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Spatial correlation of shear-wave velocity in the San Francisco Bay Area sediments

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Abstract

Ground motions recorded within sedimentary basins are variable over short distances. One important cause of the variability is that local soil properties are variable at all scales. Regional hazard maps developed for predicting site effects are generally derived from maps of surficial geology; however, recent studies have shown that mapped geologic units do not correlate well with the average shear-wave velocity of the upper 30 m, $V_s(30)$. We model the horizontal variability of near-surface soil shear-wave velocity in the San Francisco Bay Area to estimate values in unsampled locations in order to account for site effects in a continuous manner. Previous geostatistical studies of soil properties have shown horizontal correlations at the scale of meters to tens of meters while the vertical correlations are on the order of centimeters. In this paper we analyze shear-wave velocity data over regional distances and find that surface shear-wave velocity is correlated at horizontal distances up to 4 km based on data from seismic cone penetration tests and the spectral analysis of surface waves. We propose a method to map site effects by using geostatistical methods based on the shear-wave velocity correlation structure within a sedimentary basin. If used in conjunction with densely spaced shear-wave velocity profiles in regions of high seismic risk, geostatistical methods can produce reliable continuous maps of site effects.

Keywords: Site response; Geohazards; Geostatistics; Hazard mapping; SCPT; SASW; Shear-wave velocity

1. Introduction

Observations from large earthquakes (e.g. 1985 Mexico City and 1989 Loma Prieta) have shown that the stiffness of the soil at a site has a strong effect on the level of shaking. Variability in these local stiffnesses contributes to the variability of ground motions over short distances within sedimentary basins [1–5]. The engineering code has simplified these site effects into a single parameter: the average shear-wave velocity in the upper 30 m at a site, $V_s(30)$ [5]. Initial maps of site effects assign a site class, A through F, based on $V_s(30)$ measurements in each geologic unit as defined by the National Earthquake Hazards Reduction Program (NEHRP) [6].

This study seeks an appropriate model for the horizontal variability of near surface shear-wave velocity to make reliable estimates in unsampled locations. Shear-wave velocity is an important parameter because $V_s(30)$ is used to determine response spectra for building codes and detailed shear-wave velocity models are necessary for accurate ground motion modeling. Stochastic spatial models have been shown to appropriately describe the variability of soils. Fenton [7] summarizes the different stochastic models of soil properties including the sample covariance, spectral density, variance function, variogram, and wavelet variance functions. Fenton [8] used 143 cone penetration test (CPT) soundings from soil distributed over an area of 18 km^2 in which he assumes that the volume of soil is a homogeneous random field and that each sounding of tip resistance is a sample of that random field. From this study he concluded that the vertical variation of tip resistance is fractal. This implies the variability increases indefinitely as the scale of measurement increases. If the variance becomes constant at some scale, then it would be a finite variance model, and the distance at which the

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variance reaches the maximum value is called the range. The maximum variance and the range characterize the heterogeneity of a variable. Many previous studies have used similar techniques to analyze the spatial variability of soil properties and we discuss a few examples here. Elkateb et al. [9] modeled liquefaction damage with CPT measurements and assumed that the horizontal correlation structure is the same as the vertical but with an increased range. The horizontal range should be larger than vertical due to the horizontal layering of sediments. Soulie et al. [10] modeled the variability of undrained shear strength in clays and found a vertical range of 3 m and horizontal range of 30 m. DeGroot [11] compiled soil properties (including N values, tip resistance, undrained shear strength, and hydraulic conductivity) and found values for the range in the vertical direction to be between 0.5 and 3 m and the horizontal range between 15 and 30 m. These previous studies have all modeled relatively homogeneous soil deposits at the site-specific scale. The spatial extent we are interested in for regional mapping of seismic hazard is greater than an order of magnitude larger than these previous studies.

Initially, the maps of ground-motion amplification were based on previously mapped geologic units [12]. For each geologic unit, an average shear-wave velocity was determined from velocity profiles. The United States Geologic Survey (USGS) collected 210 SCPT profiles in a 140 km^2 area of the San Francisco Bay, California, which provided more detailed velocity data within each geologic unit [13]. Holzer et al. [14] produced NEHRP site class maps from these data by calculating $V_s(30)$ on a 50 m grid. The researchers set the shear-wave velocity of each geologic unit equal to the mean of the distribution of V_s values measured within each geologic unit. The shear-wave velocity profile was constructed at each node of the 50 m grid by manually contouring the thickness of each unit. They calculated $V_s(30)$ from the shear-wave velocity profile at each node. This method produced more variability of the mapped $V_s(30)$ values than regional maps based exclusively on surficial geology such as Wills et al. [6]. The variability of $V_s(30)$ in these maps results from the unit thickness contouring since the shear-wave velocity of each geologic unit is constant. Most of the profiles in this dataset do not reach depths of 30 m so this method requires extrapolation of the V_s data to depths not measured in the dataset.

As an alternative approach, we investigate the spatial variability of shear-wave velocity across geologic units within a sedimentary basin. Scott et al. [15] found that mapped geologic units do not correlate well with $V_s(30)$ measurements. The assumption of horizontal spatial homogeneity, as in the stochastic methods of Fenton [7,8] and Elkateb et al. [9] does not apply because our measurements are taken from different geologic formations such as dune sands, alluvial fans, bay mud, and artificial fill. We also do not assume that the shear-wave velocity of each geologic unit is constant.

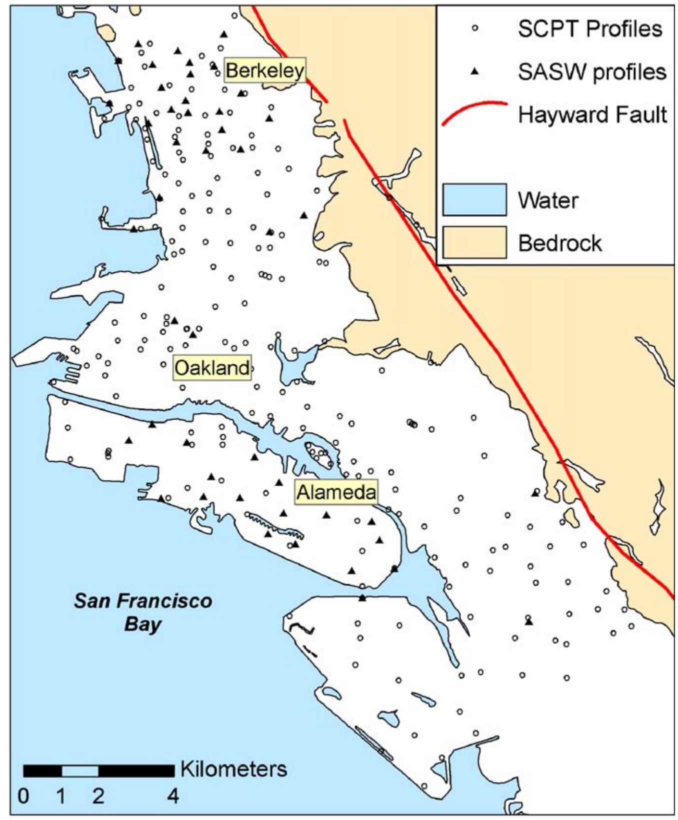

Fig. 1. Map showing the location of SCPT and SASW sites within the sedimentary basin. The SCPT data is more continuous and densely spaced than the SASW data. The SASW data is mostly grouped in two locations: near Berkeley, and near Alameda.

The two techniques used to measure shear-wave velocity in this study, seismic cone penetration test (SCPT) and spectral analysis of surface waves (SASW), each have a different role in this study. In order to map surface shear-wave velocity across a region, we need data that are densely spaced and accurately represent site response effects. The benefit of the SCPT data is that the sampling density is great enough that it can be continuously mapped. However, the measurements do not reach depths great enough to reliably characterize the $V_s(30)$. For this study, we collected 48 SASW measurements. The SASW technique accurately measures the shear-wave velocity to depths of 30 m or greater, but the 48 sites collected for this study are not as closely spaced or as spatially extensive as the SCPT data. Fig. 1 shows the measurement locations for the SASW and SCPT data used in this study. If the SASW data are strongly correlated to the SCPT data then we can use both measurements together to map seismic hazard.

2. Methods

2.1. SCPT data

The SCPT data used in this paper were collected and presented in a digital database by Holzer et al. [13]. The locations of these measurements are included in the map in