ARTICLE IN PRESS

Computers and Structures xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Computers and Structures

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

Image based modeling and prediction of nonstationary ground motions

Y. Dak Hazirbaba, J. Tezcan *

Department of Civil and Environmental Engineering, Southern Illinois University Carbondale, IL, United States

ARTICLE INFO

Article history:
Accepted 25 August 2015
Available online xxxx

Keywords:
Relevance Vector Machine
Principal component analysis
Wavelet transform
Synthetic ground motion
Eigenvalue problem

ABSTRACT

Nonlinear dynamic analysis is a required step in seismic performance evaluation of many structures. Performing such an analysis requires input ground motions, which are often obtained through simulations, due to the lack of sufficient records representing a given scenario. As seismic ground motions are characterized by time-varying amplitude and frequency content, and the response of nonlinear structures is sensitive to the temporal variations in the seismic energy input, ground motion nonstationarities should be taken into account in simulations. This paper describes a nonparametric approach for modeling and prediction of nonstationary ground motions. Using the Relevance Vector Machine, a nonparametric regression model which takes as input a set of seismic predictors, and produces as output a wavelet image showing the expected time–frequency distribution of energy, conditioned on the predictors, is developed. Demonstrative examples comparing the recorded and predicted ground motions in time, frequency, and time–frequency domains are presented.

1. Introduction

As performance-based concepts are being incorporated into seismic standards and code provisions, nonlinear dynamic analysis is becoming increasingly common in the current engineering practice. As sufficient records may not be available for a scenario dominating the seismic hazard at a given site, and a purely physics-based approach is not yet feasible, the input ground motions to be used in nonlinear dynamic analysis are often obtained by either modifying the recorded motions or generated synthetically, using time or frequency domain filtering procedures. Because the behavior of nonlinear systems is sensitive to local variations in the seismic energy input, when ground motion records are fit to a target response spectrum with little consideration given to the nonstationary character of ground motions, the accuracy of the resulting structural response estimates is questionable. Recent advances in computer technology and the growth in seismic databases have led to an increased interest in the characterization of ground motion nonstationarities and facilitated the development of new guidelines for selecting ground motion from strong motion databases and new techniques for simulations of nonstationary ground motions.

Performance assessment of structures can take three forms: intensity-based, scenario based, and time-based [1]. Recommended procedures for selecting and scaling ground motion records vary depending on the type of the assessment. To date, a variety of methods have been developed ground motion selection and scaling. A state-of-the-art review can be found in references [2–4]. Recently, engineering community has focused attention on the time-varying behavior of ground motions and its effects on seismic response of structures (e.g. [3,5–13]).

This paper describes a data-driven method for modeling and prediction of ground motions in the joint time–frequency domain. The proposed method is intended to complement existing procedures for scenario-based seismic assessment of structures. The proposed procedure consists of three main steps: (1) Conversion of each acceleration record in the dataset into a wavelet image; (2) Determination of the eigen-images of the covariance matrix of the data matrix containing the norms of wavelet coefficients; (3) Estimation of combination coefficients of the eigen-images for a given earthquake scenario. The output of the model is a wavelet image describing the expected time–frequency distribution of energy, conditioned on the predictors. Once the wavelet image is obtained, acceleration records compatible with the predicted image can be synthesised using existing techniques.

Two recent studies are particularly relevant to the proposed method: Rezaeian and Der Kiureghian [12] and Yamamoto and Baker [13]. Rezaeian and Der Kiureghian [12] generate synthetic accelerograms by passing a Gaussian white-noise process through a filter with time-varying parameters. Yamamoto and Baker [13] use wavelet packets to describe the nonstationary behavior of accelerograms, conditioned on a set of predictors. For a given earthquake scenario, and without a seed ground motion, both

* Corresponding author.

http://dx.doi.org/10.1016/j.compstruc.2015.08.019
0045-7949/

models generate fully nonstationary ground motions. This study shares the same motivation as these two studies, but it introduces a new approach for modeling ground motion nonstationarities.

This paper is based upon Dak Hazirbaba and Tezcan [14], but the current paper identifies the wavelet coefficients inside the cone of influence (COI), where edge effects become important, and removes them from the regression algorithm. Removal of these coefficients not only prevents unreliable coefficients affecting the accuracy of the model, but also increases the computational efficiency of the algorithm by reducing the size of the data matrix. As the signals used in the study are centered during the pre-processing stage, most of the coefficients in the COI are already zero or negligibly small.

The rest of this paper is organized as follows. Section 2 describes the ground motion dataset and the procedures used in pre-processing of the data. Section 3 presents the proposed regression model and demonstrates two prediction examples. Section 4 concludes the paper.

2. Input data and pre-processing

2.1. Dataset

The dataset used in this study is a subset of PEER NGA (Pacific Earthquake Engineering Research Center Next Generation Attenuation of Ground Motion Project) database that Campbell and Bozorgnia employed in developing their NGA Ground Motion model [15]. The PEER-NGA database consists of ground motion recordings of shallow crustal earthquakes in Western United States and similar active tectonic regions. The dataset used in this study only considers recordings from free-field sites and excludes aftershocks.

A typical ground motion record has three orthogonal components, two horizontal and one vertical. In this study, we only use the horizontal components. In addition, we limit ourselves to recordings from large magnitude ($M > 6.0$), strike-slip earthquakes. Table 1 lists the selected earthquakes and the number of recordings from each earthquake. Total number of records used in this study is 345.

2.2. Data pre-processing

2.2.1. Rotation of ground motions to uncorrelated directions

The directions of the horizontal pairs of ground motions depend on the orientation of the accelerometers that record the ground shaking. This dependency is clear as these two orthogonal pairs are correlated along the direction of the sensor. To remove this dependency, we used Principal Component Analysis (PCA) [16] to rotate the two horizontal components of each record into its uncorrelated directions. The use of PCA to obtain uncorrelated ground motion components is a common task in seismic data processing (see e.g. [17–19]), and a detailed mathematical description of the PCA procedure can be found in any linear algebra textbook (e.g. [20]). Below is a summary of the procedure:

- Step 1. Given two components $q_1, q_2 \in \mathbb{R}^{N_t \times 1}$ of an acceleration record sampled at N_t time points, compute the sample covariance matrix, C. Since the q_1 and q_2 are zero-mean vectors, the covariance matrix is given by

$$C = \begin{bmatrix} q_1^T q_1 & q_1^T q_2 \\ q_2^T q_1 & q_2^T q_2 \end{bmatrix}, \tag{1}$$

where the superscript T denotes the matrix transpose operation.

- Step 2. Solve the eigenvalue problem $Cv = \lambda v$ to determine the eigenvalues (λ_1, λ_2) and the corresponding eigenvectors (v_1, v_2) of C. Here, we assume that eigenvalue–eigenvector pairs are ordered so that $\lambda_1 \geqslant \lambda_2$.
- Step 3. Project the data onto the first eigenvector, $v_1 = [v_{11} \quad v_{12}]^T$. If v_1 is scaled to have unit length, i.e. $v_1^T v_1 = 1$, the projection can be computed as $q = v_{11}q_1 + v_{12}q_2$. We call q "the first rotated component" in this paper.

2.2.2. Resampling and time-domain shifting

Different accelerometers may record ground motions in time domain at different sampling rates. As a first step, we resampled the acceleration records at sampling interval $dt = 0.02$ s, using an infinite-impulse-response Butterworth filter of order 4 and cut-off frequency 25 Hz. Next, we set the duration of each record equal to 40 s by shifting it in the time domain and using truncation and zero-padding as needed, so that the energy contained in the first 20 s equals 50% of the total energy. The energy contained in the record was measured using Arias intensity, defined as [21]:

$$I_a = \frac{\pi}{2g} \int_0^T q^2(t) dt \tag{2}$$

where I_a denotes the Arias Intensity in dimensions of length per time, T is the duration of the ground motion, $q(t)$ is the acceleration record in units of acceleration of gravity.

During preprocessing, it is possible that small amplitude p-wave arrival be truncated. While this is an issue from the geophysical point of view, it will not affect seismic performance evaluations where peak structural responses are of interest.

2.2.3. Conversion of acceleration records to wavelet images

To retain the nonstationary character of ground motion records, we use Continuous Wavelet Transform (CWT). Given a mother wavelet $\psi(t)$, the CWT coefficients of a time domain signal $q(t)$ can be computed using [22]:

$$Q(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} q(t) \psi^* \left(\frac{t-b}{a} \right) \tag{3}$$

where $\psi((t-b)/a)$ is a shifted and scaled wavelet and the operator * represents complex conjugation. In this study, we use the Morlet wavelet defined as:

$$\psi(t) = \left(e^{-2i\pi t} - e^{-\frac{z_0^2}{2}} \right) e^{-2\pi^2 \frac{t^2}{z_0^2}}. \tag{4}$$

Table 1
Selected records from Campbell–Bozorgnia NGA dataset.

Earthquake ID in NGA database	Earthquake name	Earthquake magnitude	Number of records
25	Parkfield	6.19	4
31	Managua, Nicaragua-01	6.24	1
50	Imperial Valley-06	6.53	33
64	Victoria, Mexico	6.33	4
90	Morgan Hill	6.19	22
103	Chalfant Valley-02	6.19	10
115	Superstition Hills-01	6.22	1
116	Superstition Hills-02	6.54	11
121	Erzican, Turkey	6.69	1
125	Landers	7.28	67
126	Big Bear-01	6.46	38
129	Kobe, Japan	6.90	22
136	Kocaeli, Turkey	7.51	22
138	Duzce, Turkey	7.14	14
140	Sitka, Alaska	7.68	1
144	Manjil, Iran	7.37	7
158	Hector Mine	7.13	74
168	Nenana Mountain, Alaska	6.70	5
169	Denali, Alaska	7.90	9

Please cite this article in press as: Dak Hazirbaba Y, Tezcan J. Image based modeling and prediction of nonstationary ground motions. Comput Struct (2015), http://dx.doi.org/10.1016/j.compstruc.2015.08.019