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Empirical predictive model for the v_{max}/a_{max} ratio of strong ground motions using genetic programming

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ABSTRACT

Earthquake-induced deformation of structures is strongly influenced by the frequency content of input motion. Nevertheless, state-of-the-practice studies commonly use the intensity measures such as peak ground acceleration (*PGA*), which are not frequency dependent. The v_{max}/a_{max} ratio of strong ground motions can be used in seismic hazard studies as a parameter that captures the influence of frequency content. In the present study, genetic programming (GP) is employed to develop a new empirical predictive equation for the v_{max}/a_{max} ratio of the shallow crustal strong ground motions recorded at free field sites. The proposed model is a function of earthquake magnitude, closest distance from source to site (R_{clstd}), faulting mechanism, and average shear wave velocity over the top 30 m of site (V_{s30}). A wide-ranging database of strong ground motion released by Pacific Earthquake Engineering Research Center (PEER) was utilized. It is demonstrated that residuals of the final equation show insignificant bias against the variations of the predictive parameters. The results indicate that v_{max}/a_{max} increases through increasing earthquake magnitude and source-to-site distance while magnitude dependency is considerably more than distance dependency. In addition, the proposed model predicts higher v_{max}/a_{max} ratio at softer sites that possess higher fundamental periods. Consequently, as an instance for the application of the proposed model, its reasonable performance in liquefaction potential assessment of sands and silty sands is presented.

1. Introduction

Ground motion parameters or intensity measures are essentially presented in quantitative forms as a function of earthquake magnitude, source-to-site distance, faulting mechanism, and local site conditions. Beside the theoretical models, [a] majority of these equations have been empirically derived by the regression analysis of recorded strong ground motion data.

From the earliest studies in the seismic analysis of structures, it has been confirmed that the seismically-induced deformation of structures cannot be characterized by peak intensity measures (e.g. *PGA* or *PGV*) alone. In fact, it is necessary to identify frequency of input motion and its closeness to the fundamental period of the structure. Nevertheless, the commonly used intensity measures involve peak ground acceleration (*PGA*) and peak ground velocity (*PGV*), which are not frequency dependent.

Researchers have introduced several parameters to capture the frequency content of strong ground motions. Rathje et al. (1998) developed empirical models to predict the predominant and mean periods of ground motions for "shallow stiff soil" and "rock" sites. The ratio of *PGV* to *PGA* (v_{max}/a_{max} ratio) is an informative measure that can account for the frequency content of input motions. Since *PGA* and *PGV* are usually associated with motions of different frequencies, the v_{max}/a_{max} ratio should be associated with the frequency content of the motion (McGuire, 1978). Based on the theory of one-dimensional shear wave propagation through uniform elastic medium, the equations of displacement (u), velocity ($\dot{u}$), and acceleration ($\ddot{u}$) for a harmonic motion with natural circular frequency of ω can be written as

$$u(z,t) = A\cos\left(\frac{\omega z}{V_s}\right)e^{i\omega t} \quad u_{max} = A$$
$$\dot{u}(z,t) = iA\omega\cos\left(\frac{\omega z}{V_s}\right)e^{i\omega t} \quad v_{max} = A\omega$$
$$\ddot{u}(z,t) = -A\omega^2\cos\left(\frac{\omega z}{V_s}\right)e^{i\omega t} \quad a_{max} = A\omega^2 \tag{1}$$

where z, V_s, u_{max}, v_{max}, and a_{max} stand for depth, shear wave velocity of the elastic medium, maximum displacement, maximum velocity, and maximum acceleration, respectively. According to these

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equations, the ratio of peak velocity to peak acceleration at the ground surface (v_{max}/a_{max}) is proportional to $1/\omega$.

The v_{max}/a_{max} ratio obtains practical information to characterize the damage potential of near-fault ground motions and can be considered as a measure of destructiveness (Consenza and Manfredi, 2000). In fact, ground motions having higher v_{max}/a_{max} values result in larger damage potential (Zhu et al., 1988; Meskouris et al., 1992). Moreover, it has a significant influence on inelastic displacement ratio spectra (*IDRS*) for near-fault ground motions among the other parameters such as *PGV*, and the maximum incremental velocity (*MIV*) (Changhai et al., 2007). Liao et al. (2004) demonstrated that the base shear response and displacement of intermediate-period and short-period isolated bridges strongly depend on v_{max}/a_{max} and the energy of the ground motion.

In liquefaction potential assessment of granular soils, the effect of site amplification is commonly introduced by "depth reduction factor, r_d". Orense (2005) proposed an alternative relation for r_d which is dependent to the v_{max}/a_{max} of exciting motion, rather than conventional methods which ignore the frequency content of motion in site response analysis.

Trifunac (1976) found that v_{max}/a_{max} is proportional to $\exp(0.622M - 0.0035M^2)$ in all site conditions, in which M is earthquake magnitude. McGuire (1978) correlated this ratio to M and source-to-site distance, R, for soil and rock types of site conditions, as presented in Table 1. The magnitude and distance dependencies of v_{max}/a_{max} indicate that larger v_{max}/a_{max} ratios are associated with larger magnitude and with longer source-to site distances for both rock and soil site classes. The dependence of v_{max}/a_{max} ratio to source to site distance and site classes were also studied by Seed and Idriss (1982) and Yang and Lee (2007). According to their work, the v_{max}/a_{max} ratio increases with increase in source-to-site distance while it tends to be larger as the soils become softer. As a preliminary attempt, the authors (Kermani et al., 2009) developed three individual equations for the v_{max}/a_{max} ratios of three faulting styles. However, residuals and their possible bias versus the input variables were not studied in detail.

In the recent years, new aspects of modeling, optimization, and problem solving have been evolved in light of the pervasive development in computational software and hardware. These aspects of software engineering are referred to as artificial intelligence that includes artificial neural network, fuzzy logic, genetic algorithm (GA), and genetic programming (GP). In case of complicated problems, experimentalists prefer these trial approaches rather than analytical optimization. Numerous researchers applied artificial intelligence approaches in the various fields of civil engineering such as slope stability (McCombie and Wilkinson, 2002), liquefaction (Baziar and Jafarian, 2007; Baziar and Nilipour, 2003; Baykasoglu et al., 2009), liquefaction induced lateral spreading (Baziar and Ghorbani, 2005; Javadi et al., 2006), and seismic studies (Cabalar and Cevik, 2009).

Overview of the previous studies reveals lack of a rigorous relationship for this parameter in spite of its extensive applications in various problems. The study presented herein employs genetic programming (GP) to develop empirical predictive equations for the v_{max}/a_{max} ratio of strong ground motion in terms of earthquake magnitude, source-to-site distance, local site condition, and faulting mechanism. A comprehensive database of the strong ground motions assembled by Pacific Earthquake Engineering Research Center (PEER) was used to derive the equations. In addition, application of the proposed model in liquefaction potential assessment is demonstrated.

Table 1
Magnitude and distance dependency of v_{max}/a_{max} ratios (adopted from McGuire, 1978)

Site conditions	Magnitude dependency	Distance dependency
Rock sites	$e^{0.4M}$	$R^{0.12}$
Soil sites	$e^{0.15M}$	$R^{0.23}$

2. Genetic algorithm and genetic programming

As an optimization technique, genetic algorithm (GA), which was evolved from the principles of genetics and natural selection, tries to search the minima of a given function using a trial process. Genetic algorithm works by evolving a population of individuals over a number of generations. A genetic algorithm improves a randomly generated population composed of many individuals to a state that minimizes the error function. Genetic algorithm optimizes an array of input variables or chromosomes in different types such as binary strings (0, 1), real strings (0, 1, …, 9), and representation of tree (computer programs).

Koza (1991, 1992) developed a special genetic algorithm known as "genetic programming (GP)" in which each chromosome in the population is a program comprised of random mathematical functions and terminals. A function set could contain functions such as basic mathematical operators (+, −, *, /, etc.), Boolean logic functions (AND, OR, NOT, etc.), or any other user defined function. The terminal set contains the arguments for the function and can consist of numerical constants, etc. The functions and terminals are randomly selected and composed to form a computer model in a tree-like structure extending from each function and ending in a terminal. An example of a simple tree representation of a GP model is shown in Fig. 1. A new population is created at each generation by choosing individuals according to their fitness and breeding them together using the genetic operators such as cross-over and mutation. Trial generations are repeatedly produced until a process termination criterion such as a prescribed level of precision has reached (Mitchell, 1998).

3. Strong motion database and model variables

The database compiled by Power et al. (2006) during PEER-NGA project was employed in this study. It contains the strong ground motion data of shallow crustal earthquakes recorded at active tectonic regions throughout the world over a broad ranges of magnitudes, distances, and site conditions. Boore and Atkinson (2007) and Campbell and Bozorgnia (2007) excluded the data mimicking free-field condition, thereby proposed worldwide attenuation relations for *PGA*, *PGV*, and response spectra of

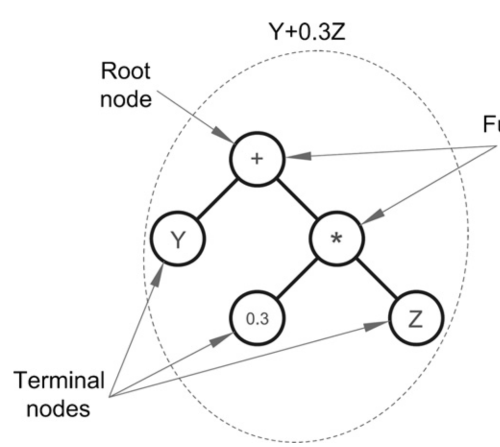

Fig. 1. Typical GP tree representation.