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Novel nonparametric modeling of seismic attenuation and directivity relationship

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Highlights

- A novel Bayesian general regression is presented for seismic attenuation modeling.
- It is a nontrivial Bayesian reformulation of the general regression neural network.
- This nonparametric approach does not require prescribed functional form.
- It resolves the subjectivity of Bayesian model selection due to prior distribution.
- The 2008 Wenchuan Ms 8.0 earthquake database was used for the demonstration.

Abstract

Seismic attenuation modeling is a core element in earthquake disaster assessment and earthquake early warning. In this paper, a novel nonparametric methodology, namely Bayesian Nonparametric General Regression (BNGR), is introduced for the modeling of peak ground acceleration attenuation relationship. In contrast to most existing methods, this method does not require a prescribed functional form of the attenuation relationship. Furthermore, it selects the proper set of variables necessary to model this relationship. Moreover, the proposed model does not only consider the epicentral distance but also the location of the measured station so it allows for the modeling of the attenuation directivity. The proposed method is demonstrated with a case study using a comprehensive database of ground motion records at 271 monitoring stations for the 2008 Ms 8.0 Wenchuan earthquake. Results show that the proposed methodology is capable to represent the seismic attenuation relationship. Furthermore, the contour plots of the peak ground acceleration provides valuable information for the study of the earthquake directivity characteristics.

Keywords: Bayesian inference; General regression; Model selection; Nonparametric regression; Peak ground acceleration; Seismic attenuation

1. Introduction

Over the last few decades, modeling of seismic attenuation relationship has received tremendous attention in the civil engineering and seismology community. In structural design practice, peak ground acceleration (PGA) is

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used to represent the amplitude and severity of ground motion and it controls the design seismic loads. Due to its importance, a number of PGA estimation formulae have been developed by use of the earthquake magnitude, epicentral distance and, in some cases, other variables characterizing the earthquake source, wave propagation path and local site condition. Regression analysis of recorded strong motion database is the common approach [1–10] and these models have to be updated when additional strong ground motion data becomes available. In the literature, they have been usually updated every three to five years or shortly after the occurrence of a large earthquake in a well-instrumented region [11–14]. A comprehensive review of some well-known predictive models can be found in [15]. It is noted that seismic attenuation model should be region-dependent because the attenuation characteristics are governed by geographical and geological conditions.

Most of the existing seismic attenuation models rely on a prescribed or predetermined mathematical functional form of the dependent variables such as earthquake magnitude and epicentral distance. Determination of such a relationship is crucial to the success of the model but it is usually obtained in a subjective manner. One way to eliminate this subjectivity is by use of nonparametric regression techniques, which do not require the prescription of a functional form. Instead, they adjust the regression surface according to the available data. Applications of nonparametric regression methods for the characterization of ground motions can be found in the literature, e.g., neural networks [16–18], support vector machines [19], multidimensional regression based on statistical error minimization [20], and interpolation methods using graphs and/or tables [2,21].

Among nonparametric methods, the General Regression Neural Network (GRNN) [22] has been applied successfully in other research areas such as econometrics [23], energy conservation [24], soil dynamics [25], image processing [26], and assessment of high power systems [27]. However, it remains a challenge to select the proper set of design variables (i.e., the inputs to the network). To resolve this problem, the Bayesian inference will be used in this study. In particular, Bayesian inference offers a rigorous framework to quantify the degree of belief of a hypothesis, events or values of parameters, as well as the plausibility of models according to measurements. It has been applied successfully to structural dynamics [28–34], damage detection [35,36], air quality prediction [37], geotechnical engineering [38–41], design of complex systems [42], subsurface flow models [43], reliability analysis [44–47], and outlier detection [48]. Although general regression is powerful, its formulation in Bayesian is nontrivial. In this paper, the general regression is reformulated under the Bayesian framework and it will be denominated as the Bayesian Nonparametric General Regression (BNGR). This novel nonparametric approach will then be used for seismic attenuation modeling using a comprehensive database of the strong-motion records due to the 2008 Ms 8.0 Wenchuan earthquake in China. BNGR does not require the prescription of explicit models but a set of potential design variables to be selected from, without specification of a parametric form. There are two special features of the proposed method. First, the subjectivity of the prior distribution in Bayesian model selection for traditional regression problems is resolved. Second, the number of model candidates to be evaluated is overwhelmingly smaller than that in traditional regression problems. These will be further elaborated in Section 3.

The structure of this paper is outlined as follows. Section 2 introduces the fundamentals of the general regression neural network (GRNN) and Section 3 presents a novel reformulation of general regression from the Bayesian inference perspective as well as a procedure for the selection of the design variables for PGA prediction. A simple numerical example is presented to help illustrate how the method works. Finally, Section 4 presents a case study using the dataset of the 2008 Wenchuan earthquake to assess the effectiveness of the proposed method.

2. General regression neural network

Modeling of seismic attenuation relationship poses a challenge in seismology and earthquake engineering due to the complex nature associated with ground motions. In the literature, traditional empirical models have been widely used and typical empirical formulae for PGA estimation take the following form:

$$L_{a,i} \equiv \ln \mathrm{PGA}_i = f(\mathbf{w}_i; \mathbf{b}) + e_i, \quad i = 1, 2, \ldots, N \tag{1}$$

where $L_{a,i}$ is the natural logarithm of the ith PGA record; $f(\mathbf{w}_i; \mathbf{b})$ is a prescribed function with unknown parameters $\mathbf{b}$ to govern the seismic attenuation relationship between $L_{a,i}$ and the design variables in $\mathbf{w}_i \in \mathbb{R}^{N_w}$ of the same record; and e_i is the residual (i.e., prediction error) modeled as a Gaussian random variable with zero mean and standard deviation σ_e. The design variables $\mathbf{w}_i$ comprise some significant influential data, such as earthquake moment magnitude, epicentral distance and site foundation type. Even though empirical models have been widely used for