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A geostatistical approach to mapping site response spectral amplifications

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ABSTRACT

If quantitative estimates of the seismic properties do not exist at a location of interest then the site response spectral amplifications must be estimated from data collected at other locations. Currently, the most common approach employs correlations of site class with maps of surficial geology. Analogously, correlations of site class with topographic slope can be employed where the surficial geology is unknown. Our goal is to identify and validate a method to estimate site response with greater spatial resolution and accuracy for regions where additional effort is warranted. This method consists of three components: region-specific data collection, a spatial model for interpolating seismic properties, and a theoretical method for computing spectral amplifications from the interpolated seismic properties. We consider three spatial interpolation schemes: correlations with surficial geology, termed the geologic trend (GT), ordinary kriging (OK), and kriging with a trend (KT). We estimate the spectral amplifications from seismic properties using the square root of impedance method, thereby linking the frequency-dependent spectral amplifications to the depth-dependent seismic properties. Thus, the range of periods for which this method is applicable is limited by the depth of exploration. A dense survey of near-surface *S*-wave slowness (S_s) throughout Kobe, Japan shows that the geostatistical methods give more accurate estimates of S_s than the topographic slope and GT methods, and the OK and KT methods perform equally well. We prefer the KT model because it can be seamlessly integrated with geologic maps that cover larger regions. Empirical spectral amplifications show that the region-specific data achieve more accurate estimates of observed median short-period amplifications than the topographic slope method.

1. Introduction

The different factors that affect ground motions can be separated into three broad categories: source, path, and instrument (Lay and Wallace, 1995). Typically, the instrument response is known and can be deconvolved from recorded ground motions. Source effects include the location, dimensions and orientation of the fault, the slip distribution, and the rupture velocity. The path effects describe how the waveform is modified between the source and the instrument; this includes reflections, refractions, and phase conversions at subsurface structures, attenuation, and the generation of surface waves. The effect of the material within a few hundred meters of the surface is often termed site effects or site response.

It has long been recognized that near-surface geologic materials substantially modify recorded ground motions at frequencies that are important for seismic hazards analysis (e.g., Borcherdt, 1970; Shearer and Orcutt, 1987; Boore, 2004). The seismic properties of the near-surface materials that affect site response are the seismic slowness (*S*, inverse of velocity, *V*), density (ρ), and attenuation. Generally, the *S*-wave slowness (S_s), is considered the most important parameters to constrain.

The National Earthquake Hazard Reduction Program (NEHRP; ICC, 2006) site classifications are defined by $V_s(30)$, defined as 30 m divided by the *S*-wave travel time to 30 m depth. In situ measurements of V_s are both time consuming and expensive. This limits the number of locations where such data are available. Researchers have addressed this need primarily by developing spatial models to predict site class or spectral amplifications at unsampled locations (Tinsley and Fumal, 1985; Wills and Silva, 1998; Wills et al., 2000; Holzer et al., 2005; Wills and Clahan, 2006; Wald and Allen, 2007; Yong et al., 2008).

Three of these methods are similar in scale to this study. Tinsley and Fumal (1985) presented an index of site amplification for Los Angeles that is primarily based on soil type, age, and the average V_s of the unit. Holzer et al. (2005) developed a three-dimensional V_s model for a portion of the San Francisco Bay Area by combining stratigraphic and V_s information from 210 seismic cone penetration tests (SCPTs) and used the V_s model to map NEHRP site class. Yong et al. (2008) created maps that classify the range of $V_s(30)$ from satellite imagery for Islamabad, Pakistan.

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Our goal is to identify and validate a method to estimate site response spectral amplifications with greater spatial resolution and accuracy than previous studies. Previous methods have focused on making predictions over large regions of interest, such as the state of California (Wills and Clahan, 2006) or the globe (Wald and Allen, 2007). The method we propose cannot be applied at such scales, and our goal is not to replace these methods. The methods outlined in this paper are appropriate for regions where special attention is warranted, such as urban regions exposed to moderate to high seismic risk. The method we employ consist of three components: (1) region-specific data collection, (2) a spatial model for interpolation of seismic properties, and (3) a theoretical method for computing spectral amplifications from the seismic properties.

Previously developed spatial models of site response can be organized in terms of increasing data availability and increasing model complexity. The Wald and Allen (2007) model does not require region-specific observations; this method correlates global topographic slope data (Farr and Kobrick, 2000) with NEHRP site class and utilizes previously published correlations of NEHRP site class with spectral amplifications (Borcherdt, 1994), herein termed the TS model.

Wills and Clahan (2006) developed a model for California that requires surficial geology maps, which are not available globally. Wills and Clahan (2006) compiled $V_s(30)$ measurements for sites throughout California and defined generalized surficial geologic units. Each unit is assigned a representative $V_s(30)$ value, which defines the NEHRP site class. The spectral amplifications can then be computed from the Borcherdt (1994) correlations.

We employ a separate but related method that we term the geologic trend (GT) method. An important aspect of this method is that seismic profiles are approximately evenly distributed throughout the region of interest. Note that this would be an inefficient strategy for a region the size of California. This is one reason why it is important to distinguish between the GT method and the Wills and Clahan (2006) method. Both methods, however, compute average V_s values for surficial geologic units. Limitations of the GT and Wills and Clahan (2006) approach include: (1) the mapped geology is a surface value while the $V_s(30)$ is a function of the materials at depths of 30 m, and (2) geologic maps are not typically collected with the application to correlations with V_s in mind (Tinsley and Fumal, 1985). Wills and Clahan (2006) compute only $V_s(30)$, but the GT method retains more of the available information in the soil profiles by computing the average S_s to a range of depths.

Aside from the GT model, we consider two alternative spatial interpolation techniques that expand on the geostatistical approach of Thompson et al. (2007). Specifically, we employ the geostatistical methods of ordinary kriging (OK) and kriging with a trend (KT). The geostatistical methods achieve a better spatial resolution than the GT model because they are capable of modeling variability within geologic units but also require more observations to achieve accurate results. We will address the accuracy of these models with a cross validation of the predicted S_s and comparisons of the predicted and observed spectral amplifications.

We also consider two alternative methods for linking seismic properties to spectral amplifications: the Borcherdt (1994) empirical correlations and the square root of impedance method (SRI), as described by Joyner et al. (1981). The Borcherdt (1994) correlations rely on a single site parameter for estimating the spectral amplifications, namely $V_s(30)$. In contrast, the SRI method links the depth-dependent seismic properties to the frequency-dependent site response amplification.

We choose to focus this study on the Kobe region because it is a densely populated urban area that is located in a deep sedimentary basin and exposed to heightened earthquake hazard. These characteristics are not unique to Kobe, but Kobe is distinguished from other such examples by the damage that was caused by the 1995 Hyogo-ken Nanbu earthquake. The maps of $V_s(30)$ presented in this article, along with the V_s profiles they are derived from, can be downloaded and viewed within the context of geographic, geotechnical, and earthquake effect data on the web-based geographic information system that we have created at http://gdcmaps.cee.tufts.edu/kobe/.

2. Data

We use the spectral analysis of surface waves (SASW) method (Nazarian and Stokoe, 1984; Stokoe et al., 1989) to estimate the S_s profiles following the methodology of Kayen et al. (2005). The SASW method has repeatedly fared well in blind comparisons to invasive measurements (Brown et al., 2002; Asten and Boore, 2005; Boore and Asten, 2008). Other surface wave methods, including passive source methods such as the multichannel analysis of surface waves (MASW) method (Park et al., 1999), may also provide inexpensive and efficient alternatives for mapping site response amplifications. Fig. 1(a) shows the locations of the 103 SASW sites included in our analysis. The geologic units are from the “Active Fault Map in Urban Area” map published by the Geographical Survey Institute of Japan at 1:25,000 scale.

The locations of the SASW surveys were chosen in two stages. First, the SASW sites were located at historical liquefaction sites for developing a deterministic and probabilistic model of liquefaction based on V_s (Kayen et al., 2010). Subsequently, the liquefaction data were augmented to extend the coverage to the edge of the basin. In the second stage, the goal was to keep the spacing between seismic profiles as uniform as possible while adding upper alluvial fan sites between the zone of liquefaction susceptible soil near the bay, and bedrock outcropping at the base of the Rokko Mountains. Specific locations were selected based on available space for seating the SASW seismometer array. Fig. 1(b) shows the locations of the temporary seismometer array that recorded aftershocks of the 1995 Hyogo-ken Nanbu earthquake (Iwata et al., 1996). We use these recordings to judge the accuracy of the different models in terms of spectral amplifications.

3. Methods

All calculations and analyses presented in this paper were completed with the free open-source software R (R Development Core Team, 2009) with the exception of the Wald and Allen (2007) topographic slope model discussed below, which was computed with Generic Mapping Tools (Wessel and Smith, 1991).

3.1. Topographic slope model

Wald and Allen (2007) presented a model that computes spectral amplifications from topographic slope. They compute slope from Shuttle Radar Topography Mission (SRTM) 30-sec global topography (Farr and Kobrick, 2000). This method predicts NEHRP site class based on empirical correlations of $V_s(30)$ with topographic slope. After obtaining site class from the topographic slope correlation, spectral amplifications can be estimated from the Borcherdt (1994) correlations with site class.

An important attribute of this model is that it is applicable across the entire globe, and thus it can be applied to Kobe. This also means that the resolution is relatively coarse: the 30-sec pixel size of the SRTM30 data is approximately a 1 km by 1 km square. We consider this model to be an appropriate baseline model to judge our proposed alternatives because it is the simplest available model, requiring minimal investment of time to obtain estimates of spectral amplifications. If we cannot improve on the Wald and Allen (2007) model, then the effort and investment into the dense SASW survey is not justified.