and distance to obtain the empirical equations for earthquakes in central California. Shoji et al. (2005) analyzed earthquakes in Japan and obtained an empirical formula for the strong shaking duration of Japanese earthquakes. The most recent study by Kempton and Stewart (2006) presented equations for predictions of strong shaking durations (of a significant duration) derived from the next generation of attenuation (NGA) global database of accelerograms for earthquakes with a magnitude range of M 5.0–7.6. Additionally, Bommer et al. (2009) used the NGA dataset and presented empirical predictive equations for additional duration definitions. Their equations can be used for estimating the strong shaking durations of shallow crustal earthquakes with M_{w} values of 4.8–7.9. Owing to the dense strong motion network and high seismicity in Taiwan, we investigate the empirical equation for strong shaking duration in the area in terms of earthquake magnitude, earthquake distance, geology and local site conditions by utilizing the high-quality motion data recorded by the Taiwan strong motion instrumentation program (TSMIP). Using a nonlinear regression procedure, similar to the procedure in Seber and Wild (2003), we obtained an empirical equation for the prediction of strong shaking durations. Although some factors related to earthquake sources, near-field effects and rupture directivity may improve the equation, the empirical equation derived here provides a first-order prediction of strong shaking durations.

1.1 Definition of effective strong shaking duration

Strong shaking duration is commonly defined as “bracketed duration” (Bolt 1973): The time interval between the first and last amplitudes greater than the threshold level of the strong shaking duration value (e.g., Pagratis 1995; Stafford 2008; Bommer et al. 2009; Kawashima and Aizawa 1989). Another definition is the “significant duration”: The time it takes for a designated percentage of the total energy to arrive (e.g., 5–95 % of the total energy) (Trifunac and Brady 1975; Martin and Haresh 1979); it has also been widely used in recent studies (Bommer and Martinez-Pereira 1999; Shoji et al. 2005; Bommer et al. 2009). Here, we combine the two definitions to produce an “effective shaking duration” (ESD) by considering both the strong ground motion amplitude and energy. The ESD was calculated in two steps. First, we limited the time interval between the first and last amplitudes by considering those values greater than or equal to a specified threshold value (0.01 g). Then, the accumulated energy of the three components produced the ESD for the time window, which has 5–95 % of the total energy within the amplitude threshold (Fig. 1). The threshold value of 0.01 g was determined by considering the possible triggered landslides PGA value in previous studies, e.g., Del Gaudio and Wasowski (2004), Sigaran-Loria et al. (2007) and Rathje and Saygili (2009). To clarify the parameters used in this study with previous studies, we summarized the type and parameters of the referred papers and this study in Table 1.

1.2 Strong ground motion data and effective shaking duration (ESD)

The TSMIP network, operated by the Central Weather Bureau (CWB), is composed of approximately 700 accelerographs at free-field sites (Shin 1993) and has recorded high-quality strong ground motion data since 1993. In 2000, the National Center for Research on Earthquake Engineering (NCREE) and the CWB committed to a free-field strong motion station drilling project to construct an Engineering Geological Database for the TSMIP (EGDT). A total of 439 free-field stations in the TSMIP network were drilled and completed the logging measurements. The values of V_s30 (the average S-wave velocity of the top 30 *m* of the strata) of the drilled station were measured by the suspension PS logging system of Kuo et al. (2012). The suspension PS logging system has two sensors at a fixed distance of 1 m. The P- and S-waves produced were received by the sensors, and the S-wave velocities of the shallow strata were then estimated.

Figure 2 displays the distribution of the strong motion stations with site classes of the TSMIP. The free-field strong motion stations of the TSMIP were divided into five site classes: A (hard rock with $V_s30 > 1{,}500$ m/s), B (firm to hard rock with 1,500 m/s $\geq V_s30 > 760$ m/s), C (dense soil and soft rock with 760 m/s $\geq V_s30 > 360$ m/s), D (stiff soil with 360 m/s $\geq V_s30 \geq 180$ m/s) and E (soft soil with $V_s30 < 180$ m/s) classes (Kuo et al. 2012). The site classification definition was determined according to the V_s30-based provisions of the National Earthquake Hazard Reduction Program (NEHRP). Most of the stations belong to class C and D sites, and the stations of class C are located around the Central Mountain and the Coastal Range. As shown in Fig. 2, site class D and E stations are mainly located within plains and basins (Kuo et al. 2012).

In this study, we noted the earthquakes from 1994 to 2012 with magnitudes of $M_L > 5.0$ and focal depths <50 km. We considered M_L rather than M_w as M_L is the more complete catalog and is the magnitude firstly determined in real time upon occurrence of an earthquake. It, thus, can be utilized further for real-time strong shaking duration prediction. The conversion between M_L and M_w for Taiwan region had been examined by Lin and Lee (2008). The magnitude in M_L is about 0.2 larger than M_w for events with M_L of 5–7. Due to no sufficient data of intra-plate events, we, thus, chose the crustal and inter-plate events with focal depths of <50 km. In total, 495 earthquakes were selected (Fig. 3). We applied the definition of ESD to the records. To avoid contamination with noise, we only chose stations that had a PGA value >0.015 g. Additionally, the ESD determined should be no <2 s. For the 495 earthquakes, using the criteria established in the data selection above, a total of 11,639 records were utilized for our study (details of the data are shown in Table 2). Of these records, 365 were utilized for site class B.

1.3 Development of the empirical equations for strong shaking duration

The duration of strong ground motion is associated with the earthquake source, propagation path and site effects.

$$\tau = \tau_s + \tau_\Delta + \tau_{site} \tag{1}$$

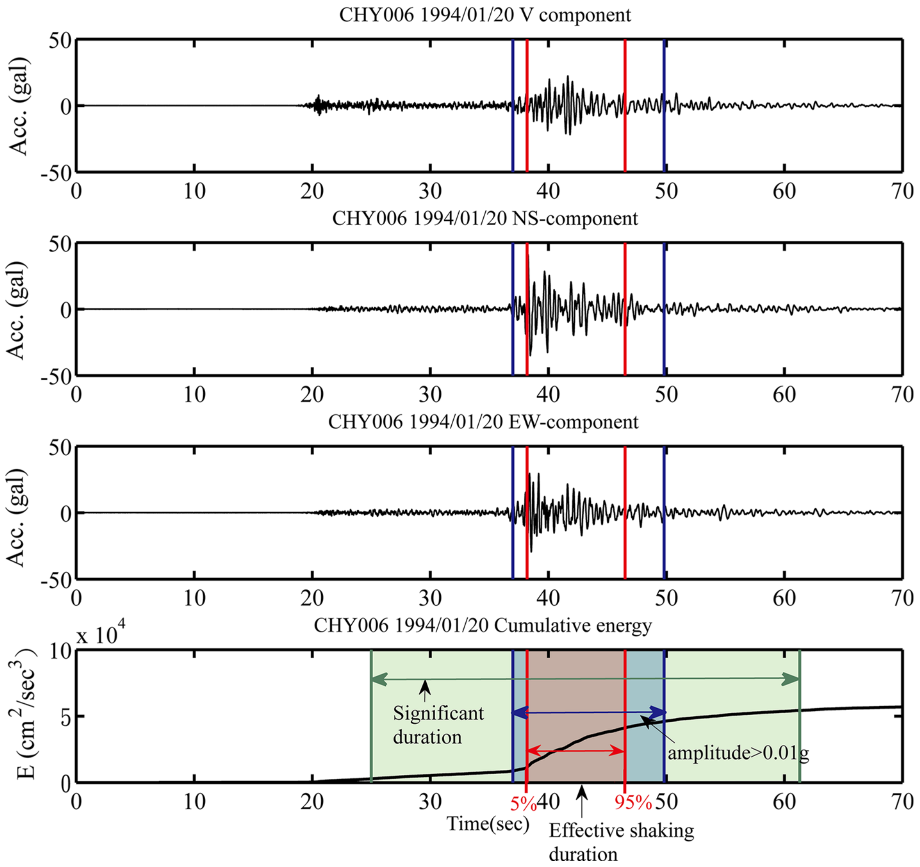


Fig. 1 Example of ESD estimations of the three component (V, NS and ES) acceleration seismograms at the CHY006 station (site class C, $V_s30 = 423$ m/s) for the 1994/01/20 $M_L = 5.58$ earthquake. The locations of this earthquake and the CHY006 station are shown in Fig. 3 (*yellow star* and *green triangle*, respectively); the earthquake has a hypocentral distance of approximately 151 km. The *bottom panel* presents the cumulative energy with time. The *blue lines* mark the time window of the acceleration ≥ 0.01 g. The *red lines* mark the time window of the accumulated energy of 5–95 % for the total energy of the acceleration ≥ 0.01 g. The *green lines* mark the time interval of the SD

Here, τ is the strong shaking duration in seconds as recorded by accelerographs at the free-field sites, τ_s represents the earthquake source duration, τ_Δ represents the propagation path dependence, and τ_{site} represents the site condition dependence. We form regression Eq. (1) by the following steps.

1. Earthquake source duration, τ_s

Hanks and McGuire (1981) and Boore (1983) assumed that the theoretical earthquake source duration is equal to the reciprocal of the corner frequency that is related to the seismic moment and stress drop index. Using the theoretical seismic source model (Abrahamson and Silva 1996; Kempton and Stewart 2006), the regression model for the source duration was formed as follows:

Table 1 Type and parameters used in referred papers and this study for prediction equation for strong shaking duration

Author	Duration parameter	Magnitude type	Distance type	Site parameter
Bolt (1973)	BD	a/n	r_{hyp}	a/n
Trifunac and Brady (1975)	SD	a/n	r_{epi}, h	Soft alluvium, intermediate rock and hard rock
Hernandez and Cotton (2000)	SD	M_{w}	r_{rup}, h	Rock, soil
Kempton and Stewart (2006)	SD	M_{w} for $M > 6$ M_{L} for $M < 6$	r_{hyp}	$Vs30$
Bommer et al. (2009)	SD	M_{w}	r_{rup}, h	$Vs30$
This study	ESD	M_{L}	r_{hyp}	$Vs30$

Duration parameters: *BD* bracketed duration; *SD* significant duration; *ESD* effective shaking duration

Magnitude parameters: M_w moment magnitude; M_L local magnitude

Distance parameters: r_{rup} the closest distance from the fault rupture; r_{hyp} hypocentral distance, source to station distance; r_{epi} epicentral distance; h hypocentral depth

Site parameter: *Vs30* average S-wave velocity of the top 30 m of the site

$$\tau_{\mathrm{s}} = \frac{1}{f_{\mathrm{c}}(M_0, \Delta\sigma_{\mathrm{I}})} = \frac{1}{4.9 \times 10^6 \beta}\left(\frac{M_0}{\Delta\sigma_{\mathrm{I}}}\right)^{1/3} = \frac{\left(\frac{\Delta\sigma_{\mathrm{I}}}{10^{1.5M+16.05}}\right)^{-1/3}}{4.9 \times 10^6 \beta} \tag{2}$$

where f_{c} is the corner frequency, β is the shear-wave velocity of the crust at the source (set as 3.2 km/s), and $\Delta\sigma_{\mathrm{I}}$ is the stress drop index that is related to the stress drop but not the true stress drop of the event. The stress drop index is calculated from the duration values using the source model (Eq. 2). M_0 is the seismic moment (in dyne-cm), which can be converted from the magnitude (M_{L}) as $M_0 = 10^{1.5M_{\mathrm{L}}+16.05}$ (Hanks and Kanamori 1979).

2. Propagation path dependence, τ_Δ, and the stress drop index, $\Delta\sigma_{\mathrm{I}}$

The logarithm of the strong shaking duration is considered to be a linear decrease with distance (Kempton and Stewart 2006), written as follows:

$$\log \tau_\Delta = c_1 r \tag{3}$$

where c_1 is a regression parameter and r is r_{hyp}, which is defined as the hypocenter distance (source to station distance) of the earthquakes in kilometers. To examine the relationship, we used the accelerogram dataset of rock site ($V_{\mathrm{s}}30 > 760$ m/s) recordings of large earthquakes ($M_{\mathrm{L}} = 6.0$–7.4) for every 0.2 magnitude interval (Fig. 4). The result fits the distance decay regression of Eq. (3) well, which suggests the appropriate regression model was chosen for the propagation path dependence, τ_Δ, of Eq. (3).

By combining Eqs. (2) and (3), the form of the regression model becomes the following:

$$\log \tau = \log\left[\frac{\left(\frac{\Delta\sigma_I}{10^{1.5M_L+16.05}}\right)^{-1/3}}{4.9 \times 10^6 \beta}\right] + c_1 r_{\mathrm{hyp}} \tag{4}$$

To determine the magnitude dependence of the stress drop index, $\Delta\sigma_{\mathrm{I}}$, which was proposed by Kempton and Stewart (2006), we investigated the magnitude dependence of

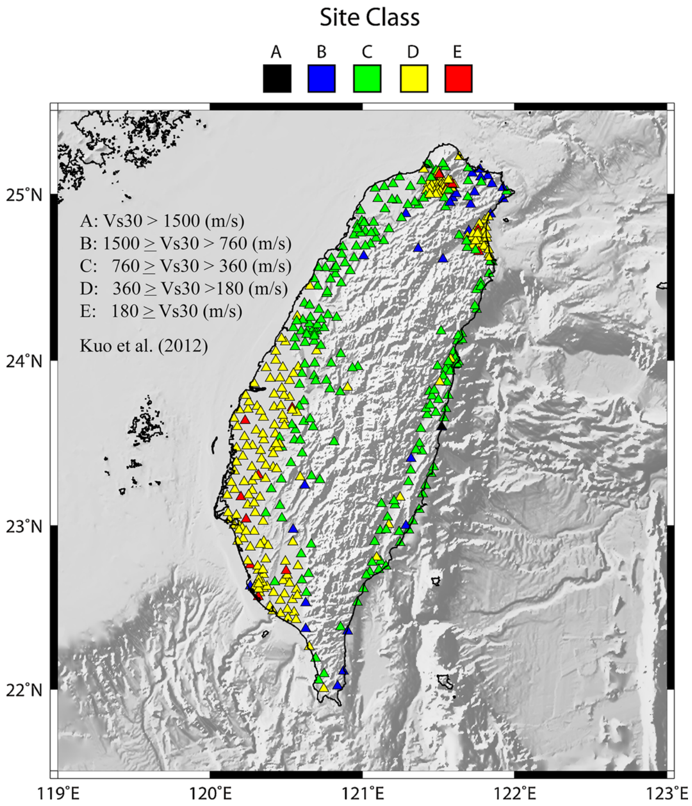


Fig. 2 Distribution of strong motion stations with the site classifications of the TSMIP. The *colors* denote site classifications as determined by Kuo et al. (2012). The number of stations for site classes *A*, *B*, *C*, *D* and *E* is 1, 29, 200, 193 and 16, respectively

$\Delta\sigma_I$ of our dataset in 0.25 magnitude bins (e.g., $M_L = 5.0$–5.25 and 5.25–5.5) and utilized a nonlinear regression procedure to examine the magnitude dependence of $\Delta\sigma_I$. To optimize the estimation of source parameters, we began by using the accelerogram dataset of rock site recordings for the regression of Eq. (4). Figure 5 shows the relationship of magnitude and $\Delta\sigma_I$ (i.e., the increase of $\Delta\sigma_I$ with magnitude). To capture the trend of the magnitude-dependent stress drop, we therefore referred to the study of Kempton and Stewart (2006) and adopted the exponential model for $\Delta\sigma_I$. The regression model was thus rewritten as follows:

$$\log\tau = \log\left[\frac{\left(\frac{\exp[b_1+b_2(M_L-M*)]}{10^{1.5M_L+16.05}}\right)^{-1/3}}{4.9\times10^6\beta}\right] + c_1 r_{\text{hyp}}, \tag{5}$$

where $M*$ is the magnitude as the $\Delta\sigma_I$ exhibits a jump (Fig. 5). The reference magnitude $M*$ is set to 5.75; b_1 and b_2 are regression coefficients. By applying the nonlinear regression procedure of Eq. (5) to the dataset of the rock site, we obtained the regression coefficients of $b_1 = 1.1538$, $b_2 = 1.3273$ and $c_1 = -0.0015$. The regression coefficients of b_1 and b_2, which are stress drop index-related coefficients, were adopted as constants in

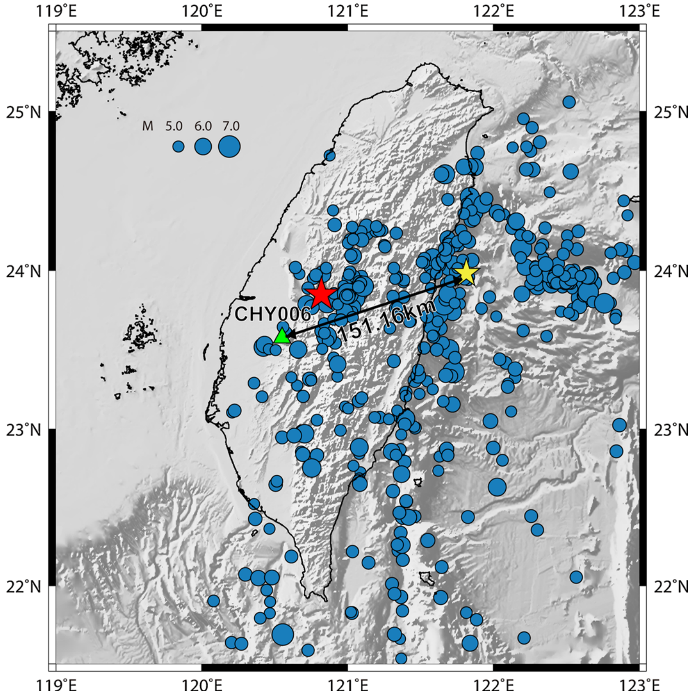


Fig. 3 Earthquake distribution of selected events from 1994 to 2012 (*blue dots*) for $M_L = 5.0$–7.3 and depth <50 km. The *red star* indicates the location of the 1999 $M_L = 7.3$ Chi–Chi earthquake. The *yellow star* and *green triangle* indicate the locations of the example earthquake and the CHY006 station, respectively, as presented in Fig. 1

Table 2 Number of events and recordings with different magnitude intervals

Magnitude (M_L)	Number of events	Number of recordings
5.0–5.2	178	1,950
5.2–5.4	113	1,327
5.4–5.6	55	735
5.6–5.2	50	1,071
5.8–6.0	29	615
6.0–6.2	24	1,211
6.2–6.4	9	620
6.4–6.6	11	1,419
6.6–6.8	16	1,565
6.8–7.0	6	769
7.0–7.2	3	60
7.2–7.4	1	297
Total	495	11,639

the final regression. The residuals of the decimal logarithm duration between the observed (τ_{obs}) and predictive (τ_e) durations ($\log \tau_{obs} - \log \tau_e$) exhibit a normal distribution with a standard deviation of $\sigma_{eq.\ 5} = 0.229$ (Fig. 6). Additionally, in Fig. 7a, b, the model

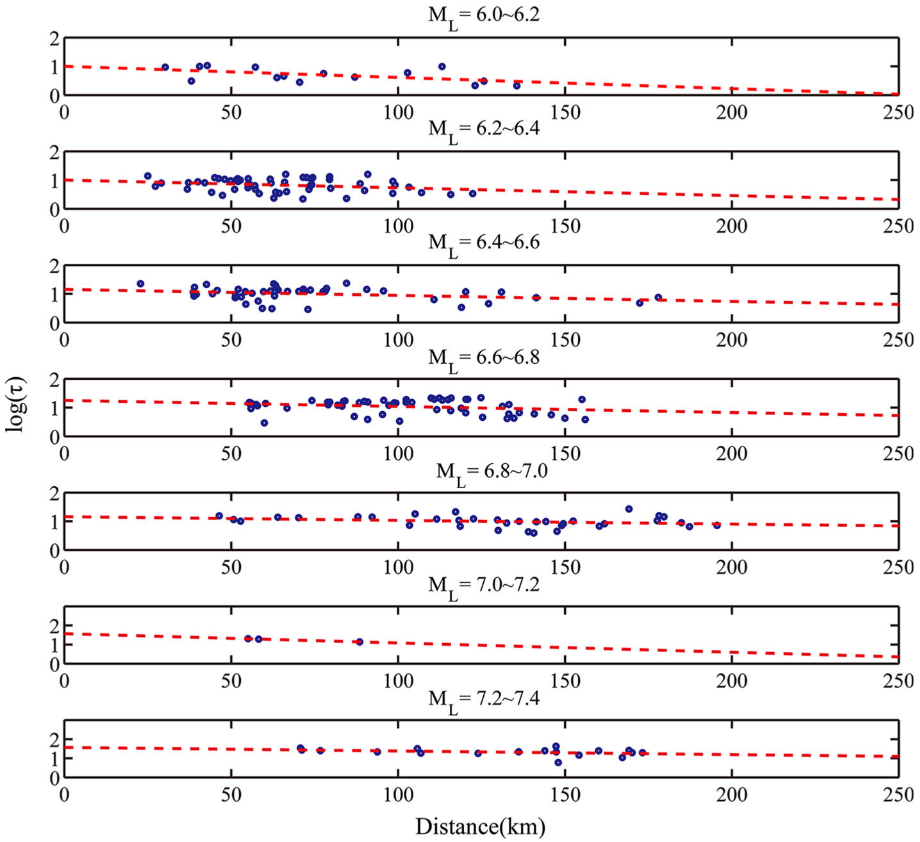


Fig. 4 Logarithm of the ESD time (*blue circles*) decays with distance at a 0.2 magnitude interval for $M_L = 6.0$–7.3. The *red dashed lines* indicate the best regression of the data

residuals of ESD were plotted as functions of magnitude and distance; they display no clear bias with magnitude or distance.

3. Site effect, τ_{site}

We further considered the site condition dependence of the shaking duration equation. We used the V_s30 values of the stations for the empirical duration equation. The form of the regression model for the site condition dependence, τ_{site}, is based on the study by Kempton and Stewart (2006) in which the residual of the logarithm duration linearly decreases with V_s30. Accordingly, the form of the duration regression equation that considers the source duration, path and site can be written as follows:

$$\log \tau = \log\left[\frac{\left(\frac{\exp[b_1+b_2(M_L-5.57)]}{10^{1.5M_L+16.05}}\right)^{-1/3}}{4.9\times 10^6\beta}\right] + c_1\,\mathrm{r_{hyp}} + c_2 V_s30 + c_3, \qquad (6)$$

where c_1, c_2 and c_3 are regression coefficients. By applying the nonlinear regression procedure of Eq. (6) to the entire dataset, we obtained our final regression coefficients:

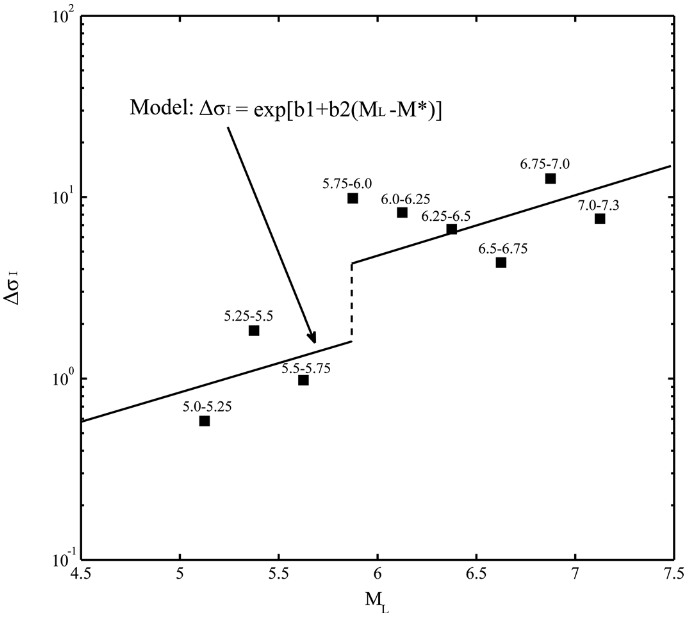


Fig. 5 Estimated stress drop index and model for the stress drop index as a function of magnitude for the ESD data

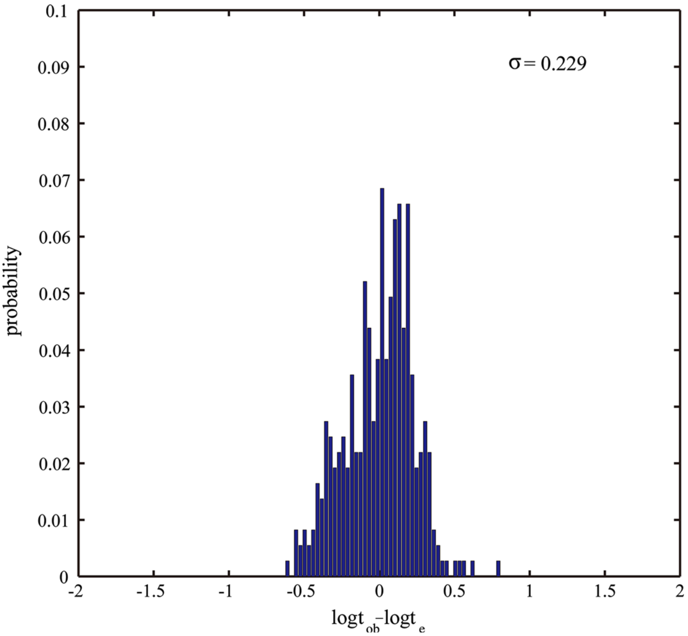


Fig. 6 Probability density of the residuals of the regression model (Eq. 5, where $b_1 = 1.1538$, $b_2 = 1.3273$ and $c_1 = -0.0015$) for $M_L > 5.0$ for the rock site data. The standard deviation is $\sigma = 0.229$

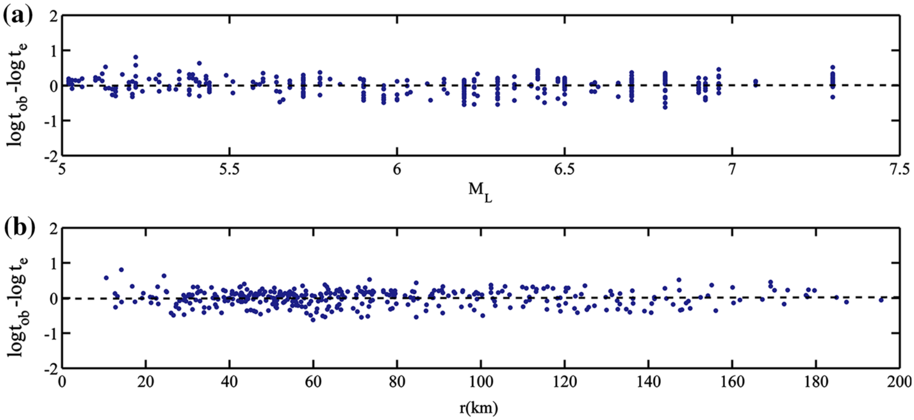
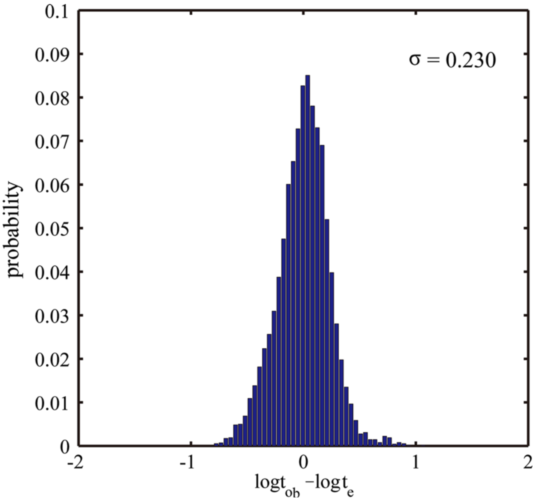


Fig. 7 Residuals of the regression model of the ESD in decimal logarithm units plotted as a function of **a** magnitude and **b** distance. The residual data are recorded by the rock site stations of the TSMIP network for $M_L > 5.0$. The *black dashed lines* indicate the residual value at zero

Fig. 8 Probability density of the residuals of the regression model (Eq. 6, where $b_1 = 1.1538$, $b_2 = 1.3273$, $c_1 = -0.0011$, $c_2 = -0.0004$ and $c_3 = 0.3038$) for $M_L > 5.0$. The standard deviation is $\sigma = 0.230$



$c_1 = -0.0011$, $c_2 = -0.0004$ and $c_3 = 0.3038$; the previously determined constants were $b_1 = 1.1538$ and $b_2 = 1.3273$. Figure 8 displays the probability density function of the regression model residuals of the duration in decimal logarithm units; it is shown as a normal distribution with a standard deviation of $\sigma_{\text{eq. }6} = 0.230$. The majority of the residual values were approximately zero. Additionally, the model residuals of ESD are plotted as functions of magnitude, distance and V_s30, as shown in Fig. 9a–c, respectively. The residuals show no significant trends. The results indicated that the derived coefficients of the empirical duration Eq. (6) provide an adequate basis for the approximate description of the strong shaking durations of earthquakes ($M_L > 5.0$ and depth <50 km) in Taiwan.

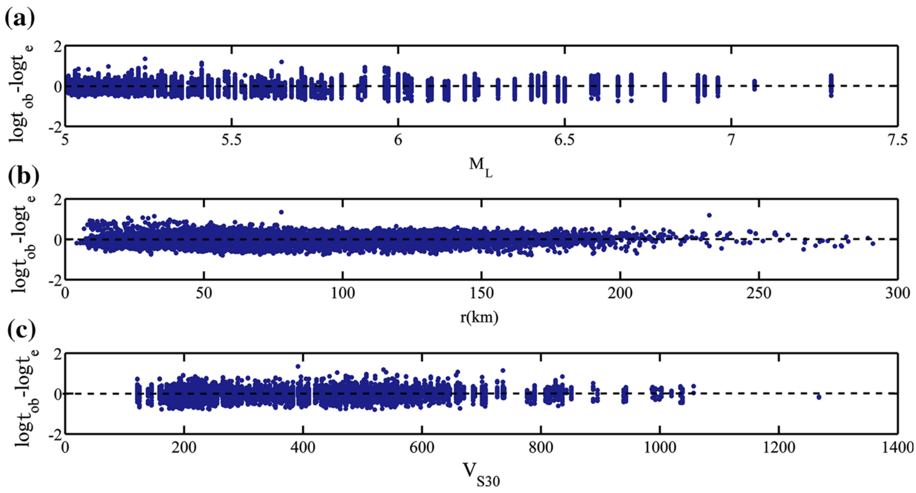


Fig. 9 Residuals of the regression model of the ESD in decimal logarithm units plotted as a function of **a** magnitude, **b** distance and **c** V_s30. The residual data are recorded by the TSMIP network for $M_L > 5.0$. The *black dashed lines* provide the residual value at zero

2 Discussion

To compare our derived prediction equation, the study by Kempton and Stewart (2006) is enlisted. We produced two duration calculations for our dataset: One calculation from our derived equation that provides the ESD, and a second calculation from the derived equation of Kempton and Stewart that provides the significant duration (SD). The M_L had been converted to M_w accordingly using the conversion derived by Lin and Lee (2008) for the equation in Kempton and Stewart (2006). The results are shown in Fig. 10 along with the magnitude scaling for $r_{hyp} = 100$ (km) and $V_s30 = 450$ (m/s) for the two derived empirical equations. The SD values of global earthquakes from the NGA dataset are also shown. Generally, the ESD is approximately 20 s less than the SD. Larger events correspond to smaller differences in the values of ESD and SD. However, the ESD and SD of the Taiwanese dataset nicely fit the derived empirical equations of the individual definition of durations. In Kempton and Stewart (2006), the definition of SD considers the energy contained (5–95 %), but it does not consider the amplitude of the ground motion. The SD can include time series with small amplitudes (amplitude <0.01 g) for small events. However, in our ESD, before taking into account the energy radiation, we first consider the time interval with amplitudes ≥0.01 g; thus, no time interval for amplitudes <0.01 g is involved. We further demonstrate the differences in ESD and SD for moderate ($M_L = 5.19$; the 1995 earthquake) and large events ($M_L = 7.3$; the 1999 Chi–Chi earthquake) (Fig. 11). The SD of 16.7 s is much larger than the ESD value (3.0 s) for a moderate earthquake ($M_L = 5.19$). A long time series with amplitudes <0.01 g was included in SD. For a larger earthquake ($M_L = 7.3$), the SD of 29.3 s is more similar to the ESD of 25.0 s. These comparisons suggest that our ESD may be more conservative in estimating the shaking duration of earthquakes. However, it could be considered a lower bound of the shaking duration, especially for moderate earthquakes.

Our derived empirical equations may provide predictions for strong shaking durations. However, many studies have suggested that various factors may impact strong shaking

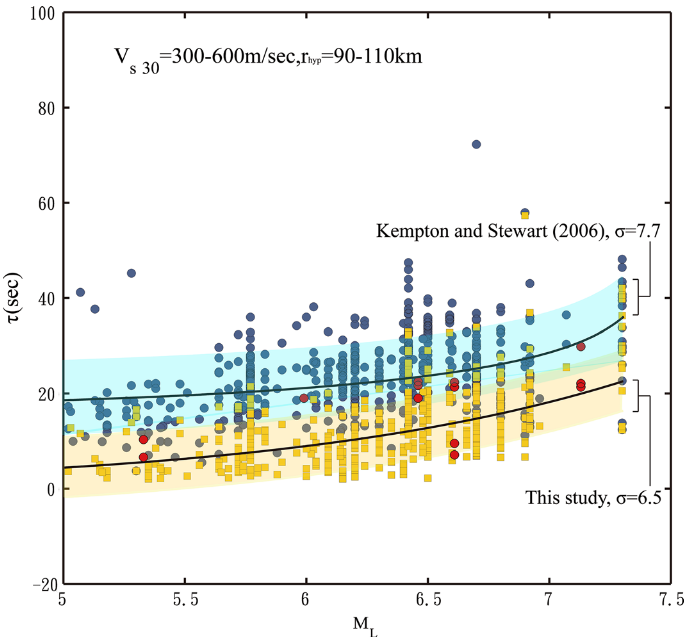


Fig. 10 Comparison of the magnitude dependence of strong shaking duration values from this study with those from the study of Kempton and Stewart (2006). The *yellow squares* show the ESD of Taiwanese earthquakes. The *blue* and *red dots* show the SD of Taiwan earthquakes and NGA data, respectively. The data are for distances of 90–110 km and V_s30 values of 300–600 m/s. The *blue* and *yellow shadows* indicate the standard deviations of the SD and ESD, respectively. The *black lines* show the empirical equation of Eq. 6 (where $r_{\mathrm{hyp}} = 100$ km and $V_s30 = 450$ m/s) and the equation from Kempton and Stewart (2006)

duration predictions. For instance, earthquake sources, near-field effects and rupture directivity may impact the predictive equations of strong shaking durations (Kempton and Stewart 2006). Wen and Yeh (1991) used the SMART1 array data in northeastern Taiwan to discuss the strong shaking durations of acceleration, velocity and displacement behaviors. They suggested that the variability in duration is primarily caused by the complicated rupture process of the earthquake source. A study by Trifunac and Brady (1975) presented the variability of duration increases with epicentral distance; they suggested that the variability of duration was caused by inhomogeneous media through which the seismic waves propagated. Additionally, Spudich et al. (1999) proposed that the stress state (extensional or compressive) and the style of faulting may influence the amplitude of strong ground motion. Ground motion amplitudes increase, and the threshold of the acceleration level is therefore exceeded for longer periods of time (Bommer et al. 2009). Somerville et al. (1997) also found that the rupture directivity effect can influence the strong shaking duration; they indicated that waves in the backward directivity region result in signals of extended duration. Additionally, many studies have suggested that structural components are expected to exhibit sensitivity to ground shaking duration (Reinoso and Guerrero 2000; Hancock and Bommer 2004; Bommer et al. 2004; Hancock and Bommer 2006). In the present paper, we did not include the aforementioned factors in our empirical equation. To reduce the variance, additional data obtained for large earthquakes are needed to further address the possible impact of the various factors (e.g., the style of faulting and

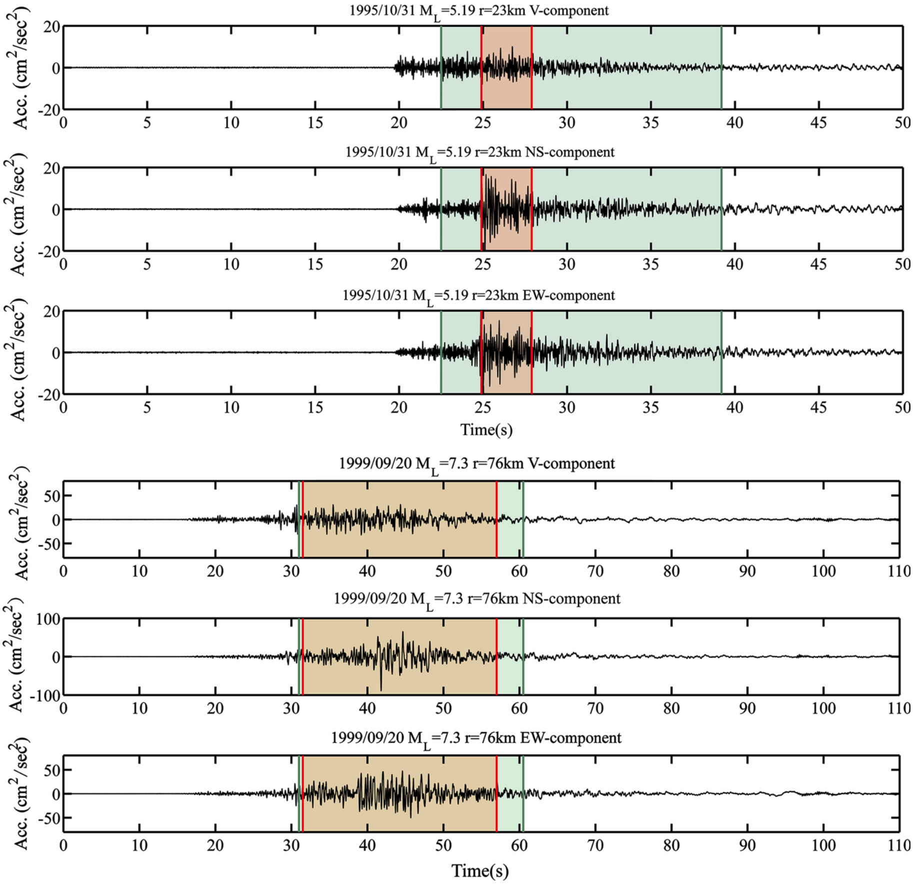


Fig. 11 Two examples of the duration of strong ground motion are presented. One example is the earthquake that occurred in 1995 with a magnitude of $M_L = 5.19$, and the other example is the Chi–Chi earthquake ($M_L = 7.3$) in 1999. The *green lines* provide the time interval of SD (*green shadow*). The *red lines* provide the time interval of the ESD defined in this study (*red shadow*)

fault rupture) on strong shaking durations. However, the fits of ESD and SD to the individual empirical equations suggest that the empirical equation in this study, despite being derived from Taiwanese earthquakes for the most part, could be considered a conservative approximation of the empirical strong shaking duration equation. This empirical equation may thus be able to provide a good constraint for assessing the potential hazards of the shaking duration of future earthquakes.

3 Conclusions

This study provided an empirical equation for the strong shaking duration of earthquakes as a function of earthquake magnitude, earthquake distance and site parameter (V_S30). We proposed a new definition of strong shaking duration (called effective shaking duration or ESD) by considering amplitude and energy factors (i.e., the presence of major energy and amplitudes larger than 0.01 g). We analyzed the strong ground motion of acceleration from the TSMIP network to obtain the empirical equation. The ESD from our definition is generally smaller than the values of SD of Kempton and Stewart (2006), but fewer differences are exhibited in larger events. The good fits of our dataset to the individual derived empirical equations for ESD and SD suggest that our derived equation from ESD is a good approximation. Our strong shaking equation could be considered a conservative yet more effective parameter for shaking durations in the assessment of possible seismic hazards. However, we have not yet considered other factors from earthquake sources, near-field effects and rupture directivity, which may also impact the predictive equation for strong shaking durations. The duration of strong ground motion is critical to estimating seismic hazards, particularly for building performance, landslide triggers and liquefaction. On a preliminary basis, our proposed empirical equations could provide the characteristics of strong shaking durations. Using the massive dataset from the TSMIP, the empirical equations derived here could also provide a reference for the global community in estimating ground shaking durations in the ground motion prediction of scenario earthquakes.

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