Numerical Modeling of Moderate Magnitude Earthquakes

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ABSTRACT: The scope of the existing NSF award is to numerically model ground motions of moderate magnitude earthquakes in the San Francisco Bay, California, USA and Osaka Bay, Japan. The numerical modeling is to focus on the effects of local soil conditions on ground motions recorded in sedimentary basins. The original NSF award's scope of work focused on the San Francisco Bay region and the Kobe region because both have suffered from recent earthquakes (the 1989 Loma Prieta and 1995 Kobe earthquakes) and also have recorded more recent moderate size earthquakes at multiple locations. Although estimation of the in-situ seismic properties was not part of the original award, the opportunity to support and improve the original goals of the award was created through collaboration with Dr. Robert Kayen at the United States Geologic Survey and Dr. Yasuo Tanaka at Kobe University. This collaboration involved collecting a dense set of in-situ seismic measurements in Osaka Bay to supplement existing data. We are using this dataset to study the spatial correlation structure of S-wave velocity in the Osaka sedimentary basin. These data complement previously collected data in the San Francisco Bay area. The Osaka data cover a broader area than the San Francisco Bay area data and reflects the spatial correlation in a second sedimentary basin. These datasets provide insight into the scale of variation of S-wave velocity within sedimentary basins, which has important implications for how accurately can it be modeled. These measurements will have important implications for how the effects of the soil conditions are estimated at unsampled locations, and how these properties are modeled in numerical simulations of earthquakes in sedimentary basins.

INTRODUCTION

It has long been recognized in the earthquake hazard community that ground motions recorded on soil are typically larger than nearby recordings on rock, assuming all other variables are equal. The effect of the near-surface soil on the ground motion recorded at the surface is called site response. The physical parameters of the near surface material that controls site response are the seismic slownesses, density, and attenuation. Generally, the *S*-wave slowness (*Ss*), or its inverse, velocity (*Vs*), are considered the most important parameters to constrain. Site response characterization is both time consuming and expensive, limiting the number of ground motion recordings where site response has been quantitatively estimated. Some researchers have responded to this problem by developing faster and cheaper methods of site response estimation to increase the number of sites that are quantitatively characterized[1]. Others have attempted to use spatial models to predict the site response at uncharacterized locations, including only the most accurate methods of site response estimation in developing the models[2,3].

This IREE Supplement funded research in collaboration with Dr. Robert Kayen at the United States Geologic Survey and Dr. Yasuo Tanaka at Kobe University that includes a large field effort to collect *Ss* data using the Spectral Analysis of Surface Waves (SASW) method. The analysis of these data will address alternate spatial models of site response, such as geology-based methods[2] and geostatistical methods[4]. In our analysis we consider three different models: i) classification by mapped surficial geology[2]; ii) ordinary kriging[4]; and iii) a hybrid of the previous two, universal kriging where the "drift" or "deterministic function" is defined by the geologic classification. We cross-validate these models using the leave-one-out method to quantify the predictive accuracy of the different methods.

The SASW field work was conducted by Eric Thompson (Tufts University graduate student) from 12 November to 13 October 2008 in Osaka bay with the help of Professor Yasuo Tanaka at Kobe University.

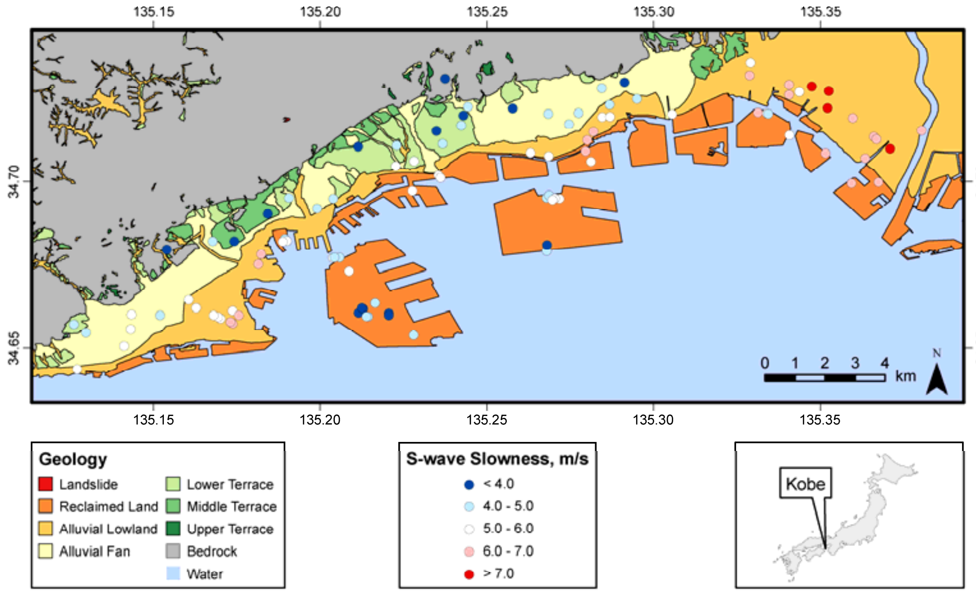


FIGURE 1 Overview of SASW data displayed on GSI map in Kobe, Japan.

Dr. Rob Kayen at the USGS provided the field equipment (including accelerometers, seismic shaker, amplifier, signal analyzer, and cables). Dr. Tanaka provided a field vehicle planned prospective sites, fieldwork logistics, and obtained access permits where needed.

Research Activities and Accomplishments of the International Cooperation

The question we address in this IREE Supplement is: At what scale is the *Ss* variable within sedimentary basins and how accurately can it be modeled? To answer this question, it is necessary to densely sample *Ss* to depths greater than 30 meters throughout sedimentary basins. Geotechnical data is usually too shallow (typically in the upper 10 to 20 meters) and seismic velocity models (*e.g.* the U. S. Geological Survey 3D velocity model for the San Francisco Bay area) do not capture the velocity heterogeneity within the sedimentary basin. We propose three tasks that will expand the current NSF proposal: (1) Collection and analysis of SASW data in the Kobe region of Osaka bay; (2) Geostatistical interpolation of *Ss* data and analysis of the correlation structure; and (3) Produce maps of *Ss* that will be useful for risk assessment.

The Kobe dataset will complement the data we collected in the San Francisco area[4] in three important ways: (1) We will gain new insight into how much the spatial correlation structure differs between two distinctively different geologic settings; (2) The catalog of earthquakes recorded in the Kobe area will increase the variety of different settings in which we can analyze the influence of the geotechnical layer on recorded ground motions; and (3) the thickness of the sedimentary basin is significantly deeper in the Kobe area, so we will be able to explicitly analyze the influence that the depth to the soil/rock interface has on the recorded ground motions.

Eric Thompson collaborated with Dr. Tanaka to process and interpret of the field data. Dr. Tanaka's expertise was extremely valuable because he is familiar with the Japanese research pertinent to the region. Dr. Tanaka helped us obtain the digital "Active Fault Map in Urban Area" published by the Geographical Survey Institute (GSI) of Japan at the 1:25000 scale. Figure 1 displays a summary of the SASW dataset on the GSI map. This geologic map is vastly superior to the geologic maps of the Osaka region that we were able to obtain in the US.

Other important information that Dr. Tanaka alerted us to is the Jibankun geotechnical database, which includes over 3000 geotechnical loggings in our field area. The Jibankun database includes standard penetration test (SPT) blow counts and soil descriptions, which are extremely helpful in understanding the earthquake hazard in the region. SPT measurements are a more traditional measurement of soil conditions than SASW, and an unexpected result of this trip is that we will be able to analyze the relationship between the SASW and SPT measurements.

The average *Ss* to depth *d* (*Ss*(*d*)) is an important parameter for seismic hazards because the frequency (*f*) dependence of the amplification of seismic waves (*A*(*f*)), can be related to *d* frequency via the quarter-wavelength approximation

$$f(d) = [4 \cdot Ss(d) \cdot d]^{-1}.$$

The amplification of an *S*-wave when completely transmitted from one material to another is directly proportional to the square root of *Ss* of the material the wave is entering, all else being equal[5,6]. This is easily shown when we note that the energy contained in an *S*-wave is proportional to $\rho \cdot Vs \cdot A^2$ and ignore the effects of density (ρ).

Geostatistics provides a quantitative framework for estimating variables, and the associated uncertainties, that vary in space. Following the standard notation[7], we model *Ss(d)* as a random field

$$Ss(\mathbf{s}) \equiv \mu(\mathbf{s}) + \delta(\mathbf{s}),$$

where $\mathbf{s} = (s_1, s_2, s_3)$ is the position vector, the deterministic model $\mu(\mathbf{s})$ describes the spatial fluctuation of the mean, and the correlated error process $\delta(\mathbf{s})$ includes any spatially uncorrelated white-noise measurement error and the spatially correlated zero-mean variation of $Ss(\mathbf{s})$ about $\mu(\mathbf{s})$.

To characterize the spatial correlation structure of $Ss(\mathbf{s})$ it is convenient to plot the variance as a function of separation distance, called the variogram

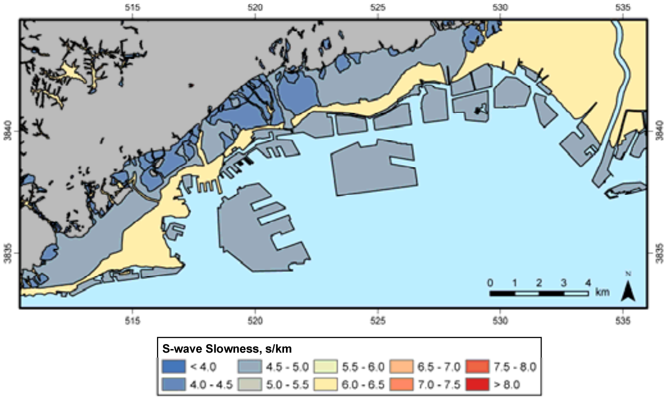
$$2\gamma(h) = \mathrm{var}\left[Ss(\mathbf{s}_1) - Ss(\mathbf{s}_2)\right],$$

where *h* is the Euclidean distance between two locations s_1 and s_2, and we often describe the spatial correlation structure with the semivariogram, $\gamma(h)$. We need a parametric semivariogram model, $\hat{\gamma}$, in order to predict $Ss(\mathbf{s})$ at unsampled locations using the kriging methods. The process involves (1) constructing an empirical semivariogram from observed values; (2) selecting a variogram model form, $\hat{\gamma}(h)$, and (3) optimizing the model parameters to fit the empirical semivariogram.

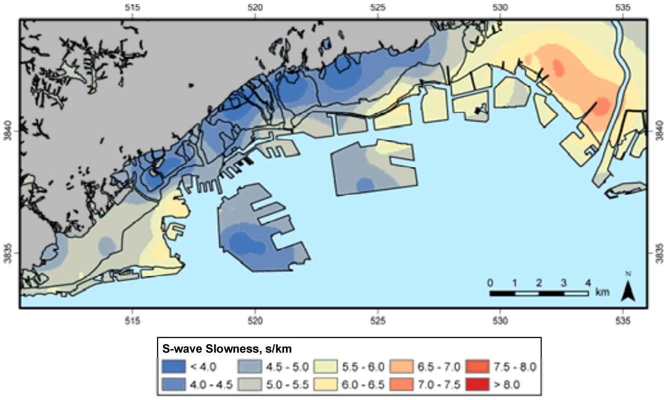
Previous studies of the spatial correlation structure of near surface seismic properties have assumed an exponential correlation model[4]. The correlation model we use here is the Whittle-Matérn model, which is a generalization of the exponential model

$$\hat{\gamma}(h) = \sigma^2 \left[1 - \frac{2^{1-\nu}}{\Gamma(\nu)} \left(\frac{h}{a} \right)^{\nu} K_{\nu}\left(\frac{h}{a} \right) \right],$$

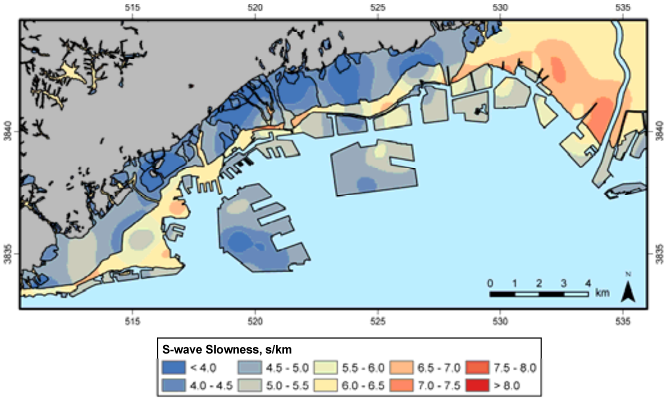
where the sill variance $\sigma^2 > 0$, range parameter $a > 0$, shape parameter $\nu \geq 0$, and K_ν is the modified Bessel function of the second kind of order ν.



(A) Estimates based on homogeneous geologic units assumption.



(B) Oridnary kriging estimates.



(C) Universal kriging estimates.

FIGURE 2 Continuous maps of *Ss(20)*.

Figure 2 shows continuous maps of *Ss(20)* for the three different spatial models: (1) the homogeneous geologic unit method; (2) ordinary kriging; and (3) universal kriging. These maps are the basis for constructing seismic hazards maps in this urban area that account for the local soil site conditions. Note the difference between the predictions by ordinary kriging and universal kriging in the northeast corner of Figure 2 where the predictions are far away from the nearest observation. The ordinary kriging estimates trend toward the mean of all the observed values as the distance to the nearest observation increases. This is

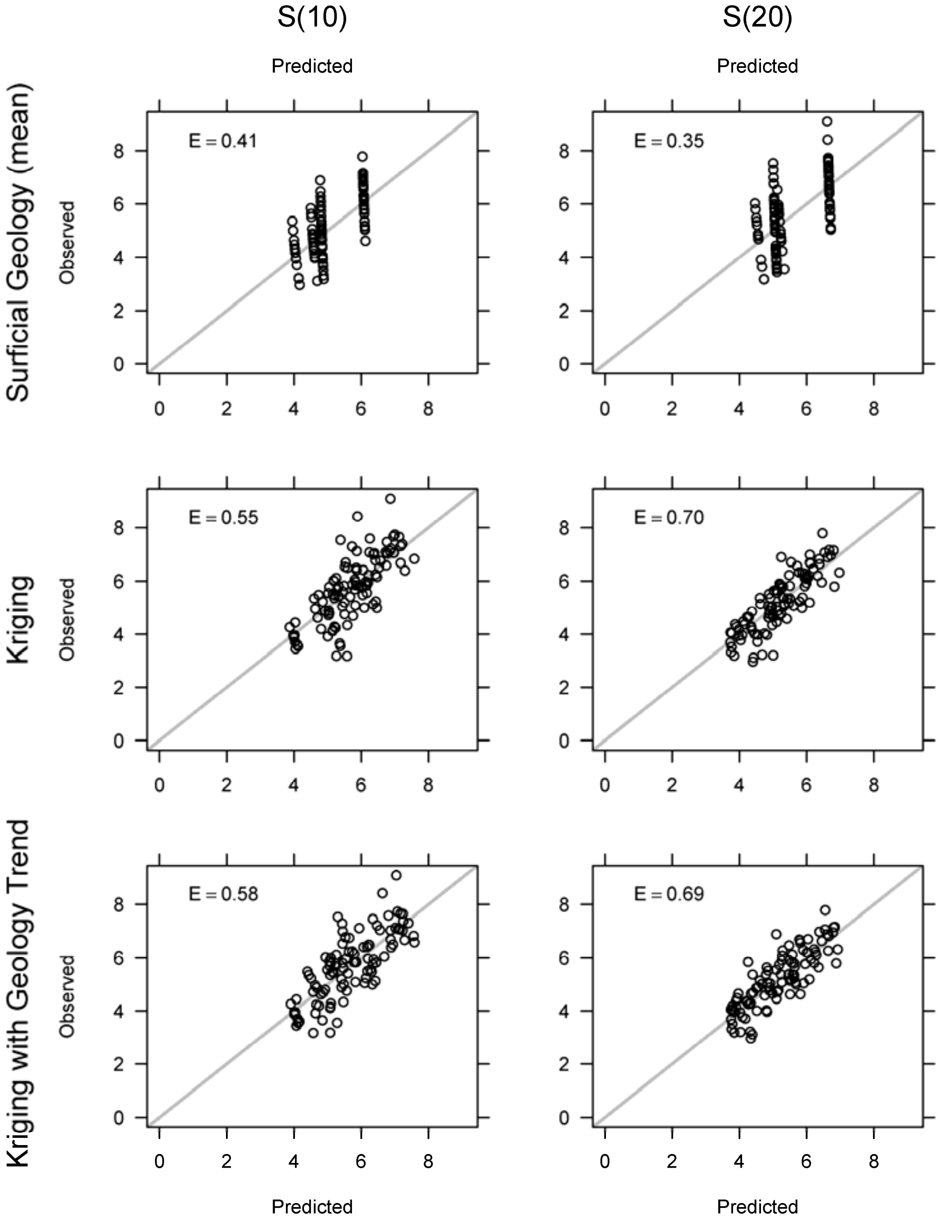


FIGURE 3 Cross validation of three methods for predicting the average slownesses using the leave-one-out method. Top: Geologic-mean method. Middle: Kriging. Bottom: Kriging using the geologic-mean model as the deterministic trend.

because an underlying assumption of ordinary kriging is that the mean value of the random field is stationary. The universal kriging model, however, allows the mean to vary as a function of geologic unit. Thus, in the same northeast region of the map where the observations are scarce, we see that the universal kriging predictions in Figure 2 (c) mean value of the geologic unit, shown in Figure 2 (a).

To assess the predictive accuracy of these models we perform a leave-one-out cross validation and compute the coefficient of efficiency[8] (*E*) as a goodness of fit parameter. Figure 3 summarizes the cross validation results. Figure 3 shows that the surficial geology method does better for *Ss(10)* than *Ss(20)*, indicating that variations in geology with depth are an important limitation to the surficial geology method. In contrast, the kriging methods perform better for *Ss(20)* than *Ss(10)*, indicating that the spatial correlation structure is more reliable when the *Ss* is averaged over a larger volume of material. Further, both ordinary kriging and universal kriging models outperform the geology based method. The two geostatistical methods, however, perform equally well. Further analysis is needed to determine which method is more accurate, such as an external cross validation. Our preliminary preference is for the universal kriging model because E is substantially greater than zero for the geology based method, which indicates that the geology-based mean outperforms the population mean. Thus, including the geology based mean as the drift function should improve the predictive accuracy. Further work is needed to verify this.

BROADER IMPACTS OF THE INTERNATIONAL COOPERATION

The supplemental award initiated a new collaboration between a female faculty member and her graduate student at Tufts University and a senior researcher in Japan. The collaboration brings international exposure to the faculty member and graduate student's research. With Prof. Tanaka's assistance, the U.S. researchers were introduced to the previously collected standard penetration data (the Jibankun geotechnical database, which includes over 3000 geotechnical loggings). The collaboration expanded the work of the current award by developing an additional dataset of shear wave slowness in the Osaka Bay sedimentary basin. The U.S. researchers have already initiated a new project with the host researchers on the visualization of subsurface data in the Osaka bay region.

The supplemental award provided a valuable first experience in Japan for the graduate student. He worked closely with Prof. Tanaka as well as another Japanese graduate student.

DISCUSSION AND SUMMARY

This NSF IREE supplement resulted in the collection of in-situ measurements that constrains spatial correlation structure within the Kobe sedimentary basin. We collected 26 *Ss* profiles, which combined with 77 previously collected profiles, results in a dataset of 103 profiles in the basin. This is an analogous dataset to one that was analyzed as part of the existing NSF Award[4]. The spatial correlation structure was evaluated with three models i) classification by mapped surficial geology[2]; ii) ordinary kriging[4]; and iii) a hybrid of the previous two, universal kriging where the "drift" or "deterministic function" is defined by the geologic classification. We cross-validate these models using the leave-one-out method to quantify the predictive accuracy of the different methods. Our results showed that both geostatistical models performed better than the geology based model.

The collection of the data was made possible through close collaboration with Prof. Yasuo Tanaka at Kobe University. Analysis of the data has greatly benefited from the collaboration with Dr. Tanaka because he is familiar with the research pertinent to the Kobe sedimentary basin, and is able to help us cast the research in a context that illuminates the implications of our findings from the perspective of the Japanese researchers. Dr. Tanaka has also helped us find other datasets that we could not have know about or used otherwise. The collaboration initiated during this award has already produced one journal article (in preparation) and has lead to discussions on future collaborative projects.

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