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STOCHASTIC SITE RESPONSE ANALYSIS OF A DEEP SITE

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ABSTRACT: This paper presents the results of analyses demonstrating the effects of introducing stochastic variability into site response analyses. Analyses were conducted at three deep sites in the Fraser Delta. The site response analyses are part of a larger investigation into seismic risk assessment and cost-effective seismic retrofit of BC schools. Data are available at each school location to a depth of 30m from three SCPTs and one SPT. Information on soil properties at depths greater than this, is found in a report published by the Geological Survey of Canada, which compiled information from several deep borings to produce generalized curves for shear wave velocity in the Fraser River Delta. From these data mean shear wave velocity depth profiles and standard deviation were determined for the deep sites. To account for uncertainty in the soil properties Stochastic Monte Carlo simulations with a large number of realisations were used. These sites were analysed using the nonlinear program DESRA-2 for each realisation and surface spectra were calculated. An average spectrum for all the realisations in the analysis was used for each school project. This paper focuses on the Monte Carlo process and shows typical results.

1. Introduction

This paper presents the results of analyses demonstrating the effects of introducing stochastic variability of site properties into site response analysis. Analyses were conducted at three school locations Gilmore, Thompson and Woodward in Richmond, British Columbia (Figure 1). The work was carried out as part of a broader investigation into seismic risk assessment and cost-effective seismic retrofit of BC schools. The BC Ministry of Education contracted The Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) to develop performance-based technical guidelines (APEGBC 2006, APEGBC 2011, APEGBC 2013) to be used by engineers in assessing and retrofitting at risk schools in BC. As part of the work in developing these guidelines, the ground motion amplification potential of school sites was studied by researchers at The University of British Columbia (UBC). This paper focusses on one aspect of the amplification study, the incorporation of uncertainty into the site response analyses. The input motions used in this paper were representative of the three seismic threats to the area: crustal, sub-crustal and subduction earthquakes. However, the inputs should not be considered the definitive motions to be used at depth in the Fraser River Delta. The focus here is not on seismic hazard itself but demonstrating the potential benefits of incorporating stochastic variations in soil properties into the site response analysis of deep soil sites.

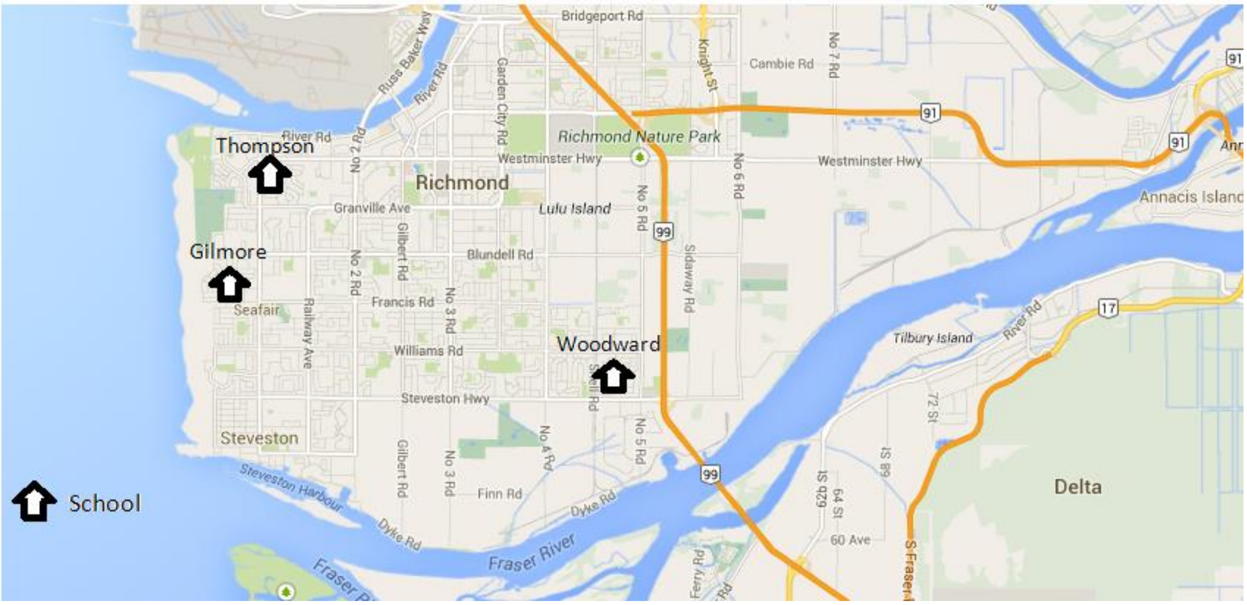


Fig. 1 – The three school sites

2. Geotechnical Data

2.1. Soil properties for the top 30m

Geotechnical site investigations were conducted at each of the three schools using three Seismic Cone, Penetration Tests (SCPTs), to depths of 30m at each school. The shear wave velocity (V_s) profiles attained from one of each of the three boreholes at the three school sites in shown in Figure 2. The plot shows clearly the variability of the velocity profiles.

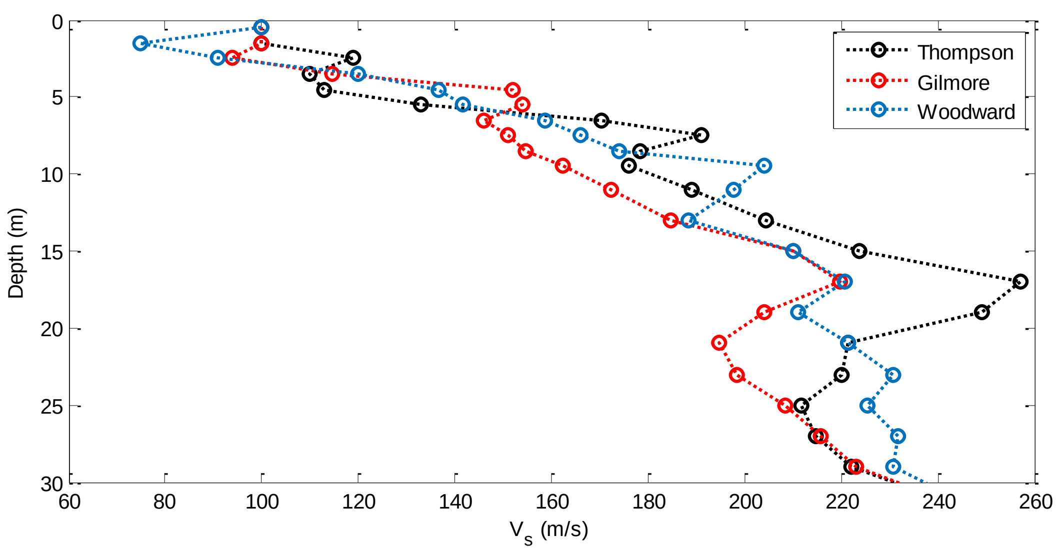


Fig. 2 – V_s profiles from the three school sites

The V_s profiles are generally similar in trend, but there are large differences in velocities in the stiffer, deeper layers. The cone resistance, q_c and pore pressure, u_2, data, recorded at 0.05m intervals are recovered from the SCPT data. The undrained shear strength is estimated using Equation 1 developed by Robertson and Cabal (2010). This strength and V_s are required input parameters for site response analyses. A value of 14 was selected for N_{kt} (Robertson and Cabal, 2010)

$$s_u = (q_t - \sigma_v)/N_{kt} \quad (1)$$

2.2. Soil properties at depths from 30m to 300m

The depths of the analyses conducted in this paper are 300m. This depth corresponds to the depth of three very deep borings made in Richmond by the Geological Survey of Canada (GSC). The shear wave velocity at this depth corresponds to the depth of Site Class C soils, the reference site class in the building code (NBCC 2010). A total of 50 soil layers, each with independent soil properties, was used in modelling the site.

Soil properties in the depth range of 30-300m were taken from a report by Hunter and Christian (2001). They presented an empirically derived depth dependant V_s relationship for the delta by combining information from many site investigations in the region, including three boreholes of approximately 300m. The mean values of shear wave velocities for all depths 30-300m, together with the V_s profiles in the top 30m from Figure 2, are shown in Figure 3.

The other variable input parameters are the unit weight of the soil, γ (units of kN/m^3), the friction angle, φ (used in the calculation the maximum shear strength of sands, s_u), and N_{kt}, the parameter used to infer the s_u values from the measured q_c values above 30m.

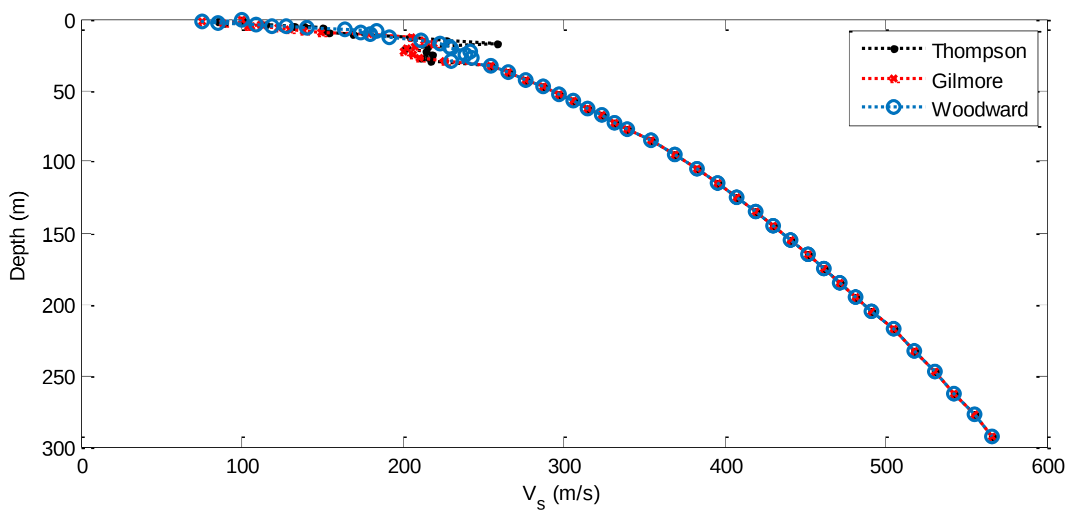


Fig. 3 – V_s profiles from the three school sites incorporating the Hunter and Christian (2001) V_s-depth relationship

3. Description of the Site Response Analysis

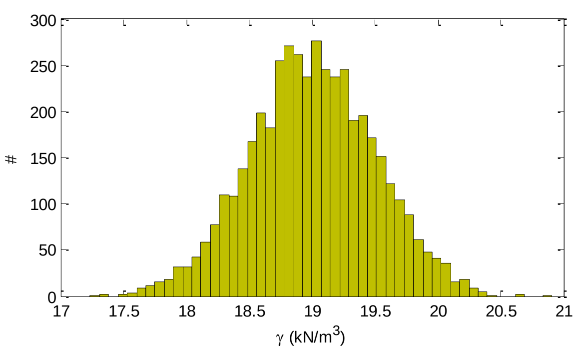
Site response analysis is generally performed, either to estimate the seismic hazard and ground motion amplification at a site, or as a precursor to Soil Structure Interaction (SSI) analysis. At its most basic, it is the vertical propagation of horizontally acting shear waves of an input seismic motion. Time histories of acceleration (or velocity, displacement, etc.) are calculated at various depths from input level up to the surface. There are a number of different methods of performing site response analysis, from linear to nonlinear, and from 1D to 3D. Analyses for the present study were conducted using the nonlinear 1D program DESRA-2, developed by Lee and Finn (1978) and updated by Finn et al. (1994). DESRA-2 is a direct nonlinear time domain soil response code. DESRA-2 models the nonlinear hysteretic behavior of soil. The accuracy of the results of DESRA-2 have been verified in a variety in different situations: using field observations (Finn et al., 1982), in laboratory simple shear tests (Finn, 1981), and even in laboratory centrifuge tests (Hushmand et al., 1987). All analyses are conducted using total stresses. DESRA-2 is used as the main analytical tool in the calculation of the site response. MatLab (MatLab, 2014) is used to generate input files and manage output files and process results.

To account for uncertainty in the soil properties we used Stochastic Monte Carlo simulations with a large number of realisations. A surface spectrum was calculated for each realisation. An average acceleration response spectrum of all the realisations was used to characterize the hazard at each site. Input motions

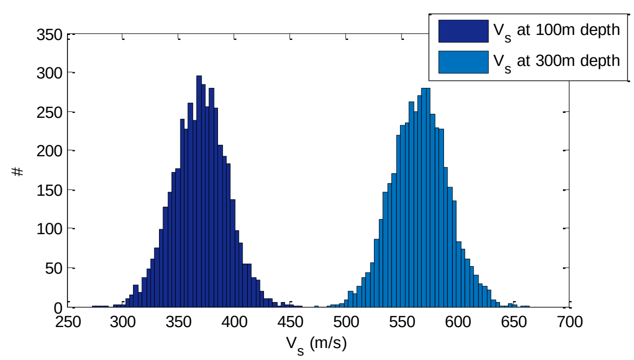
The input motions used here are the motions developed for the school retrofit program and scaled to the NBCC 2010 Site Class C hazard spectrum for velocity in the period range of 1.0s to 2.0s. Hence, these motions are representative only. To determine the motions that should be input at the base of the 300m deep soil column, a more detailed investigation including deconvolution methods are required. This is the subject of a more detailed study currently underway by the authors at UBC. Thirty motions are used: ten from each of three types of sources; crustal, subcrustal and subduction. The amplification of the input motions as they are propagated to the surface is the main focus of this paper. The amplification is defined as the ratio of the outcrop surface spectra to the outcrop input spectra.

3.1. Monte Carlo Simulation

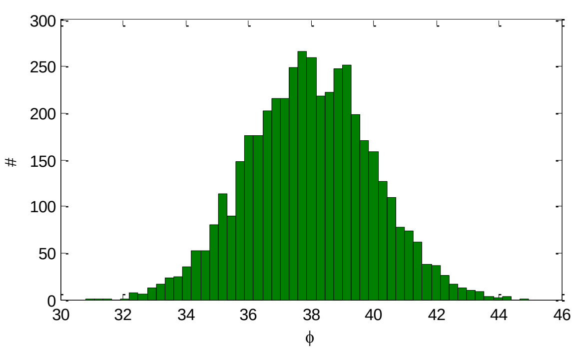
Monte Carlo Simulations were used to account for uncertainty in the soil properties by varying the parameters used in the DESRA-2 analyses. Figures 4(a)-(d) show the variation of soil properties generated by 4,500 simulations.



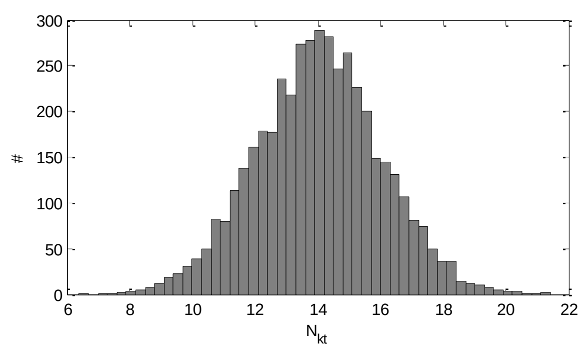
(a) Histogram of γ values



(b) Histogram of V_s values



(c) Histogram of φ values



(d) Histogram of N_{kt} values

Fig. 4 – Histograms showing data used for Monte Carlo simulation

4. Site Response Analyses Results

4.1. Monte Carlo example 1

Two simple examples are presented to illustrate how the Monte Carlo Simulation works. The response of the site of the Gilmore school to a record from the 1995 Kobe earthquake (PEER, 2015, database number 1111), scaled by a factor of 0.99) is analyzed for 50 different simulations of site properties. The material properties that are varied using Monte Carlo simulations for examples 1 and 2 are tabulated in Table 1.

Table 1. Variables (material properties) generated using Monte Carlo methods.

Material property	**Mean value**	**Standard Deviation**
V_s (above 30m)	Taken from SCPT data	25m/s or 75m/s
V_s (below 30m)	Varies with Hunter and Christian (2001) equation	25m/s or 75m/s
N_{kt}	14	2
φ	38°	2°
γ	19kN/m^3	0.5kN/m^3

The results of the first example are summarised in Figure 5, which presents the response spectra for each simulation and the mean of the 50 simulations and the spectrum of the input motion. The standard deviation of the V_s values uses in this first example is 25m/s. The spectra of the surface motions of the 50 simulations are in blue and the mean of the 50 spectra in red. Figure 6 shows the range of simulated values of V_s and Figure 7 shows the range in density, γ.

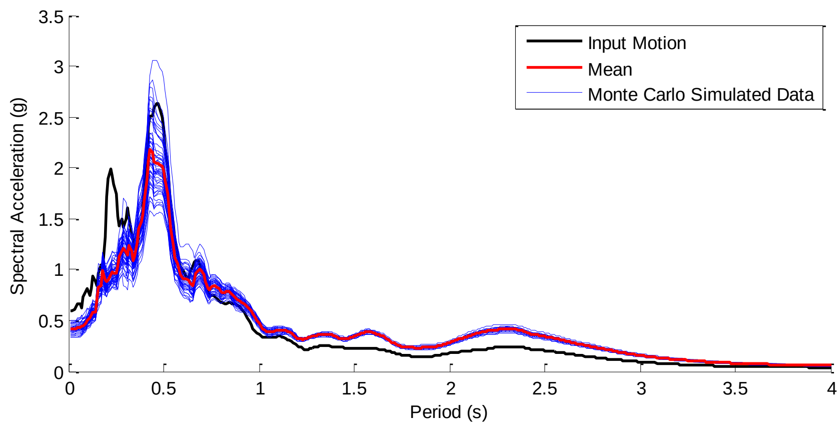


Fig. 5 – Example 1 simulation response spectra

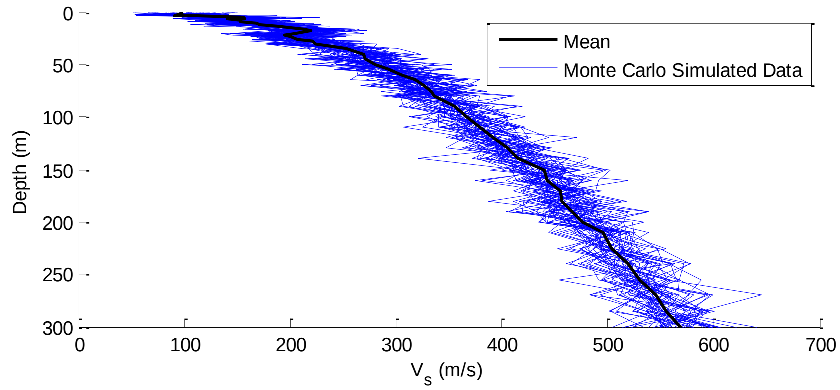


Fig. 6 – Example simulation variation in V_s

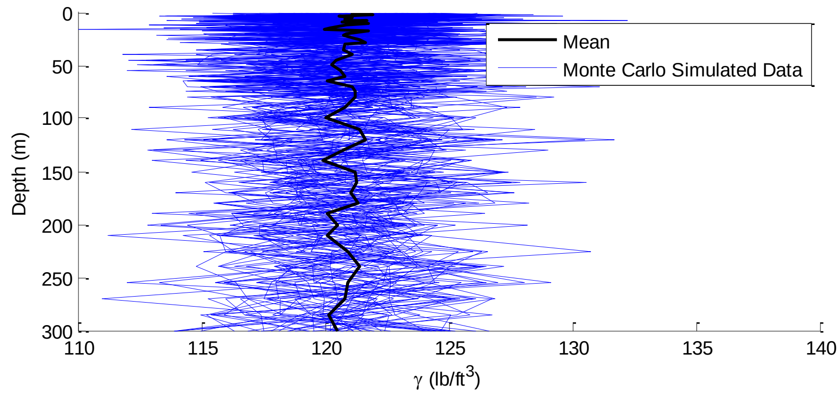


Fig. 7 – Example simulation variation in γ

4.2. Monte Carlo example 2

The standard deviation of the V_s in the example above was 25m/s. To illustrate how crucial this variable is to the simulation process, Figure 8 presents the results of a similar simulation to that presented in Figures 5 to 7 but with the standard deviation of V_s increased to 75m/s. There is a much wider range in response.

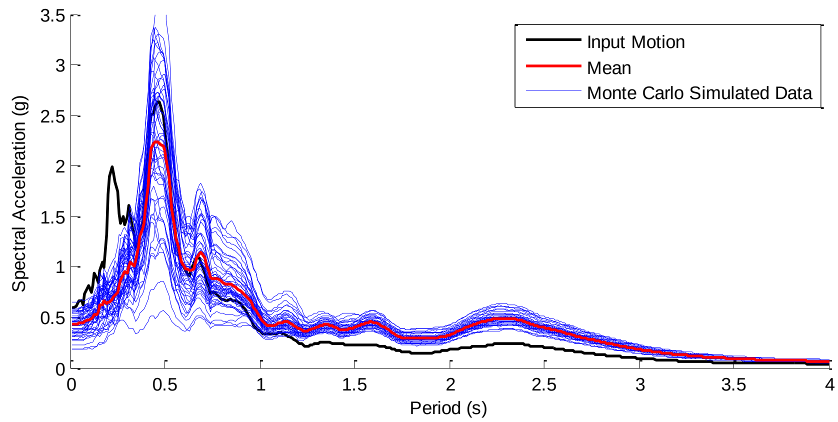


Fig. 8 – Example simulation response spectra

The impact of the increased standard deviation on response spectral values is illustrated in Figure 9 which shows the average spectral acceleration values of V_s σ=25m/s and V_s σ=75m/s. There is an increasing and significant difference between the spectra at periods greater than 1.0s including the critical period range for design of 1.0-2.0s.

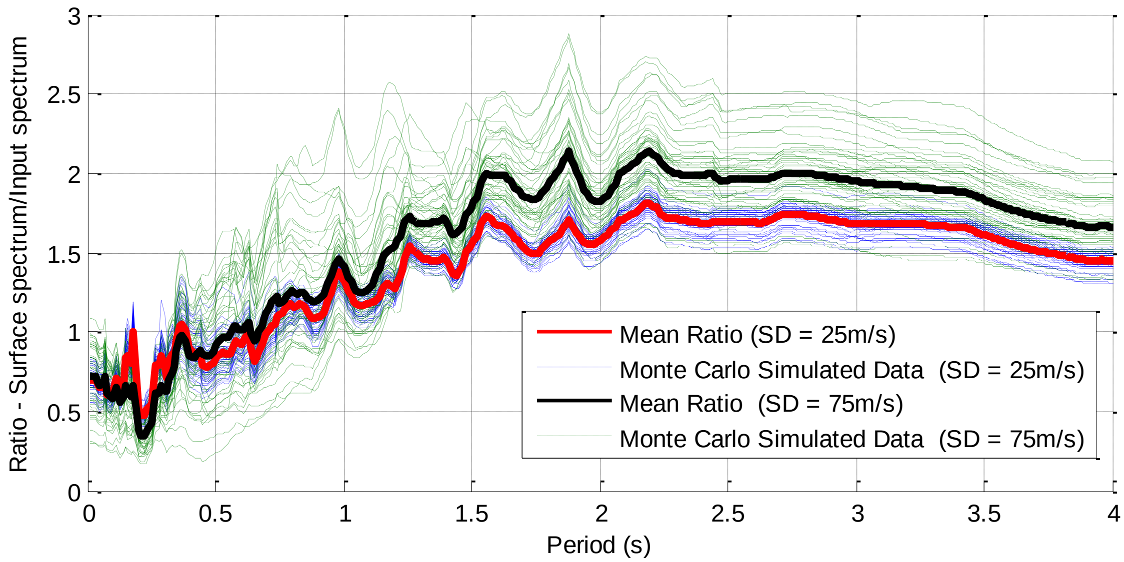


Fig. 9 – Spectral Ratios of Examples 1 and 2

4.3. Full stochastic analysis

Figures 5 to 8 and Figure 9 present the results for a variety of different soil columns, which are generated using Monte Carlo sampling methods, to a single input motion. To generalise these results we perform such simulations, where the soil column in generated in the same way, but all 30 of the ground motions considered in Pina et al. (2010) are applied, and the results of the amplification to all motions are considered together. To this end Figures 10, 11 and 12 are presented.

In each of these Figures all the simulations for each site are combined. That is, each figure presents the results of the 30 ground motions being applied to the model using the measured properties from the 3 boreholes at each school, and 50 variations of each of these simulations using Monte Carlo sampling. In each figure there are therefore, 30×3×50 = 4,500 simulations, which are plotted, along with the mean and the mean plus one standard deviation, σ. The results are presented as spectral ratios.

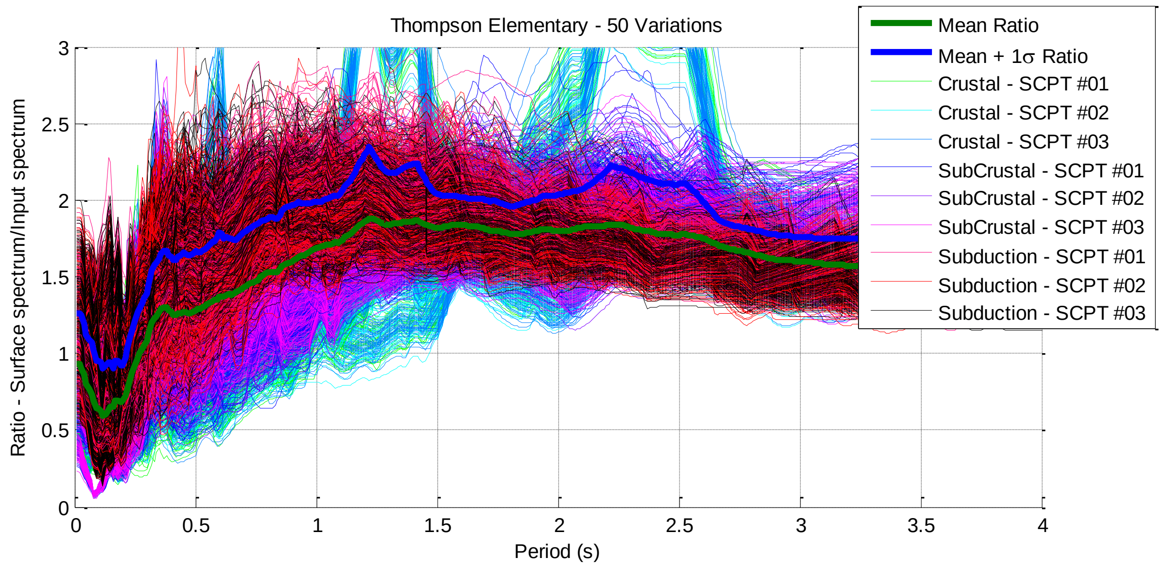


Fig. 10 – Summary of the results for the Thompson School

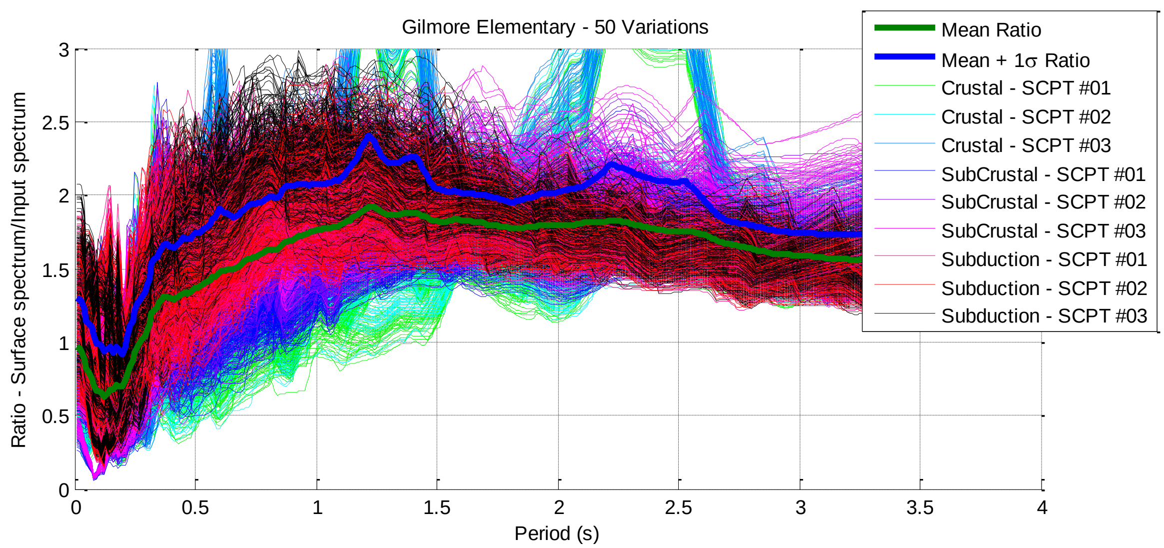


Fig. 11 – Summary of the results for the Gilmore School

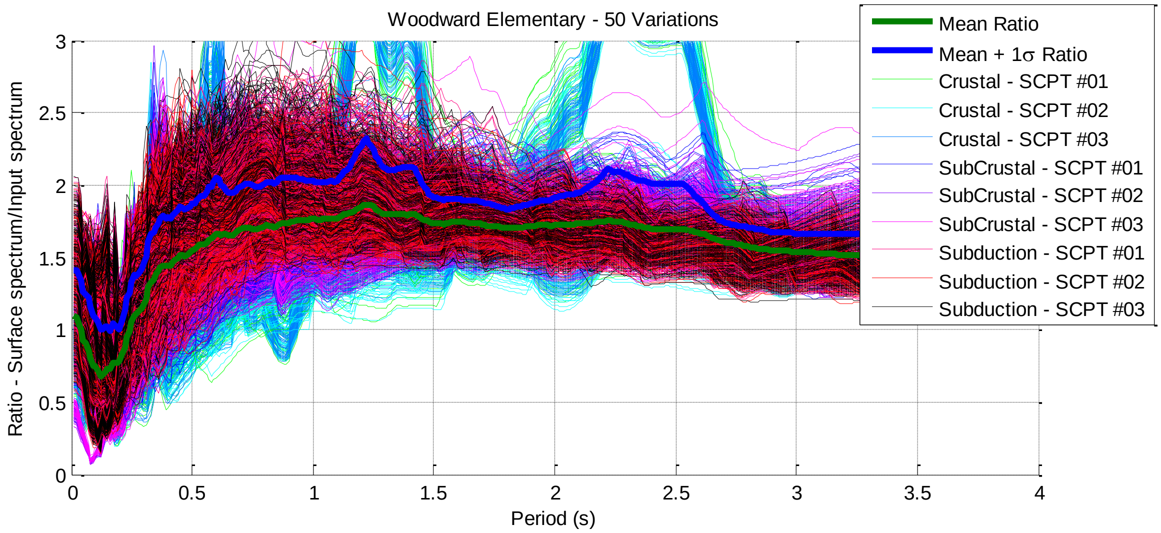


Fig. 12 – Summary of the results for the Woodward School

The average spectral ratio, for the period range of interest of 1s to 2s is 1.81, 1.82 and 1.76 for the Thompson, Gilmore and Woodward School sites, respectively. (The spectral ratio, at the period value of 1s is 1.69, 1.76 and 1.77 for the Thompson, Gilmore and Woodward School sites, respectively.) The range in the spectral response in all three Figures is large. The spectral response at the mean+1σ is made available to provide a rational basis for more conservative design than that based on the mean.

5. Conclusions

Stochastic Monte Carlo simulation is an effective way of coping with the uncertainty in the soil properties used in nonlinear 1D site response analyses. It has been used in the site response analyses of three deep (300m) school sites located in Richmond, BC to investigate the effect of uncertainty on amplification factors at the sites. The simulations resulted in stable mean values of spectral accelerations. The major uncertainties in properties were associated with the shear wave velocities in the depth range 30-300m. To gage the sensitivity of the mean values to uncertainty in V_s, a credible range in the standard deviation of V_s from 25m/s to 75m/s was explored. The mean spectral response in the period range of interest for retrofit design of 1-2seconds, increased by 15% as the standard deviation in V_s went from 25m/s to 75m/s.

6. Acknowledgements

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