When deterministically modeling the propagation of seismic waves, shallow shear-wave velocity plays a crucial role in predicting measures of shaking intensity such as peak ground velocity (PGV) and duration. The Clark County Parcel Map provides us with a data set of >10,000 geotechnical velocities in and around Las Vegas Valley, measured with SeisOpt® ReMi™ by Optim SDS. This is an unprecedented level of geotechnical detail. Las Vegas Valley is a geologic basin having similar geologic properties to some areas of Southern California. We analyze elementary spatial statistical properties of the Parcel Map, and calculate its spatial variability. We then analyze the same spatial statistics from the PGV maps computed from two geotechnical models that incorporate the Parcel Map as input. Plotting a histogram of the Parcel Map’s 30-meter depth-averaged shear velocity (Vs30) values shows the data to approximately fit a bimodal normal distribution with $\mu_1 = 400$ m/s, $\sigma_1 = 76$ m/s, $\mu_2 = 790$ m/s, $\sigma_2 = 149$ m/s, and $p = 0.49$, where $\mu$ is the mean, $\sigma$ is standard deviation, and $p$ is the probability mixing factor for the bimodal distribution. Based on plots of spatial power spectra, the Parcel Map appears to be fractal between 0.1 and 10 cycles/km spatial frequency, or 0.1 to 10 km wavelengths. The 1-d spatial spectra exhibit the same fractal dimension in the N-S and the E-W directions, indicating isotropic scale invariance for the 2-d spatial spectra. We configured finite-difference wave propagation models at 0.5 Hz with LLNL’s E3D code, utilizing the Parcel Map as input, to compute a PGV map of the shaking intensity expected from a scenario earthquake (Black Hills M6.5). The resulting PGV map is fractal over the same spatial frequencies as the Vs30 maps associated with their respective models. The fractal dimension is systematically lower in all of the PGV maps as opposed to the Vs30 maps, showing that the PGV maps are richer in lower spatial frequencies. This is potentially caused by seismic waves averaging through spatial heterogeneities as they propagate. Finally, we develop a method to produce a comprehensive and adaptable Vs30 geotechnical model containing the Parcel Map overlain on stochastically generated Vs30 values. This model preserves the spatial statistics across the entire modeled map, and implements the deterministic features discovered by the Parcel Map.
refraction microtremor data at an unprecedented resolution. Not only does this data set provide a shallow shear-wave velocity map for Las Vegas Valley (LVV), but it also constrains an integral parameter to the prediction of peak ground velocities from model earthquake scenarios (Louie, 2008; Louie et al., 2011b). The >10,000 data points systematically cover almost the entire Las Vegas Valley at a spacing of approximately 300 meters, to an average depth of resolution of 50 meters. The data set is used to classify earthquake hazard in LVV using the USGS NEHRP and IBC (BSSC, 1997) earthquake hazard classification schema. The basin is mapped with a classification rating based on the geotechnical velocities measured by the data set. The site-specific classifications result in the Clark County Parcel Map.

Motivation and Objectives. In Southern California, seven years of effort to measure shallow (<300 m depth) shear-velocity profiles at hundreds of sites have resulted in a data set that allows spatial and geostatistical analysis of the variance and uncertainty in site conditions. The USGS NEHRP Southern California panel has sponsored most of this prior work, from the 60-km-long transect of 200 sites across the LA Basin by Thelen et al. (2006) to the regional assessment of over 75 CISN recording sites reported in Louie et al. (2008) and Thompson (2010). We provide an assessment of that data set for its impacts on the prospects for high-frequency deterministic earthquake simulations, on our understanding of why ground motions vary from one station to another, and on our ability to place limits on future strong-motion intensities.

Until a detailed Parcel Map such as Clark County’s can be measured for every urban area at risk of earthquakes, we need to find a stopgap method for making use of the data that are available, to estimate the strength and variability of potential earthquake shaking. By quantifying spatial and geostatistical variance and uncertainty in site conditions, we develop a method to augment SCEC’s current Community Velocity Model (CVM; Magistrale et al., 2000) with a stochastic geotechnical layer that holds to the site specific spatial statistics identified within the Parcel Map. We configure two scenario earthquakes, on the Black Hills fault and the Frenchman Mountain fault, using the modeled stochastic geotechnical layer, and compare the results against those of the same scenarios calculated using the Parcel Map with no stochastic model. We investigate the spatial statistics of the ground motions output from both the stochastic-geotechnical scenarios and the Parcel Map scenarios. This allows us to understand how much detail is required in the CVM to push deterministic calculations to frequencies of 1 to 5 Hz, and the effects heterogeneous shallow geotechnical velocities have on computed peak ground velocities (PGV).

Background. Since Borcherdt and Glassmoyer (1992) investigators have known that near-surface variations in shear velocity correlate with ground-motion amplification – but only partly. Other effects add much additional variance to ground motions (Shani-Kadmiel et al., 2012). A few examples are basin thickness (Field, 2001; Gvirtzman and Louie, 2010), geometric focusing effects (Graves et al., 1998), and interference between horizontally propagating modes (Olsen, 2000; Stephenson, 2005). There are many additional source and path effects on ground-motion variance that this work will not address.

The measurement of three urban shear-velocity transects at close spacing across Los Angeles, Las Vegas and Reno (respectively Thelen et al., 2006; Scott et al., 2006; Scott et al., 2004) and dense measurement campaigns throughout urban basins such as by Kaiser and Louie (2006) in a Wellington, New Zealand neighborhood and throughout urban Clark County by
Louie (2011a) leave no doubt that shallow shear velocities are highly variable down to very close measurement spacing. The urban transects, having a minimum 300-meter measurement interval, show fractal spatial variances, with fractal dimensions between 1.5 and 1.8 (Figure 1). The fractal variance trend may well maintain all the way down to the 300 m minimum spacing, meaning that nearby sites can never be confidently correlated, and spatial velocity distributions can never become smooth enough to be predicted by a map of geologic or soil units.

Figure 1: Spectral analysis of spatial variance of Vs30 measurements along three urban geotechnical transects—Los Angeles Basin (blue, Thelen et al., 2006); Las Vegas (red, Scott et al., 2006); and Reno (green, Scott et al., 2004). Vs30 is the average shear velocity from the surface to 30 m depth. The linear trends on the log-log plots suggest fractal variance; with the slope of the line giving the fractal dimension $D$ (Mela and Louie, 2001).

Louie et al. (2011a) mapped over 10,000 geotechnical site measurements in Clark County, Nevada of shallow shear velocity, over an area of 600 square miles. Figure 2 shows a portion of the Clark County Parcel Map. The Parcel Map has relatively smooth and correlated measurements of NEHRP class B (blue in Figure 2, by velocity criteria alone) on the southwest side of Las Vegas Valley, with a sharp boundary to highly variable NEHRP class C and D areas in the central and eastern parts of the Valley (green and orange in Figure 2). Across Southern California, Thompson (2010) examined the spatial variability of the Louie et al. (2008) measurements at 75 CISN stations, the 200 Thelen et al. (2006) transect measurements, and about 100 additional site characterizations in the Next-Generation Attenuation (NGA) Project data base (Power et al., 2008). The kriging process of estimating an average Vs30 (the depth-averaged shear velocity from the surface to 30 m depth) map can also estimate the standard deviation of the average, and how it increases away from the measured points according to the fractal dimension. Outside the deep basins and away from the soft sites, the Vs30 prediction uncertainty exceeds 25%.

Deterministic scenario models we have run for the Las Vegas basin suggest that this fractal heterogeneity of site conditions may cause additional ground-motion variance not only at
the site of the variance, but also at sites far removed from it (Louie et al., 2011b). Deterministic scenarios computed for Las Vegas Valley by Louie et al. (2011b) and Savran et al. (2011) at 0.5 the effects on predicted ground motions of two Vs30 maps: one derived from the data (Louie et al., 2011a) with high spatial variance; and another with smooth Vs30 correlated only to the geologic map. The time histories of ground motion predicted from the two models were generally similar but differ in many details at their higher ground motions.

Figure 2. Map showing a portion of the >10,000 Vs30 data points of the Clark County Parcel Map (Louie et al., 2011a) plotted on top of IBC default geotechnical velocities (BSSC, 1997) for rock (blue) and soil (green) areas. The cooler areas on the map represent areas that have higher Vs30 and should see lower ground motions; whereas the warmer areas have lower Vs30 and represent a higher expected ground motion. This entire region comprises the top surface of the model grid for the Black Hills fault scenario computation (Louie et al., 2011b).

METHODS

Parcel Map Statistics. The high resolution of the Parcel Map enables us to perform geostatistical analysis at a level of detail that is unprecedented. With 300 m sample spacing, each geologic or soil unit has many measurements. This multiplicity provides results showing the fractal properties with unprecedented accuracy. The spatial statistics have fundamental effects on ground motions when modeling earthquake scenarios. As well, understanding the distribution of geotechnical velocities throughout Las Vegas Valley is as important. Determining the probability density of the data, we gain knowledge about the average velocities of the predominant site types
in the basin. In order to approximate the probability density function of the Parcel Map, we plotted the Vs30 data as a histogram of occurrences of the range of velocity values. The histogram analysis does not provide any indication of spatial variation in the data set, but it provides a standard basis for further statistical analysis.

The spatial statistics allow us to quantify a parameter, fractal dimension, on which to base our stochastic model of the geotechnical velocities in Las Vegas Valley. The spatial statistics are collected on the entire geotechnical model for the Black Hills earthquake scenario of Savran et al. (2011) shown in Figure 2, because we are interested in understanding the effects of stochastic noise on ground-motion prediction. To calculate the fractal dimension of a data set using a power spectrum, Mela and Louie (2001) use, following Carr (1995):

$$D = \frac{5 - \beta}{2}$$  \hspace{1cm} (1)

where $D$ is the fractal dimension and $\beta$ represents the absolute value of the slope obtained from the power-law fit to the power spectrum of the data set. The power spectrum is sampled spatially as opposed to temporally, so the data-sampling interval is equal to the spacing of the finite-difference grid used to model the earthquake scenario region. Calculating the spectrum in each of the cardinal directions allows us to understand the variance in both the North-South and East-West directions. We derived summed spectra in each direction by calculating the 1D power spectrum of each vector of the Vs30 map (Figure 2), and calculating an arithmetic average across all the vectors at each frequency.

**Stochastic Modeling of the Parcel Map.** Understanding the spatial statistics is the key to stochastic modeling of the Parcel Map. Our goal is to replicate the same spatial statistics discovered in the Parcel Map, as well as any other non-deterministic features discovered in our analysis. We speculate that the data set will possess isotropic self-similar behavior, due to the stochastic randomness observed in the geotechnical velocities collected by Kaiser and Louie (2006) in Wellington, New Zealand, and by Thelen et al. (2006) in Los Angeles. Based on previous interpretations of such data sets, we have indications the Parcel Map Vs30 data will possess fractal spatial variance. We try and replicate the stochastic spatial variance seen using white, pink, and Brownian noise generators across a model map. The generated random noise is smoothed using an adjustable square kernel of adjustable dimension on the map, and then scaled to add a pre-specified percentage of noise to a background Vs30 model map.

In order to produce a model map similar to the Parcel Map and uphold the deterministic features, we first produce the deterministic background model containing IBC default velocities (BSSC, 1997; Louie, 2008) based on the Saltus and Jachens (1995) and Langenheim et al. (1998) geologic maps for southern Nevada, in the area of Figure 2. In our models, the IBC default geotechnical velocities are 500 m/s for sediment or basin sites, and 760 m/s for bedrock sites. The Saltus and Jachens (1995) and Langenheim et al. (1998) maps distinguish basin from bedrock, producing the blocky deterministic basin (green) and bedrock (blue) areas at the edges of Figure 2, outside the coverage of the Clark County Parcel Map. The background maps provide no site-specific regions of higher or lower velocity within any basin or bedrock area, such as the high-velocity caliche-cemented soils in the western portion of Las Vegas Valley noted by Louie et al. (2011a).
The white noise generator produces evenly distributed random noise, with no decrease in power at the higher-spatial-frequency part of the spectrum. The white noise modulates the IBC default geotechnical velocities at every grid point. White noise does not replicate natural processes as well as pink or Brownian noise (Mela and Louie, 2001); however, we include it to better understand the spatial statistics of the Parcel Map. Theoretically, white noise should display equal power across all frequencies, resulting in physically unrealistic variance in the Parcel Map.

To model the stochastic variation with pink noise the random variance in velocity must fit a Gaussian distribution. This is most simply accomplished using the Central Limit Theorem to approximate the Gaussian distribution. Pink noise decays as $1/f$ on the spectrum whereas white noise decays as $1/f^0$ and Brownian or red noise decays as $1/f^2$, where $f$ is frequency. Brownian noise has a fractal dimension of 1.5, and pink noise has a fractal dimension of 2, from Mela and Louie (2001). Based on the observations of Louie et al. (2008) and Thompson (2010), a fractal dimension of 1.5 to 1.8 would indicate the randomness as some type of fractional Brownian motion. In order to obtain this fractional component, a square-smoothing kernel is applied to the model map. The dimensions of the kernel can be chosen by the analyst, and is expressed in kilometers. For our stochastic geotechnical models, we smoothed the random noise over scenario-modeled seismic wavelength, or 3.0 km.

Red or Brownian noise is integrated white noise and can be modeled using a random walk approach, where the walker takes an equidistant step in a randomly determined direction until the walk is complete. As with the other two, the modeled Brownian noise will modulate the base map’s deterministic default IBC values. The noise is scaled to an amount of noise selected by the analyst. The methods used to generate the three different types of stochastic maps were integrated into Louie’s (2008) ModelAssembler program for the Nevada ShakeZoning project, with source code available at crack.seismo.unr.edu/nsz. However, our Brownian noise generator did not perform as intended, so we will focus here on the pink noise models of the Parcel Map.

The stochastic noise modulating the background map containing the IBC default geotechnical velocities aims to preserve the spatial statistics of the Parcel Map. However, the method cannot account for the deterministic features of the Parcel Map. Our final method for creating model geotechnical maps is to overlay the Parcel Map measurements on top of the stochastic model, producing a model map accounting for the deterministic features in Las Vegas Valley as well as the preserved spatial statistics of the Parcel Map throughout the modeled data set.

**Trial Scenarios.** In order to examine the effects of the stochastic model maps of geotechnical velocities on earthquake ground motion predictions, we configured two earthquake scenarios on hazardous faults in Las Vegas Valley. The USGS defines a hazardous fault as any fault thought responsible of an Mw $>$6.0 earthquake in the Quaternary period (USGS and NBMG, 2012). We chose the Frenchman Mountain fault, a range-bounding fault located in eastern Las Vegas Valley at the base of the Frenchman Mountain, as well as the Black Hills fault located in Eldorado Valley to the southeast of Las Vegas Valley.

Louie et al. (2011b) and Savran et al. (2011) outlined the Nevada ShakeZoning process we use to predict earthquake ground motions in Las Vegas Valley. The finite-difference code E3D, by Larsen et al. (2001) of Lawrence Livermore National Laboratories, solves the elastic wave equation in three dimensions from kinematic representations of earthquake ruptures. Our Nevada ShakeZoning models use E3D to propagate the waves, and ModelAssembler (Louie,
to configure model parameters specific to Las Vegas Valley, such as lithologic information, basin thickness, and geotechnical velocities; all from external data sets such as the Parcel Map. For each of the scenarios the basin thickness data are assembled by overlying Langenheim et al. (1999) results at high resolution in Las Vegas Valley atop the Saltus and Jachens (1995) results for basin-floor topography across the Intermountain West. Nevada ShakeZoning assembles geotechnical velocity maps in the same fashion. The Parcel Map (Louie et al., 2011a) is overlain on the IBC default geotechnical velocities to produce the input geotechnical layer, Figure 2. Each earthquake scenario is calculated twice, once using the stochastic model and the other using the Parcel Map. Flinchum et al. (2012) to provide validation of Nevada ShakeZoning synthetics against recordings of a 1992 earthquake in southern Nevada.

**Frenchman Mountain scenario**– The Frenchman Mountain fault is an average west-dipping normal fault with an 18 km-long concave rupture zone with an average strike of N1°E, on the eastern edge of LVV at the base of Frenchman Mountain. The slip rate used to estimate the moment magnitude was <0.2 mm/yr (USGS, 2012). The magnitude calculated for this scenario was Mw6.7 with a seismic moment of 1.38 x10^{26} dyne/cm. The ShakeZoning grid created for this scenario has 419-North-South (NS) by 585-East-West (EW) by 81-deep grid nodes with grid spacing dx=dy=dz=0.25 km, to minimize the grid dispersion artifacts from the 0.5 Hz wave modeling.

**Black Hills scenario**– The Black Hills fault is a southeastern-dipping normal fault with a 9 km rupture zone and an average strike of N31°E, located just outside the southeastern part of LVV along the southeastern base of the Black Hills. The slip rate used to calculate the moment magnitude was <0.2mm/yr (USGS, 2012). The magnitude calculated for this scenario was Mw6.5 with a seismic moment of 6.64x10^{25} dyne/cm. This is probably the largest-magnitude scenario that would be reasonable for such a short fault. The ShakeZoning grid created for this scenario has 400-EW by 585-NS by 75-deep grid nodes with grid spacing dx=dy=dz of 0.2 km to allow for 0.5 Hz wave propagation.

**RESULTS**

**Parcel Map Statistics.** The histogram plot of the Parcel Map (Figure 3) displays two normally distributed average geotechnical velocities in and around Las Vegas Valley. In the lower-velocity sediments, the average Vs30 in the basin was 399.1 m/s, and 789.6 m/s in the higher-velocity rocks, or bedrock. The variance of bedrock Vs30 measurements is greater than the variance of basin sediment Vs30 measurements, suggesting the lognormal distribution of Vs30 seen by Louie et al. (2008) and Thompson (2010). The mixing coefficient, $p$, of the bimodal distribution indicates an equal number of high and low velocity measurements throughout the basin and surrounding bedrock.

Now that we have an idea of the variance in Vs30 throughout the Las Vegas urban area, we can analyze the spatial statistics of the Parcel Map, most specifically the fractal dimension. Figure 4 presents the summed spectra of each vector across the assembled geotechnical map of Figure 2, in both cardinal directions. Both of the power spectra exhibit similar fractal dimensions in each direction, with $D=1.67$ in the E-W direction and $D=1.66$ in the N-S direction. The geotechnical map possesses a fractal dimension between pink and Brownian noise. When creating stochastic model geotechnical maps, obtaining a map with a fractal dimension matching the geotechnical data will be an important criterion for verifying the model. The isotropic scale invariant behavior seen in the Parcel Map must also be taken into consideration for the model.
Figure 3. Probability density of $V_s30$ measurements in the Clark County Parcel Map alone (from Louie et al., 2011a, with no IBC defaults). The distribution of the data set can best be described by a bimodal normal distribution. The normal distributions provide confidence the spatial statistics can be modeled using either pink or red noise. The IBC default velocities (BSSC, 1997) fall very close, if not within, the standard deviation of $V_s30$ in the Parcel Map.

Figure 4. Spatial power spectra taken from the assembled geotechnical model of Parcel Map measurements (Louie et al., 2011a) superimposed over IBC default $V_s30$ values assigned according to geology (BSSC, 1997; Louie, 2008). The summed EW spectra are on the left, summed NS spectra on the right. Fractal dimensions are computed from the sloping green fit lines, using Mela and Louie (2001).

**Modeling the Parcel Map.** We developed modeling routines, producing the stochastic $V_s30$ maps, in the preexisting ModelAssembler environment developed by Louie (2008). This new code allows us to configure earthquake scenarios using preexisting attenuation, density, and
basin depth models available for any location in the world, such as Southern California, and to
calibrate the stochastic models against the Parcel Map, or the stochastic properties of any
geospatial data set. Due to the limitations of our models, only the statistical features can be
modeled, with no deterministic features. The complete Nevada ShakeZoning source code is
available at crack.seismo.unr.edu/ma.

Figure 5 shows two different stochastic models approximating some of the statistics of
the Parcel Map. The models most resembling the Parcel Map result from adding to the IBC
default base map forty percent random noise smoothed with a square-kernel over the dimensions
of one wavelength, or approximately 3.0 km. Only the pink, 1/f, noise model could be made to
display the appropriate spatial statistics. The fractal dimension of the smoothed white noise
models (e.g., Figure 5, left) ranged from 1.75 to 1.9, systematically resulting in higher fractal
dimensions than the data show.

![Figure 5. Maps showing stochastic models for Vs30 in Las Vegas Valley. All of the models contain 40% added stochastic noise, smoothed using a square smoothing kernel of one modeled wavelength of 3.0 km. The color scale of Vs30 values for these maps is different from the one used in Figure 2, to better show the variations.](image)

The model geotechnical maps containing forty percent added pink noise smoothed over
one modeled wavelength (e.g., Figure 5, right) proved to be the best match to the spatial statistics
seen in the Parcel Map. The fractal dimension in the E-W direction is $D=1.69$ and $D=1.73$ in the
N-S direction. The model slightly over-estimates the variance of the Parcel Map. However it
does display the isotropic variance we sought. Both the stochastic model and the Clark County
Parcel Map display similar power spectra.
Trial Scenarios. To begin to understand the effects of stochastic noise on wave propagation, we test the pink noise stochastic geotechnical map (Figure 5) with our Nevada ShakeZoning 3D calculations of elastic wave equation through heterogeneous media. We compare the stochastic models against two previously run scenarios (Savran et al., 2011), the Frenchman Mountain fault scenario and the Black Hills fault scenario.

The differences in maximum peak ground velocity (PGV) predicted by Nevada ShakeZoning between the Parcel Map and the stochastic model are small, but at any given location the “amplification” of the result of one model over the result of the other is often a factor of two or more. The most notable differences in predicted ground motion result from regions with abnormally high Vs30, such as the caliche sediments in western Las Vegas Valley. Despite the differences from deterministic features of the Parcel Map, the predicted ground motions show many similarities, such as the streaking features of the seismic waves propagating through the high frequency variations seen in the Parcel Map and stochastic model.

Frenchman Mountain scenario– Just like the Vs30 data, we will compare the effects of stochastic noise on wave propagation by analyzing the spatial statistics of the PGV map calculated from our earthquake model. The spatial statistics provide a means of comparison between the PGV effects of the Parcel Map and our stochastic model. The fractal dimensions of the two calculated data sets are within 0.1% of each other, indicating the calculations result from seismic waves propagating through media with isotropic high-frequency variations. Figures 7 and 8 shows the PGV for both Frenchman Mountain scenarios, as well as the corresponding spatial PGV spectra.

Black Hills scenario– As with the Frenchman Mountain scenario, the power spectra calculated from the PGV maps resulting from the Parcel Map and from the stochastic geotechnical model for Vs30 are nearly identical in their linear slopes. The same streaking pattern is noticed from wave propagation through Las Vegas Valley. Again, the maximum PGVs from the two Black Hills scenarios are indistinguishable. Figures 9 and 10 show the PGV maps for the two Black Hills scenarios and their corresponding spatial spectra. The Black Hills scenario adds extra complexity to the wave propagation, as the waves are guided into the basin.
from the southeast in Eldorado Valley. This wave-guiding process introduces complex geometries into the wave propagation path due to the geometric focusing effects.

Figure 7. (Left). Peak Ground Velocity map calculated from an Mw 6.7 Frenchman Mtn. earthquake scenario, with the Parcel map data included. The maximum PGV of the scenario is 143 cm/s. (Right) Spatial power spectra from the scenario PGV map, indicating a fractal dimension of 1.378, and from the Parcel Map Vs30 data.

Figure 8. (Left) Peak Ground Velocity map calculated from a Mw 6.7 Frenchman Mtn. earthquake scenario, with the stochastic pink-noise geotechnical model included instead of the Parcel Map. The maximum PGV of the scenario is 143 cm/s. (Right) Spatial power spectrum from the stochastic-scenario PGV map, indicating a fractal dimension of 1.356.
Figure 9. (Left) Predicted PGV from an Mw 6.5 earthquake scenario on the Black Hills fault, computed using the Parcel Map. The maximum PGV for this scenario is 167 cm/s, with maximum amplification in Eldorado Valley. (Right) The fractal dimension of the PGV map is lower than that of the Parcel Map, potentially due to the waves averaging over fine-scale heterogeneities in the basin.

Figure 10. (Left) Predicted PGV from an Mw 6.5 earthquake scenario on the Black Hills fault, computed using the pink-noise stochastic geotechnical map instead of the Parcel Map. (Right). The fractal dimension of this PGV map is identical to the PGV map calculated using the Clark County Parcel Map.
To gain the benefits of both models, we superimposed the Clark County Parcel Map over the stochastic model of the geotechnical velocities. This results in a stochastic model comprised of the deterministic features of the Parcel Map in Las Vegas Valley, and extending the spatial statistics of the Parcel Map throughout the finite difference grid. This method is developed into the ModelAssembler, and will develop this type of Vs30 model anywhere an appropriate data set is available. If not, the analyst can still modulate default geotechnical velocities with random noise.

![Combined Model](image)

**Figure 11.** This map shows the combined model of geotechnical velocities in Las Vegas Valley and surrounds, plotted with the same color scale as Figure 2. Notice similar variance between the Vs30 values inside the valley as those in the surrounding bedrock. The white color represents a Vs30 of exactly 0.76 km/s. This model preserves the spatial statistics seen in the Parcel Map, and also implements the deterministic features discovered by it.

**CONCLUSIONS**

Our effort to stochastically model geotechnical velocities throughout Las Vegas Valley provides analysis on the effects of stochastic noise on ground motion predictions. The effects of high-spatial-frequency geotechnical variance on wave propagation are not as great as they could be in our models, due to the upper-frequency restriction on our calculations, which is 0.5 Hz. One notable feature discovered from our analysis of the Clark County Parcel Map (Louie et al., 2011a) is the isotropic behavior of its fractal dimension. This indicates the stochastic process...
controlling Vs30 variance acts equally in both directions. This quality of the Parcel Map results makes this data set a good candidate to model using a stochastic process. Since these data can be represented as fractal, they conform to a self-similar process, meaning the same variance is seen throughout the data set at a range of scales.

The smoothed pink noise model best represented the spatial statistics seen in the Parcel Map. The white noise method produced too much variance at high spatial frequencies, even with many different trial smoothing kernels applied. Many physical features can be modeled using pink or Brownian noise. However, due to the close match we achieved with pink noise, we did not pursue the Brownian noise generator any further. The stochastic geotechnical model using pink noise at 40%, noise smoothed over one modeled wavelength, most closely resembled the Parcel Map data (Figures 2 and 5, right).

Looking at Figure 1, we can see the fractal dimensions observed from Vs30 transects in Los Angeles, Reno, and Las Vegas range from about $D=1.4$ to $D=1.8$. The fractal dimension of the Parcel Map lies within these bounds, and nearly matches the spatial statistics of the San Gabriel River transect across San Gabriel Valley and the Los Angeles Basin (Fig 4). This fact, plus the other geological similarities between San Gabriel Valley, Los Angeles Basin, and Las Vegas Valley make the high-resolution data of the Parcel Map an important tool for understanding the geotechnical properties of basins in Southern California. Due to the similar geologic processes responsible for forming and filling these basins, we might expect to see similar properties from a high resolution Vs30 data set in Southern California, as we now observe in the Clark County Parcel Map.

Las Vegas Valley is composed of three primary sedimentary bodies, lacustrine, sandy alluvium, and caliche-cemented alluvium, resulting in an expected tri-modal distribution of the geotechnical velocities. However, the lacustrine sediments show velocities that fit within one standard deviation of $\mu_1$, the lower-velocity mean (Figure 3). Because of this, statistically, only two predominant average velocities are present. We equate these with $\mu_1$ being the soft-sediments in the basin and $\mu_2$ as the cemented alluvium and the bedrock surrounding the basin. Based on the average velocities discovered in the Parcel Map, possibly a more realistic model could be constructed using these velocities, as opposed to the IBC default Vs30.

The trial earthquake scenarios showed similar effects of stochastic noise on ground motion prediction. The area of concern is primarily located within Las Vegas Valley, where seismic risk is much higher. Figure 7 (left) shows the Mw 6.7 Frenchman Mountain scenario PGV map utilizing the Parcel Map as input parameters into the model. Fig 8 (left) is the same scenario PGV map result, but with the Parcel Map replaced by the stochastic geotechnical-velocity model. The most obvious effect of the Parcel Map on the scenario shaking maps is the region of less intense shaking in the western, caliche-cemented and higher-velocity portion of the valley.

We notice similar streaking features and geometric focusing effects in both scenarios as well as very similar PGV near the source and throughout the basin. The resulting power spectra calculated from both scenario PGV maps, in Figures 7 (right) and 8 (right), are almost identical. The similar fractal dimension of the resulting PGV indicates the stochastic models produce the same spatial statistics in the PGV results, as does the Parcel Map. We notice similar features in the Black Hills scenario results (Figures 9 and 10, left). However, the de-amplified shaking in the Parcel Map’s high velocities on the west side of the valley is less apparent due to the longer path the seismic energy must take from Eldorado Valley.
If we compare the fractal dimension seen in the geotechnical data sets with the PGV from either scenario, we notice a much lower fractal dimension in the calculated PGV map (Figures 4, 7, 8, 9, 10). The lower PGV-map fractal dimension represents more ordering of the map values, or less variability, in any direction. The lower fractal dimension is a result of the seismic waves averaging across high-spatial-frequency variations during propagation.

Looking at Figures 7 or 9, the power spectrum of the Parcel Map Vs30 is plotted alongside the spectrum of the corresponding scenario PGV maps. This comparison allows us to identify the resolution required to effect the scenario calculations. The linearity of the Parcel Map spectrum seems to continue up to a spatial frequency of 2/km, which equates to a resolution of 500 m. Based on this analysis, one measurement every 500 m may be sufficient resolution to affect our 0.5 Hz calculations. Higher-frequency calculations require tighter spacing of finite difference nodes, so this number may change as we pursue scenario models at higher frequencies, on the order of 5-10 Hz.

The end product of this research is displayed in Figure 11. The Clark County Parcel Map is superimposed over the stochastic model, allowing for the spatial statistics of the Parcel Map to be preserved over all of the input geotechnical model. While generating stochastic models to represent geotechnical velocities in a region cannot account for unknown site conditions or be a substitute for a measured data set of a region, these model maps can be applied to areas of incomplete or sparse data. Coupled with some geologic knowledge of an area, this method could effectively bolster current community velocity models.

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Nevada ShakeZoning open-source model-assembly codes, data sets; and results including papers, presentations, and scenario wave-propagation animations are available at: http://crack.seismo.unr.edu/NSZ/