The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

THE DURATION CHARACTERISTICS OF EARTHQUAKE GROUND MOTIONS

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ABSTRACT:

The duration of strong shaking is one of the key parameters in engineering analysis and earthquake resistant design of structures, since the damaging effects of an earthquake as well as operational reliability of equipment are often related to the duration of strong shaking. There are several definitions of duration, as described in the paper. In this study, the so-called relative significant duration has mainly been applied. A model is presented for the relative significant duration using regression analysis based on an appropriate data set for moment magnitude and source-to-site distance. The data set applied is taken from the ISESD databank and contains shallow strike-slip earthquakes from Armenia, Greece, Iceland, Italy, Slovenia and Turkey. Main emphasis is placed on rock site conditions. The relative significant duration appears to represent the S-phase of ground shaking in the near and intermediate fault area reasonably well, but for the cases studied the S-waves create the dominating horizontal seismic action on structures. However it is also seen that the uncertainties reflected by the residual error can be significant.

KEYWORDS: Seismology, earthquake, strong ground-motion, duration of ground motion, regression modelling, ISESD databank

1. INTRODUCTION

The duration of strong shaking is one of the quantities needed in engineering analysis and earthquake resistant design of structures. Estimate of duration is required as an input into any probabilistic analysis as well as for Monte Carlo simulation of time series. Duration of strong shaking plays an important role regarding operational reliability of equipment during earthquakes. Furthermore, the damaging effects of an earthquake are strongly related to the duration of strong shaking. This is especially the case for deterioration of masonry and reinforced structural concrete as repeated cycles of seismic action presumably lead to repeated cracking of the masonry/concrete and yielding in the reinforcement steel resulting in strength degradation and low cycle fatigue. As the structure degrades its stiffness decreases and effective natural period increases. This implicitly assumes that the longer period content of the ground motion occurs after the shorter period motions that initiate stiffness degradation.

The influence of duration on the seismic response of soils is universally acknowledged and methods for the assessment of liquefaction potential consider the duration of motion. There is, by contrast, no such unanimous view regarding the influence of duration on inelastic structural response. Intuitively, the inelastic response of a structure should depend on both the amplitude of the shaking – to take the structural elements to their cracking or yielding states – and the duration of the shaking, since the latter should control the amount of inelastic deformation accumulated. Although the severity of the loading and hence damage to structures is shown to be governed by the spectral amplitude of the ground motions, the period of the critical spectral acceleration changes with increased degradation and time and is influenced by the phase difference and duration of the strong shaking (Bommer et al., 2004). However, the degree to which strong-motion duration influences the damage experienced by buildings during earthquakes remains a subject of debate and investigation (Bommer et al., 2006). Iervolino et al. (2006) came to the conclusion that the answer to the question "does duration matter for inelastic response" depends on the considered demand measure.

It has been suggested (Bolt, 1973; Trifunac and Westermo, 1982; Novikova and Trifunac, 1994) that the duration of strong ground motion should be considered separately in several narrow frequency bands. Thereby considering the motion as being composed of several separate portions, whose position in the record can be specified. This can be useful when studying the source of an earthquake and the related wave propagation phenomena as well as the resulting structural response of individual structures. In this study, however, a more global perspective was chosen, in order to develop a relatively simple model that could describe the dependence of duration on earthquake magnitude and epicentral distance.

2. DEFINITION OF GROUND MOTION DURATION

Several different definitions have been proposed for ground motion duration measure. Bommer and Martines-Perreira (1999) reviewed about 30 different definitions of duration. The most commonly used are bracketed, uniform and significant durations, both absolute and relative. They need to be calculated with user-specified limits, which make direct comparison between the derived results often difficult. The definitions for these three types of duration estimates are given in the subsequent sections.

2.1. Bracketed duration

The *absolute bracketed duration* is specified as the length of the time interval between the first and last occurrence of a ground acceleration exceeding a fixed threshold value. It can be defined formally as:

$$\tau_{ab} = \max(t) - \min(t) \tag{2.1}$$

where t is the solution of:

$$H\left(\left|a(t)\right| - a_o\right) = 1 \tag{2.2}$$

Here, $H(\cdot)$ is the Heaviside step function, $a(t)$ is recorded acceleration component as a function of the time t, and a_o is the threshold given as an absolute value, usually 0.05 g (Bolt, 1973).

The *relative bracketed duration* is specified as the length of the time interval between the first and last time the ground acceleration exceeds a threshold value defined as a fraction of the peak ground acceleration. Formally this can be stated as:

$$\tau_{rb} = \max(t) - \min(t) \tag{2.3}$$

where t is the solution of:

$$H\left(\left|a(t)\right| - \alpha_o PGA\right) = 1 \tag{2.4}$$

Here, $H(\cdot)$ is the Heaviside step function, $a(t)$ is recorded acceleration component as a function of the time t, α_o is the fraction (often taken as 0.05) and PGA denotes the peak ground acceleration. The bracketed duration can therefore be considered to be an intensity-dependent measure of energy.

2.2. Uniform duration

The *absolute uniform duration* is specified as the length of time for which the ground acceleration exceeds a fixed threshold value (Sarma and Casey, 1990). Formally it can be defined as follows:

$$\tau_{au} = \int_0^{\infty} H\left(\left|a(t)\right| - a_o\right) dt \tag{2.5}$$

Here, $H(\cdot)$ is the Heaviside step function, $a(t)$ is recorded acceleration component as a function of the time t, and a_o is the user defined threshold given as an absolute value. It follow from the definitions that the absolute bracketed duration is greater or equal than the absolute uniform duration for a given acceleration component and any given threshold, i.e. $\tau_{ab} \geq \tau_{au}$.

The *relative uniform duration* is specified as the total length of time for which the ground acceleration exceeds a threshold value given as a fraction of the peak ground acceleration. Formally it can be defined as follows:

$$\tau_{ru} = \int_0^{\infty} H\left(\left|a(t)\right| - \alpha_o PGA\right) dt \tag{2.6}$$

Here, $H(\cdot)$ is the Heaviside step function, $a(t)$ is recorded acceleration component as a function of the time t, PGA denotes the peak ground acceleration and α_o is the fraction (often taken as 0.05) of the peak ground acceleration defining the threshold value. It follow from the definitions that the relative bracketed duration is greater or equal to the relative uniform duration for a given acceleration component and any given threshold, i.e. $\tau_{rb} \geq \tau_{ru}$.

2.3. Significant duration

The *absolute significant duration* is defined as the length of the time interval between the two time points when the Arias intensity exceeds two separate fixed threshold values. This can be expressed as follows:

$$\tau_{as} = \int_0^\infty \{H(AI(t) - AI_1) - H(AI(t) - AI_2)\}dt \qquad (2.7)$$

Here, $H(\cdot)$ is the Heaviside step function, $AI(t)$ is the Arias intensity (Arias, 1970) as a function of the time t, and AI_1 is the first threshold commonly defined as 0.01 m/s and AI_2 is the second threshold usually taken as 0.125 m/s. Bommer and Martinez-Pereira (1999) call this quantity 'effective' duration.

The *relative significant duration* is defined as the length of the time interval between when the normalised Arias intensity exceeds two separate fixed threshold values. This can be expressed as follows:

$$\tau_{rs} = \int_0^\infty \{H(A(t) - A_1) - H(A(t) - A_2)\}dt \qquad (2.8)$$

Here, $H(\cdot)$ is the Heaviside step function, $A(t)$ is normalised Arias intensity, as a function of the time t, defined as $A(t) = AI(t)/\max(AI(t))$, A_1 defines the first threshold usually given as 0.05 and A_2 is the second threshold commonly taken as 0.95 (Trifunac & Brady, 1975). Hence the relative significant duration is the time span when 90% (or comparable user defined fraction) of the wave energy is released at a given location.

3. ANALYSIS AND RESULTS

The data used in the following is obtained from the ISESD data bank found on the web site: http://www.isesd.hi.is (see also Ambraseys et al. (2004)). The ISESD is one of the best available sources for European and Mediterranean strong ground motion data. More than 3,000 acceleration time histories from earthquakes in Europe and adjacent areas are archived in the database.

The authors study areas are the transform zones in North and South Iceland, where the seismicity is characterized by shallow strike-slip earthquakes of magnitude up to 7. Data from the Icelandic Strong-Motion Network is a considerable part of the available data, especially for strike-slip source mechanism. Hence, the study area of the seismic environment in Iceland should be fairly well reflected by the applied data, but the data chosen for this study was from shallow strike-slip earthquakes from Armenia, Greece, Iceland, Italy, Slovenia and Turkey. Main emphasis is placed on rock site conditions. The distribution of the applied data in terms of moment magnitude and source distance is displayed in Figure 1. The data set shown contains 71 tri-axial strong-motion records recorded at rock sites in 13 shallow strike-slip earthquakes. This data set is reasonably complete within the magnitude range of 5.5 to 6.5 but is especially lacking more data for magnitudes above 6.5.

It is found that the absolute durations for a fixed threshold value tend to decrease with increasing distance to the causative source, while the relative duration measures tend to increase with increasing distance to source. In cases when duration is used in connection with quantities like peak ground acceleration to model seismic action it is common to use the relative duration measures rather than the absolute ones (Trifunac and Westermo, 1982). In our assessment of duration we have chosen to follow this practice. Furthermore, we have primarily applied the relative significant duration in the following analysis (see Eqn.2.8). The Significant Duration (Trifunac et al. 1975) defines ground motion duration as the length of the time interval between the accumulation of 5% and 95% of ground motion energy, where ground motion energy is defined by the Arias Intensity (Arias 1970). Since the data includes ground motion from different tectonic environments and different spectral intensities, the Arias energy definition is more applicable, than the intensity driven energy measure of the bracketed and uniform duration estimate. Another reason for using the relative significant duration is that it appears to represent the S-phase of ground shaking in the near and intermediate fault area rather well. This is important, because for the data applied the S-waves create the dominating horizontal seismic action on structures.

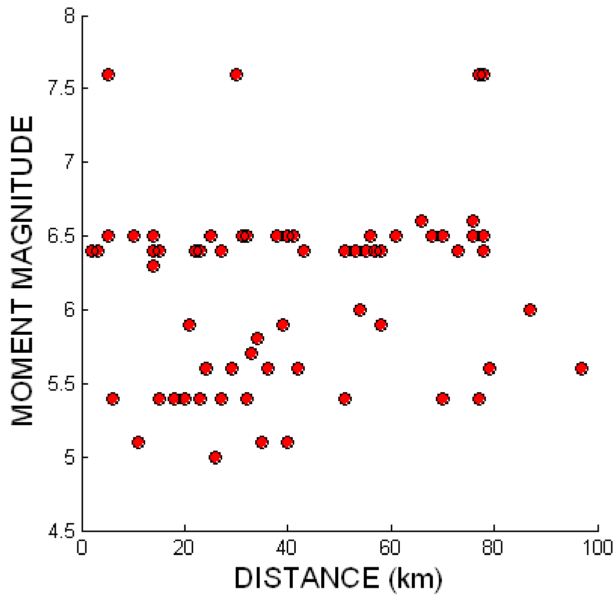

Figure 1 Distribution of the applied data in terms of moment magnitude and source distance. The data set shown contains 71 tri-axial strong-motion records recorded at rock sites in 13 shallow strike-slip earthquakes.

The following simplified model is fitted to the selected dataset of shallow strike-slip earthquakes with near vertical fault plane. That is:

$$\log_{10}(\tau_{sr}) = b_1 + b_2 M_w + b_3 \log_{10}\sqrt{d^2 + b_4^2} \tag{2.9}$$

Here, M_w is moment magnitude, d is distance to surface trace of the fault, b_1, b_2, b_3 and b_4 are regression coefficients. It is seen that the b_4 coefficient is a depth parameter to prevent singularity for d = 0. The regression analysis gave the following coefficients:

$$[\ b_1,\ b_2,\ b_3,\ b_4,\ \sigma\ ] = [\ -1.3877,\quad 0.2451,\quad 0.6280,\quad 4.50,\quad 0.1663\ ] \tag{2.10}$$

These parameters refer to distance in km and duration in s. The last coefficient, σ, represents the residual error. According to Jarque-Bera test the residual are approximately normal distributed (5% significance level) with standard deviation equal to 0.166 (log-scale).

The results of the regression analysis are displayed in Figure 2 using linear scales and normalized duration. As can be seen there is considerable scatter in the displayed results, however, the data fits within the error bounds of ± one standard deviation and the model seems to display the general trend of the data fairly well. The observed scatter is linked to the fact that ground motions are affected by the three main factors such as source, path and local site effects. Shoji et al (2005), using data with hypocentral distance between 15 and 600 km, found the scatter of data for the duration to get larger and larger when the hypocentral distance increases. As an explanation, it may be considered that the variance of the duration is associated with the effect of scattering and attenuation of seismic waves for longer travel paths. It is also indicated that the variance of the duration can be influenced by local soil conditions.

A slightly different view of the suggested model is given in Figure 3, which shows the model points for magnitude 6.5 earthquake (solid line) along with data from the South Iceland earthquakes on 17 and 21 June

2000 (Sigbjornsson and Olafsson, 2004), represented by the circles. In this case we use a logarithmic scale for the distance to emphasize the near fault area. The dashed lines indicated ± one standard error as obtained from the whole dataset applied. Visually the fit of the model to these data appears fare, even though the model tends to give longer duration for distances shorter than 10 km than the duration reflected by the data points.

Finally, Figure 4 gives the relative significant duration as a function of distance to surface trace of the causative fault for different earthquake magnitude values. It is seen that the relative significant duration in the near fault area is not expected to exceed 10 s on the average. However, it is also found that the uncertainties reflected in the standard error can increase this value significantly. This increase can be almost 50% if one standard deviation is added to the mean values reflected in the curves of Figure 4.

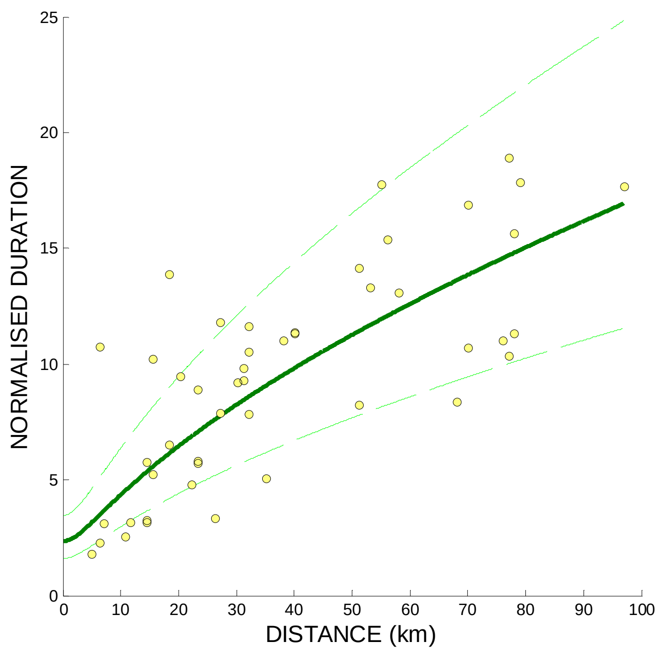

Figure 2 Relative significant duration of shallow strike-slip earthquakes. The solid line is the suggested model obtained by regression analysis and the circles are data from the applied dataset. The dashed lines represents gives the model ± one standard deviation.

4. CONCLUSIONS AND FINAL REMARKS

The duration of strong shaking is one of the quantities needed in engineering analysis and earthquake resistant design of structures as well as playing an important role regarding operational reliability of equipment during earthquakes. There are several definitions of duration. In our assessment of duration, we have mainly applied the relative significant duration, which is defined as the time interval between two separate fixed threshold values of the normalised Arias intensity are exceeded.

A model is presented for the relative significant duration using regression analysis based on an appropriate data set for moment magnitude and source-to-site distance. The data set applied is taken from the ISESD databank and contains shallow strike-slip earthquakes from Armenia, Greece, Iceland, Italy, Slovenia and Turkey. Main emphasis is placed on rock site conditions.

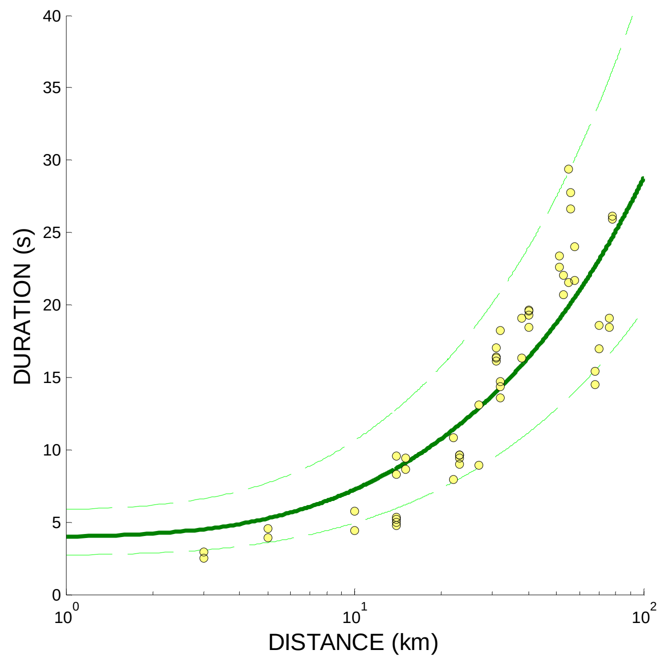

Figure 3 Relative significant duration of shallow strike-slip earthquakes. The duration values obtained for the June 2000 South Iceland Earthquakes compared to suggested duration model (solid line). The dashed lines represent the model ± one standard deviation of full dataset.

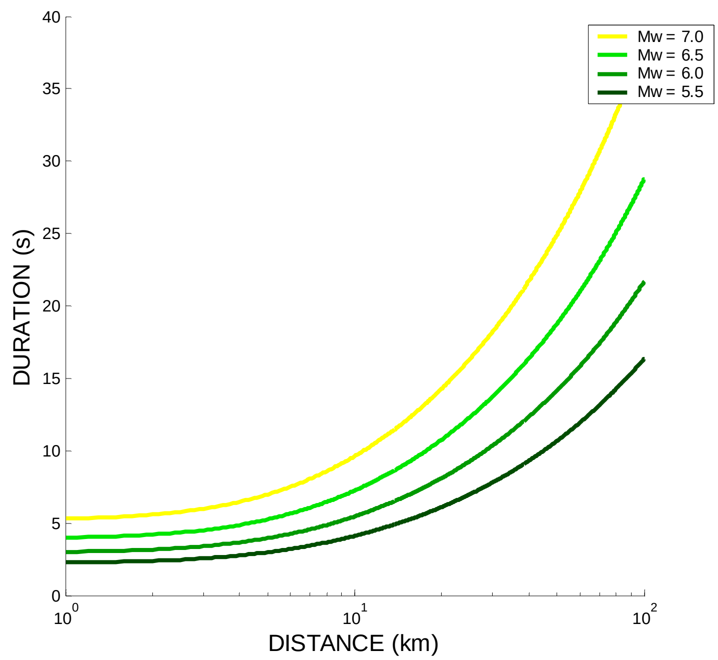

Figure 4 Relative significant duration of shallow strike-slip earthquakes with near vertical fault plane. Suggested model representing duration as a function of distance to surface trace of causative fault for different magnitude values.

The relative significant duration appears to represent the S-phase of ground shaking in the near and intermediate fault area reasonably well, but for most of the cases in our study it is the S-waves that create the dominating horizontal seismic action on structures.

The earthquake motion duration is seen to increase with increasing magnitude and epicentral distance, as expected. The fit of the regression model to the recorded data set appears reasonable. However, it is seen that the uncertainties reflected by the residual error can be significant, which is in line with the findings of other investigators.

The duration of strong ground shaking during earthquakes can play an important role in the response of foundation materials and structures, particularly when strength or stiffness degradation is encountered. A thorough seismic hazard assessment should therefore include an estimation of the expected duration of strong motion, which first requires criteria to define the part of an accelerogram considered to represent the duration of strong ground motion. The earthquake motion duration parameters presented in this paper provide a basic data required for simulating a random earthquake excitation suitable to aseismic analysis and design of modern engineering structures.

ACKNOWLEDGEMENTS

The presented work was supported by Landsvirkjun and the University of Iceland Research Fund.

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