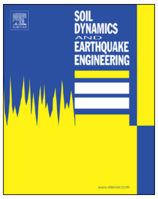
Soil Dynamics and Earthquake Engineering 78 (2015) 89–98

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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



Correlation of Arias intensity with amplitude, duration and cumulative intensity measures

Brendon A. Bradley*

Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand

ARTICLE INFO

Article history:
Received 6 March 2014
Received in revised form
28 May 2015
Accepted 7 July 2015
Available online 6 August 2015

Keywords:
Arias Intensity (AI)
Correlation coefficient
Ground motion selection
Generalized conditional intensity measure (GCIM)
Vector hazard analysis.

ABSTRACT

This manuscript examines the correlation of Arias intensity (AI) with nine amplitude-, duration-, and cumulative-based ground motion intensity measures. The correlations are determined using ground motions from active shallow crustal earthquakes in the NGA-West1 database, and recently developed ground motion prediction equations (GMPEs). Multiple GMPE combinations and bootstrap sampling are used to explicitly consider correlation uncertainties due to model selection and finite sample effects, respectively. It is shown that AI is highly correlated with high-frequency amplitude-based intensity measures and negatively correlated with significant duration intensity measures. AI also has a strong, but not perfect, correlation with cumulative absolute velocity (CAV), which is also a cumulative measure of ground motion severity. Particular attention is given to the physical interpretation of the observed correlations of AI and other intensity measures, often in comparison to those obtained with CAV. Parametric equations are developed to enable the obtained correlations to be easily used in applications such as ground motion selection and vector hazard analysis.

1. Introduction

Arias intensity, AI [1], is a cumulative ground motion intensity measure (IM), computed based on the time integral of the squared acceleration, as given by Eq. (1)

$$\mathrm{AI} = \frac{\pi}{2g}\int_0^{t_{max}} [a(t)]^2 dt \tag{1}$$

where $a(t)$ is the ground motion acceleration at time t, t_{max} is the total duration of the ground motion, and g is the acceleration of gravity. Eq. (1) is a specific version of AI for the commonly considered case of zero damping [2]. As can be seen from the integral definition of Eq. (1), AI considers the ground motion acceleration amplitude, frequency content (i.e., the value of the integrand between zero-crossings will be frequency-dependent), and duration of ground motion. The fact that AI captures these three general aspects of ground motion severity makes it notably different from other conventional intensity measures which are often a measure of peak amplitude (e.g., peak ground acceleration/velocity, and response spectral ordinates). From a theoretical standpoint, AI, represents the cumulative energy per unit weight absorbed by an infinite set of single-degree-of-freedom oscillators having a uniform distribution of fundamental frequencies on $(0, \infty)$ [1].

Several studies have reported a strong correlation between AI and various metrics of seismic response, such as short-period structural response [3,4], macroseismic intensity [3], slope stability and landslides [5–8], and soil liquefaction [2,9]. Several robust empirical ground motion prediction equations (GMPEs) are now also available for the prediction of AI based on worldwide active shallow crustal earthquakes, e.g., [10–12], allowing the aforementioned correlations with seismic response to be utilized in a forward prediction sense.

In addition to the use of AI as a single measure of ground motion severity, it can also be considered as part of a set (or vector) of ground motion IMs for more advanced analyses (often, but not necessarily, site-specific), e.g., [13,14]. The increasing emphasis of performance-based earthquake engineering, in which seismic performance is often assessed using time domain seismic response analysis, is placing an increasing emphasis on the selection of ground motion records with adequate consideration of the cumulative nature of ground motions, particularly for larger magnitude earthquakes which produce ground motions with damagingly-long durations. While the consideration of ground motion amplitude and frequency content are often explicit in ground motion selection, via the examination of a ground motion's response spectra, less attention is often devoted to the consideration of the cumulative and duration-related aspects of a ground motion. A key requirement for the consideration of cumulative

---

* Tel.: +64 3 364 2987x7395.
E-mail address: brendon.bradley@canterbury.ac.nz

http://dx.doi.org/10.1016/j.soildyn.2015.07.009
0267-7261/

ground motion IMs, such as AI, in ground motion selection is the availability of empirical correlation equations between AI and various other commonly adopted amplitude- and duration-based ground motion IMs [15]. Such correlation equations are also a requirement in vector probabilistic seismic hazard analysis [16,17].

The absence of robust AI correlation equations provides the motivation to develop the models as presented in this paper. First, the various intensity measures considered for correlation with AI are presented, and the utilized GMPEs and ground motion dataset explained. The methodology for computation of the correlation coefficients is then provided, particularly focusing on consideration of uncertainty in the correlation coefficient due to GMPE model selection and finite sample effects. The obtained empirical correlation results are then presented, parametric models developed, and compared with several point-estimated correlations obtained in previous studies. The obtained AI correlations are then discussed in the context of similar correlations previously developed for CAV, and the possible uses of both of these cumulative ground motion IMs in applications outlined.

2. Empirical correlation of Arias intensity with other intensity measures

2.1. IMs examined

The other IMs considered herein to compute the correlation with AI are: (i) peak ground acceleration, PGA; (ii) peak ground velocity, PGV; (iii) (pseudo) spectral acceleration, SA, for periods from 0.01 to 10 s; (iv) acceleration spectrum intensity, ASI [18]; (v) spectrum intensity, SI [19]; (vi) displacement spectrum intensity, DSI [20]; 5–75% and 5–95% significant duration (Ds_{575} and Ds_{595}, respectively); and (vii) cumulative absolute velocity (CAV) [10,21]. CAV, in particular, like AI, is also a cumulative measure of ground motion intensity, and several parallels for these two IMs are made throughout this paper. It can be seen that the nine other IMs considered cover a range of amplitude-, duration-, and cumulative-based measures of ground motion severity. The number of ground motion IMs considered herein is limited because of scope, and also those which are deemed to have robust GMPEs (discussed in the subsequent section), and it is not intended to imply that other IMs are not important indicators of the severity of a ground motion.

2.2. GMPEs adopted

Despite the theoretical appeal of AI, and its strong correlation with various seismic response parameters, there have been relatively few GMPEs developed [10]. Following the creation of two pioneering AI prediction models developed in the 1970s using limited data [22,23], two decades passed before several other AI models were developed based on regional active shallow crustal data [24–27]. Presently, three models exist which are developed from worldwide active shallow crustal data: Travasarou et al. [12] (T03), Foulser-Piggott and Stafford [11] (FS11), and Campbell and Bozorgnia [10] (CB12). These three models are those considered herein and a comparison of their predictions is provided for various magnitude, source-to-site distance, and site conditions in Fig. 1. The T03 model utilized 1208 ground motions from the Pacific Earthquake Engineering Research (PEER) database, and provides predictions for three binary site classes. The FS11 and CB12 models both utilize sub-sets of the NGA-West1 database [28] and provide predictions for a V_{s30}-based site classification.

The predicted distributions of the other aforementioned intensity measures for a given rupture scenario were obtained using various GMPEs applicable for active shallow crustal tectonic regions. Distributions of the amplitude-based intensity measures PGA, PGV, SA, ASI, SI, and DSI were computed using four of the NGA-West1 [29] ground motion prediction equations: Boore and Atkinson [30], Chiou and Youngs [31], Campbell and Bozorgnia [32], and Abrahamson and Silva [33]. These four GMPEs are herein referred to as BA08, CY08, CB08 and AS08, respectively. These NGA-West1 GMPEs provide explicit predictions for PGA, PGV and SA, and can also be used to predict ASI, SI and DSI using analytical equations based on SA GMPEs [20,34,35]. Herein, for example, a prediction of SI using the Bradley et al. [35] analytical equations

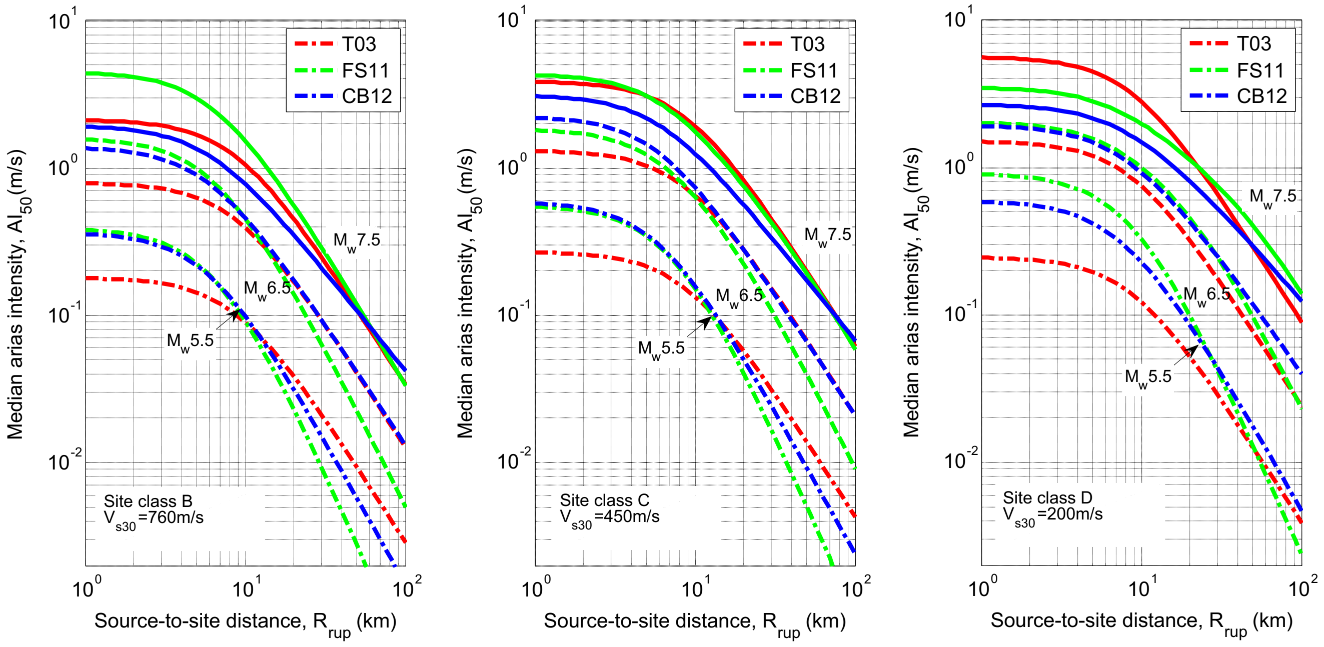


Fig. 1. Comparison of the median predictions of the three considered AI GMPE's for various magnitudes, source-to-site distances and site conditions. Line color indicates the different GMPE's, while line style indicates the considered magnitudes. The considered fault is a vertical strike-slip fault with a depth to the top of the fault plane dependent on event magnitude (depths of $Z_{TOR} = 5$, 2, and 0 km for magnitudes of $M_w = 5.5$, 6.5, 7.5).