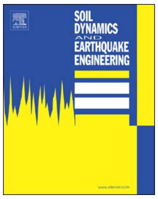
Soil Dynamics and Earthquake Engineering 102 (2017) 65–74

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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



Empirical correlations between the effective number of cycles and other intensity measures of ground motions

Wenqi Du[a,*], Gang Wang[b]

[a] Institute of Catastrophe Risk Management, Nanyang Technological University, 50 Nanyang Avenue Singapore
[b] Dept. of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon Hong Kong

ARTICLE INFO

Keywords:
Effective number of cycles
Correlation coefficient
NGA database
Ground motion selection
Liquefaction potential

ABSTRACT

The effective number of cycles is an important ground motion parameter for the assessment of liquefaction potential. In this paper, empirical correlations for two measures of the effective number of cycles with seven amplitude-, cumulative-, and duration-based intensity measures (IMs) are studied and compared, based on the NGA strong motion database and several ground motion prediction equations. The adopted definitions of the effective number of cycles include an absolute measure (N_A) and a relative measure (N_R). It is shown that N_A is highly correlated with high-frequency IMs, such as spectral acceleration (SA) at short periods, Arias intensity, and negatively correlated with signification durations (Ds). On the other hand, N_R shows generally negative correlations with both amplitude- and cumulative-based IMs. N_R also exhibits small-to-moderate positive correlations with Ds, which are commonly regarded as similar parameters to the effect number of cycles. Simple parametric functions are provided to describe the N_A-SA and N_R-SA correlations for various cases. The importance of considering multiple IMs rather than SA only in ground-motion selection is also briefly demonstrated.

1. Introduction

The number of cycles of ground motions has been widely recognized as one of the critical parameters in geotechnical earthquake engineering. Many studies (e.g., [1,2]) have concluded that the number of cycles of shakings is strongly correlated with the buildup of pore water pressure in liquefiable soils. As summarized by Hancock and Bommer [3], there are dozens of definitions to count the effective number of cycles, by converting all irregular amplitude cycles to an equivalent number of uniform cycles. The concept of equivalent number of cycles is commonly used for evaluating liquefaction potential [4–6].

Due to the complex features of ground motion time histories, single ground motion intensity measure (IM) cannot adequately characterize earthquake loadings. Therefore, a set of IMs (vector-IMs) is often required in some practical applications, such as the estimation of earthquake-induced slope displacement [7,8]. Since current ground motion prediction equations (GMPEs) only provide the means and standard deviations for specific IMs, empirical correlations among the residuals of these IMs are then the key requirement to contrast the joint distribution of vector-IMs. These empirical correlations are indispensable in vector-based probabilistic seismic hazard analysis [9] and scenario-based ground motion selection approaches, e.g., [10–12].

Recently a number of researchers have studied empirical correlations between the residuals of multiple IMs, such as spectral accelerations (SA) at multiple periods, Arias intensity (Ia), cumulative absolute velocity (CAV), and significant durations (Ds), e.g., [13–18]. However, to the knowledge of the authors, there are no existing correlation models involving the number of effective cycles. Bommer et al. [19] has studied the correlations between several duration parameters and effective numbers of ground motion cycles. Yet, they did not aim at evaluating the correlations between the residuals of these IMs, making it difficult to be used in some applications such as ground motion selection.

The objective of this paper is to examine the empirical correlations between the effective number of cycles and other commonly used IMs. The definitions of these employed IMs are firstly discussed, associated with the utilized GMPEs and ground motion database. Secondly, the estimated correlation coefficients between the residuals of these IMs are presented; simple parametric models are also proposed to readily predict the empirical correlations. The influence of rupture distance (R_{rup}) on the resulting correlation coefficients is then examined. Finally, based on the correlation results, some recommendations are provided regarding the use of different definitions of the effective number of cycles for practical applications.

---

[*] Corresponding author.
E-mail address: wqdu@ntu.edu.sg (W. Du).

http://dx.doi.org/10.1016/j.soildyn.2017.08.014
Received 17 November 2015; Received in revised form 9 July 2017; Accepted 25 August 2017

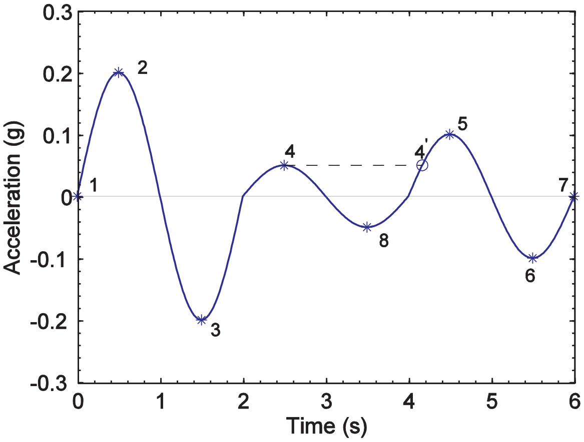


Fig. 1. A demonstrated example of the use of rainflow-counting approach. This segment consists of several sine waves, which can be counted as five half cycles (1–2; 2–3; 3–4-4′ – 5; 5–6 and 6–7) and one full cycle (4–8-4′). The amplitudes of the five half cycles are 0.1, 0.2, 0.15, 0.1, and 0.05 g, respectively; the amplitude of the full cycle is 0.05 g. The segment yields values of N_A and N_R as 0.09 and 1.125, respectively.

2. Selected IMs and ground motion database

2.1. Effective number of cycles

As summarized in Hancock and Bommer [3], there are many cycle-counting definitions in the literature, which can be mainly classified into several categories: peak counting, level crossing counting, range counting, and indirect counting methods. These cycle-counting definitions were developed for low-cycle fatigue testing [20]. Among these definitions, the rainflow range-counting method is the most popular since it quantifies both the high-frequency and low-frequency cyclic waves in broadband signals. This method counts a history of peaks and troughs in sequence which can be regarded as starting and ending points for defining each cycle. The algorithm can be simplified as: (i), the signal is turned clockwise as 90°; (ii), an imagined source of water will flow down the "pagoda roofs" from their upper tops; (iii), the water will drip down when it reaches the edge. It will stop when it comes to a point that is already wet (quantified by previous flow), or it reaches opposite beyond the vertical of the starting point; (iv), the steps (ii)-(iii) can be repeated to get a series of half-cycles. The detailed algorithm of this approach can be found in References [3,21]. Fig. 1 shows a simple example about the application of the rainflow-counting technique. Total five half-cycles and one full-cycle are identified for this wave. Besides, prediction equations for the effective number of cycles based on the rainflow-counting approach have been proposed [22], which can be directly used to account for the statistical distributions of these IMs.

Similar to the cyclic damage parameter for low-cycle fatigue failure used by Malhotra [23], the absolute definition of the effective number of cycles can be expressed as:

$$N_A = \sum_{i=1}^{2T_n} u_i^2 \tag{1}$$

where u_i is the amplitude of the i-th half cycle obtained by the rainflow range-counting method; T_n is the total number of cycles; and N_A is the absolute measure of the effective number of cycles. It is noted that the exponent coefficient is set as 2 herein, which reflects the relative importance of different amplitude cycles. A higher value of the exponent coefficient represents a larger contribution caused by large-amplitude cycles.

Relative definitions of the effective number of cycles are commonly used in earthquake engineering. A typical relative definition of the number of cycles, in which each amplitude u_i is normalized by the maximum amplitude of all half-cycles, $u_{\max}$, is expressed as:

$$N_R = \frac{1}{2}\sum_{i=1}^{2T_n}\left(\frac{u_i}{u_{\max}}\right)^2 \tag{2}$$

where N_R is the relative measure of the effective cycles. A value of 2 is also adopted for the exponent coefficient.

It is worth noting that only the effective number of cycles obtained by the rainflow-counting method is considered in this paper, due to its popularity and robustness. The selected measures of cyclic numbers can be applied in most practical cases. The aforementioned empirical equations proposed by Stafford and Bommer [22], which are termed as SB09 model hereafter, will be used to predict N_A and N_R in the following section. The SB09 model utilized a subset of the Pacific Earthquake Engineering Research (PEER) NGA-West1 database [24], employing moment magnitude M_w, rupture distance R_{rup}, site parameters and the depth to the top of rupture (Z_{tor}) as indicators. A set of equations has been proposed by Stafford and Bommer [22], while only the basic equations without the consideration of Z_{tor} or directivity effect are used in this study. The median predictions of the SB09 model for N_A and N_R with respect to M_w and R_{rup} are shown in Fig. 2. It should be noted that the other few prediction equations using different counting methods, e.g., [25], are not considered due to the scope of this paper.

2.2. Other IMs considered

The other IMs considered herein are listed as: (a) peak values of ground motion time histories, including peak ground acceleration (PGA) and peak ground velocity (PGV); (b) SA at multiple periods; (c) cumulative-based intensity measures, including Ia and CAV; and (d) ground motion duration parameters, including significant durations defined as time intervals over which 5–75% and 5–95% of Ia are built

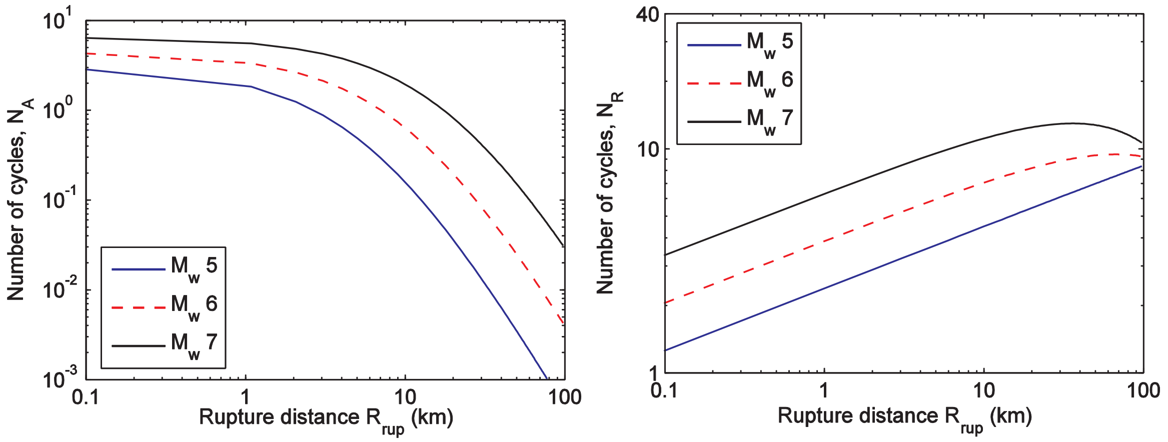


Fig. 2. Median predictions of the SB09 model for the effective number of cycles N_A and N_R, respectively. The V_{s30} value is set as 400 m/s for predicting N_R.