Influence of site conditions on strong earthquake duration

Deng-Ke Jiu
Graduate Student, Faculty of Architecture, Civil and Transportation Engineering, Beijing University of Technology, Beijing, China

Yan-Gang Zhao
Professor, Faculty of Architecture, Civil and Transportation Engineering, Beijing University of Technology, Beijing, China

Hai-Zhong Zhang
Assistant Professor, Engineering Research Subject Architecture, Kanagawa University, Yokohama, Japan

Zhao-Hui Lu
Professor, Faculty of Architecture, Civil and Transportation Engineering, Beijing University of Technology, Beijing, China

ABSTRACT: The duration of strong earthquakes plays an important role in seismic design. There are many definitions and calculation methods of strong earthquake duration, but the analysis of strong earthquake duration considering site effect are not enough. The purpose of this paper is to analyze the variation trend of strong earthquake duration with site conditions. In this paper, based on a large number of actual seismic waves recorded on different sites, the duration of strong earthquakes under different site categories is calculated. It is found that the duration of strong earthquakes does not all decrease with the increase of shear wave velocity. And the duration varies with the site effect under different magnitude and epicentral distance classifications.

1. INTRODUCTION

The duration of strong ground motion is one of the three elements to describe the characteristics of earthquake ground motion, and also a key parameter affecting the seismic performance of the structural system. The duration of strong earthquake has a significant impact on the nonlinear seismic response of engineering structures, especially the cumulative damage. With the continuous accumulation of earthquake damage experience, the influence of strong ground motion duration on damage has been gradually paid attention to. For example, some earthquakes with large acceleration and response spectrum peaks but short duration have little damage to the structure. However, compared with the ground motions with large acceleration and short duration, the ground motions with the middle peak acceleration and long duration tend to cause greater damage(Naeim 2001). Therefore, the duration of strong earthquake is an important basis for evaluating the damage of earthquake ground motion.

The earliest duration is defined as the source rupture time(Bommer and Martinez-Pereira 2008). With the continuous increase of ground motion records, the study of strong earthquake duration began to use recorded seismic waves, which can be roughly divided into two categories: absolute duration and relative duration. Absolute duration refers to the bracketed duration based on the threshold of the absolute value of acceleration. Relative duration refers to the duration that can reflect the change trend of ground motion intensity or energy, such as equivalent stationary duration, energy moment duration, etc(Xie and Zhou 1984). Later studies also gave different definitions of duration. They determined the duration according to the strong ground motion image, trying to separate only the strong motion interval in the record to more accurately reflect the main energy carried by this ground motion(Taflampas et al. 2009). However, the definition of strong earthquake duration only based on ground motion records cannot reflect the influence of source and site characteristics on strong earthquake duration in actual conditions. Researches show that the rupture mode, magnitude, distance between point and source, propagation path and site conditions all affect the duration of strong earthquakes. At present, most empirical formulas for the duration of strong earthquakes regard the duration as the sum of three parts, that is, the duration of the source, the duration of the extension of the seismic wave propagation path and the extension caused by the site(Trifunac and Todorovska 2012). The change caused by the site is more uncertain, and its impact on the duration of strong earthquakes can be prolonged or shortened. Therefore, more researches are devoted to predict strong earthquake duration by introducing parameters which can reflect site conditions. For example, Kempton and Jonathan put forward three kinds of time duration models of site impact in 2006, which are simple binary model, V_{S30} model and comprehensive model considering basin depth(Kempton and Stewart 2006).

However, these models have complex functional relationships and limited application conditions. The most important thing is that the parameterization of site conditions is relatively simple, which cannot fully reflect the impact of the site. In 2009, based on the Next Generation Attenuation (NGA) database of the United States, Bommer proposed a prediction formula for the duration of strong earthquakes including magnitude and fault distance on the previous basis(Bommer et al. 2009). Arjun and Kumar in 2011 selected Japanese earthquake records with focal distance less than 50km and magnitude greater than 5 to establish a neural network to estimate strong motion duration(Arjun and Kumar 2011). But the selected seismic wave is conditional and does not cover more comprehensive ground motion records. There is a common problem in these researches on the duration of strong earthquakes, that is, they are all committed to fitting a simple duration formula without detailed analysis of the variation trend of duration affected by the site(Wang et al. 2022).

According to such research status, this paper focuses on the analysis of the influence of site conditions on the duration of strong earthquakes and the changing trend. A large number of actual strong ground motion records and site characteristics are used to calculate the duration of strong earthquakes under different actual site classifications. Firstly, the paper summarizes and introduces the existing definitions and advantages of strong earthquake duration. Then, based on the ground motion and site information provided by the K-net and Kik-net database in Japan, the time duration results are calculated and its variation trend affected by various conditions is analyzed. Finally, conclusions and prospects are given.

2. DEFINITION OF EXISTING STRONG EARTHQUAKE DURATION

The duration used in various researches and applications is strictly the duration of strong vibration. When an earthquake occurs, the interval between the time when the seismic wave first travels to a certain point and the time when the ground motion at this point finally ends is called the total duration of ground motion at this point. In the field of seismic engineering, the beginning and the last weak part of the seismic wave have little significance for the actual engineering research. The main research object is the part of the strong vibration of the seismic wave, usually called the strong earthquake duration. Therefore, the study of strong earthquake duration has practical significance and value(Wei 2015).

In general, the existing definitions of strong earthquake duration can be roughly divided into five basic types. The first type is the bracket duration, which refers to the time interval between the first time and the last time when the value is greater than the set minimum value. The second type is uniform duration, which refers to the sum of all time intervals exceeding the set minimum value. The third type is significant duration, also known as energy duration. It defines the duration according to the time interval when the Arias intensity accumulates to a certain extent according to Husid diagram. The fourth type is the effective duration, which is determined according to the fixed threshold value of the Arias intensity accumulated to the set proportion. The fifth type is the structural response duration. This calculation method uses the first three duration definitions to calculate the response duration of the single degree of freedom oscillator. The calculations and characteristics of various types of durations are shown below.

2.1. Bracket duration

The bracket duration refers to the time interval between the first and the last exceeding the set amplitude of design ground motion. The set amplitude can generally be 0.025g, 0.05g, 0.10g, or u times the peak acceleration of seismic wave.

The advantage of bracket duration is its clear definition, while the disadvantage is that the minimum amplitude of the artificially set boundary directly affects the final duration of strong earthquakes. Especially when the absolute calculation criterion is adopted, some seismic waves with low strength may have zero duration calculation result of strong earthquakes. However, for ground motions with extremely large acceleration peaks, using this definition method to calculate duration may lead to the situation that the structure has been damaged due to excessive peak value before timing.

2.2. Uniform duration

The uniform duration defines the duration of brackets. It refers to the sum of all accelerations exceeding the minimum amplitude set in a time history. The minimum amplitude of this setting can generally be 0.025g, 0.05g, 0.10g, or μ times the peak acceleration of seismic wave, but it is usually smaller than the duration of brackets.

The advantage of consistent duration is that it can screen out all the acceleration peaks which may cause structural damage in a single ground motion, and highlight the characteristics of strong motion. The disadvantage is that its calculation process is discontinuous and it is inconvenient to use.

2.3. Significant duration

Significant duration is the duration expressed by the energy in the earthquake process, which is a widely used definition of earthquake motion duration. Therefore, significant duration is also called energy duration or important duration. The time duration definition method is expressed by Husid function, and the calculation formula is $5\% \leq \int_0^t a^2(t)dt / \int_0^T a^2(t)dt \leq 95\%$. It is expressed in D_{5-95} and called 90% energy duration. The other commonly used energy duration is 70% energy duration. The two commonly used definitions are $5\% \leq \int_0^t a^2(t)dt / \int_0^T a^2(t)dt \leq 75\%$ (D_{5-75}) and $15\% \leq \int_0^t a^2(t)dt / \int_0^T a^2(t)dt \leq 85\% (D_{15-85})$.

The significant duration is the integral result of the square of all accelerations in the time axis of a ground motion. This definition method highlights the influence of the amplitude of the ground motion and contains the energy information of the ground motion. It is the mainstream method at present.

2.4. Effective duration

The effective duration is measured by the Arias strength calculated from the acceleration time history. The calculation concept is similar to the significant duration, the difference is that the beginning and end of strong earthquake segment are limited by absolute values. The calculation formula is $D_{eff} = t_f - t_0$. Where t_0 is the time when Arias strength accumulates to a specified value, t_f is the time when the Arias strength of the remaining ground motion records is equal to a specified value.

One disadvantage of effective duration is that the results are unstable. Because the end of the actual ground motion time history will interfere with the Arias strength value, which will cause fluctuations in the duration results.

Therefore, the effective duration lacks applicability and is only used in the elastic-plastic analysis of single degree of freedom systems in general.

2.5. Structural response duration

The structural response duration refers to the duration of significant influence of ground motion on structural response. The calculation process can include the natural frequency and damping of the structure, which is rarely used at present.

The definition of structural reaction duration is a bold attempt to lead duration into structural calculation. However, there is still a disadvantage, that is, the same ground motion will produce different duration calculation results due to different structures. The calculation results of this definition are greatly affected by the structural characteristics, while the characteristics of the ground motion itself are ignored.

3. DATA SELECTION AND CLASSIFICATION

In order to deeply analyze the influence of source and site characteristics on strong earthquake duration in practical projects, this paper calculates and analyzes the correlation between strong earthquake duration and magnitude, distance and site characteristics based on a large number of real seismic records. Therefore, 16660 seismic ground motion records were selected from Strong motion Seismograph Networks (K-NET, Kik- NET) of Japan (NIED 1995). Their magnitude range is 4-9 and the epicenter distance is 10-262km. The magnitude M_j used in K-NET and KiK- NET is the Japanese Meteorological Agency magnitude. The peak value of the acceleration time history recorded each time is greater than 20 gal. This setting is to ensure sufficient signal-to-noise ratio. These seismic ground motions are recorded by 338 stations in Japan. The average shear wave velocity (V_{S30}) at 30m of the upper soil layer of these sites varies between 106-1437m/s. In NEHRP (2000), the sites are classified into four categories (BCDE) according to these shear wave velocity values. Based on the standard proposed by Hatzigeorgiou (2010), 98% of these seismic ground records are far field (R>20km) and do not contain near fault (R<10km) movements, and 2% of the records are between the two(Hatzigeorgiou and Liolios 2010).

According to the shear wave velocity, the acceleration time histories of 16660 earthquake ground motions are divided into four types of sites B, C, D, E. In order to obtain the influence of different magnitudes and epicentral distances on the duration of strong earthquakes, the magnitudes are further divided into three categories: small earthquakes (4,5.5), moderate earthquakes (5.5,6.5) and large earthquakes (6.5, -). The epicentral distances are divided into three categories: near earthquakes (10,50), moderate earthquakes (50, 100) and far earthquakes (100, -). The detailed classification and the number of seismic records under various classifications are shown in Table 1-4.

Table 1: Classification and Quantity of Seismic Waves in Site B

Site	Site B [760km/s,1500km/s]								
Number	3032								
Magnitude	4<=M<5.5			5.5<=M<6.5			M>=6.5		
Number	1998			714			320		
Epicentral distance	[10,50)	[50,100)	[100, -)	[10,50)	[50,100)	[100, -)	[10,50)	[50,100)	[100, -)
Number	1102	700	196	142	298	274	40	102	178

Table 2： Classification and Quantity of Seismic Waves in Site C

Site	Site C [360km/s,760km/s]								
Number	4284								
Magnitude	4<=M<5.5			5.5<=M<6.5			M>=6.5		
Number	2576			1018			690		
Epicentral distance	[10,50)	[50,100)	[100, -)	[10,50)	[50,100)	[100, -)	[10,50)	[50,100)	[100, -)
Number	1326	978	272	164	384	470	102	176	412

Table 3： Classification and Quantity of Seismic Waves in Site D

Site	Site D [180km/s,360km/s]								
Number	6418								
Magnitude	4<=M<5.5			5.5<=M<6.5			M>=6.5		
Number	2878			1808			732		
Epicentral distance	[10,50)	[50,100)	[100, -)	[10,50)	[50,100)	[100, -)	[10,50)	[50,100)	[100, -)
Number	1606	1566	706	194	568	1046	104	116	512

Table 4： Classification and Quantity of Seismic Waves in Site E

Site	Site E [-,180km/s]								
Number	4284								
Magnitude	4<=M<5.5			5.5<=M<6.5			M>=6.5		
Number	1628			944			354		
Epicentral distance	[10,50)	[50,100)	[100, -)	[10,50)	[50,100)	[100, -)	[10,50)	[50,100)	[100, -)
Number	828	594	206	124	278	542	38	68	248

4. INFLUENCE OF MAGNITUDE, EPICENTRAL DISTANCE AND SITE CONDITIONS ON STRONG EARTHQUAKE DURATION

The 90% energy duration method mentioned in Section 2 is used to calculate the duration of strong earthquakes recorded by all seismic waves under each classification. The calculation comparison results under each category are shown in Figure 1-3.

Figure 1 shows the underground results of four classification sites of B, C, D, E.

It shows that under the fixed field, the duration of strong earthquakes increases with the increase of magnitude in the same epicenter distance classification; Especially, when R ∈ (10, 50), the duration of strong earthquakes decreases with the increase of magnitude in the site C, D and E. With the increase of epicentral distance, the duration of strong earthquakes also increases, and the amplitude gradually increases too. And the duration of strong earthquakes also increases from site B to site E.

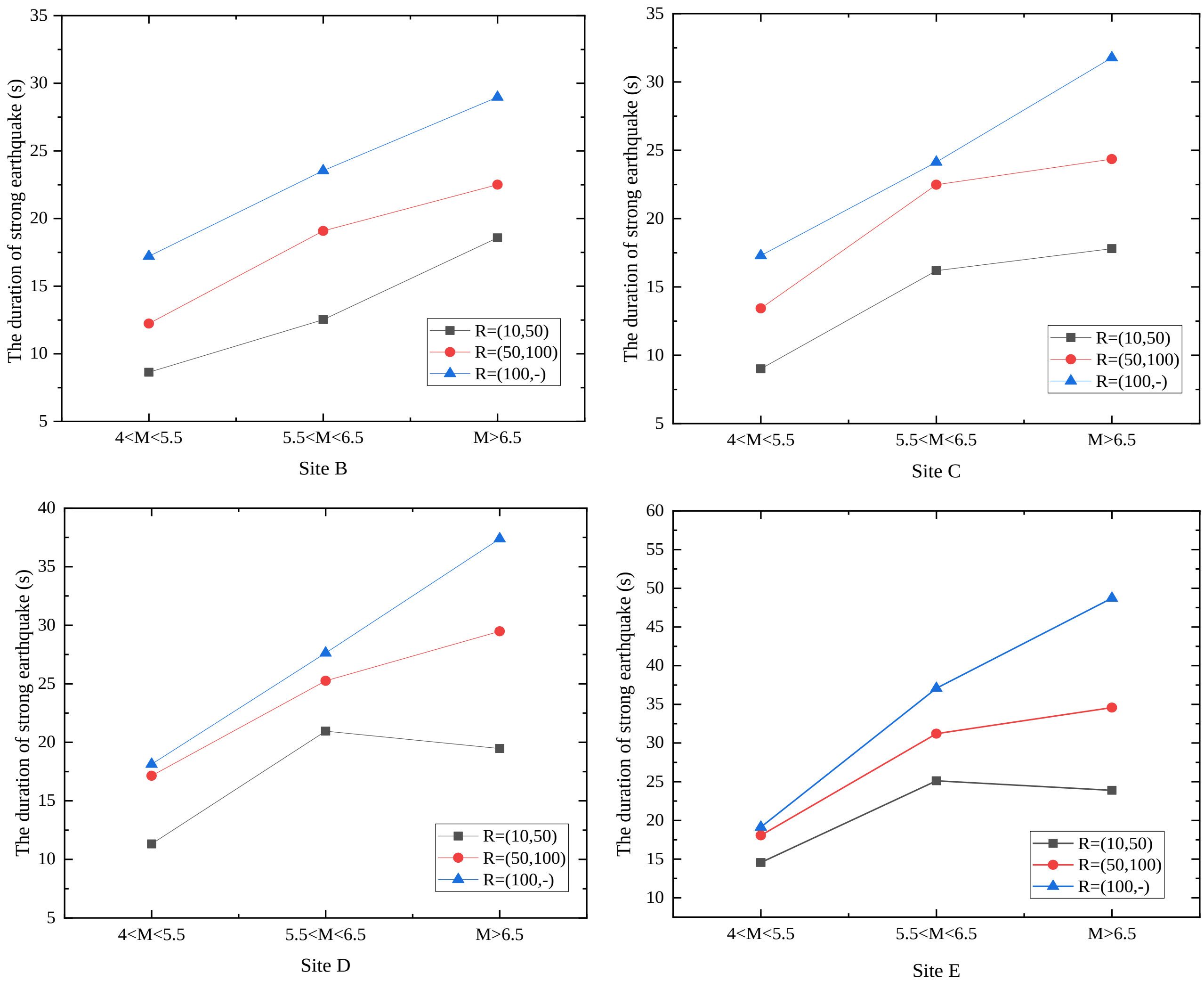

Figure 1: Variation trend of duration with magnitude and epicentral distance under different sites

Figure 2 shows the calculation results of strong earthquake duration under three kinds of epicenter distance classification.

It can be seen from Figure 2 that under a fixed epicenter distance and magnitude classification, the duration of strong earthquakes increases gradually with the site softening; However, when R ∈ (10, 50), the duration of large earthquake M ∈ (6.5, -) is smaller with the calculation result of site C than site B. The magnitude increases from small to large, and the duration of strong earthquakes increases gradually; In particular, when R ∈ (10, 50), the duration of strong earthquakes of moderate earthquakes M ∈ (5.5, 6.5) in soft ground (D and E) is greater than that of large earthquakes M ∈ (6.5, -). In general, as the site becomes soft from C to E, the result of strong earthquake duration shows an increasing trend.

Figure 3 shows the calculation results of strong earthquake duration under three magnitude classifications.

It can be seen from Figure 3 that under the classification of a certain fixed magnitude and epicenter distance, the duration of strong earthquakes increases with the softening of the site. With the increase of epicentral distance, the duration increases gradually. In general, with the increase of magnitude, the duration is also increasing; Moreover, when the small earthquake M ∈ (4,5.5), the increase of the duration of a strong earthquake slows down with the increase of source distance, while when the large earthquake M ∈ (6.5, -), the increase increases with the increase of source distance.

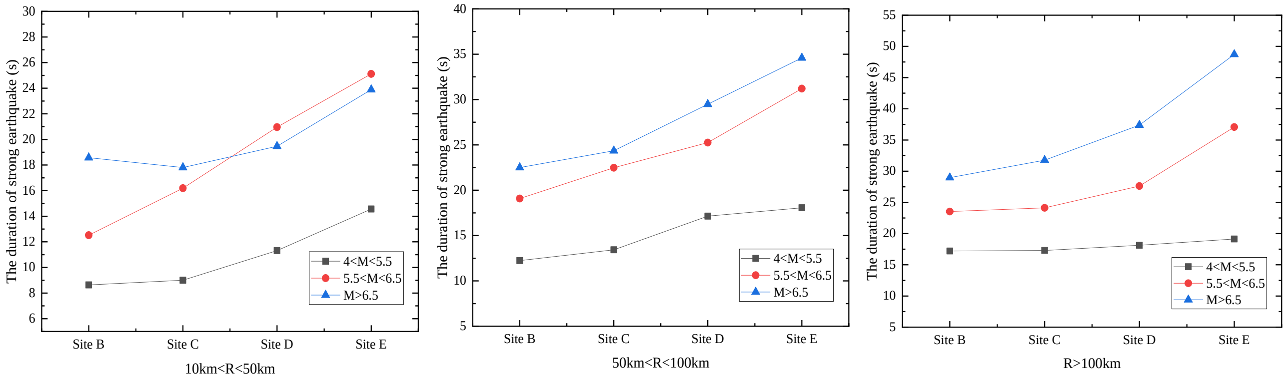

Figure 2: Variation trend of duration with magnitude and sites under different epicentral distance

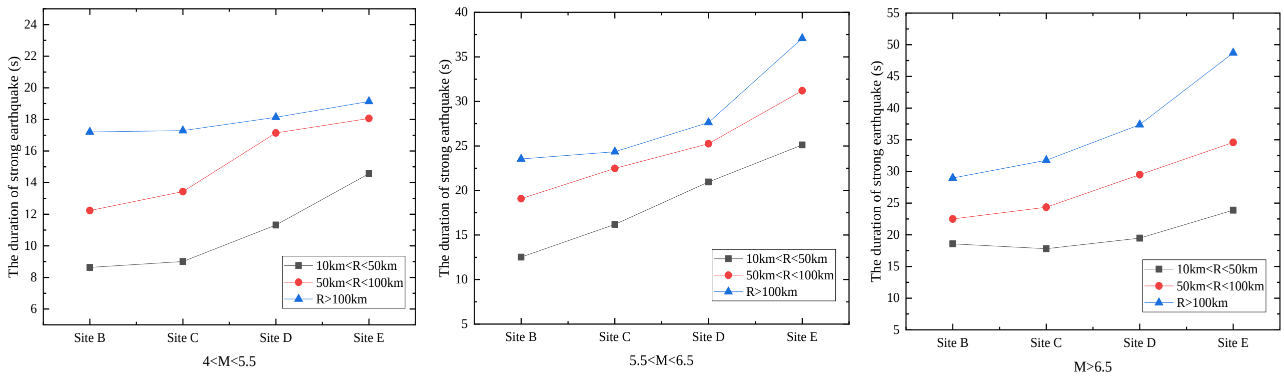

Figure 3: Variation trend of duration with sites and epicentral distance under different magnitude

According to the calculation results shown in all these figures, it can be found that magnitude, epicenter distance and site all have a very significant impact on the duration of strong earthquakes. The site is only divided according to shear wave velocity, and its impact on duration is not as simple as magnitude and epicenter distance. Therefore, the influence of site characteristics on the duration of strong earthquakes is very complex. It is still necessary to continue to study the influence of other site characteristics continuously.

5. CONCLUSIONS AND DISCUSSIONS

In this paper, 16660 actual strong ground motion records from K-NET and KIK-NET are used to calculate the duration of strong ground motions under different magnitudes, epicentral distances and site classifications. Through the comparative analysis of the calculation results, the following conclusions can be drawn:

Generally, the duration of strong earthquakes increases with the increase of magnitude. Especially for large earthquakes, the magnitude plays a leading role in calculating the duration of a strong earthquake. At this time, the influence of epicentral distance and site on the calculation results is not significant.

The duration of strong earthquakes usually increases with the increase of epicentral distance, but is limited by magnitude and site. In various sites with small magnitude, the duration decreases with the increase of epicentral distance.

Site characteristics have a dominant and complex effect on the duration of strong earthquakes. The duration varies with the site at different magnitudes and epicentral distances. In the far field of small earthquakes, the change of the site has little effect on the duration; The near field of small earthquakes is greatly affected by the site, and the duration increases gradually with the site softening; In the near field of moderate earthquakes, the duration increases significantly as the site becomes soft. Consequently, site conditions have a more significant impact on small and moderate earthquakes, and the duration of strong earthquakes of large earthquakes is still dominated by magnitude.

Based on the above conclusions, we find that, in addition to the source characteristics, the influence of site conditions on the duration of strong earthquakes cannot be ignored. In view of the complexity of the impact results, the relationship between the characteristic parameters of each site and the duration of ground motion still needs to be studied in detail. Based on this starting point, the follow-up research will comprehensively consider the impact of various site characteristics on the duration of strong earthquakes.

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