Comparing physics-based Next-Level ShakeZoning computations with USGS ShakeMap statistics for So NV earthquake scenarios

WILLIAM H. SAVRAN, BRADY FLINCHUM, GABRIEL PLANK, COLTON DUDLEY, NICHOLAS PRINA, and JOHN N. LOUIE, Nevada Seismological Laboratory, Nevada System of Higher Education, MS 0174, University of Nevada, Reno, NV 89557
(louie@seismo.unr.edu; wsavran@gmail.com)

ABSTRACT

A group of students at the Nevada Seismological Laboratory (NSL) are modeling earthquakes on several southern Nevada faults surrounding Las Vegas Valley using the physics- and geology-based “Next-Level ShakeZoning” process; and alternatively the statistical USGS ShakeMap tool. Next-Level ShakeZoning involves using the ModelAssembler Community Modeling Environment to generate geologic-model grids from geotechnical shear-velocity and basin-thickness maps. The USGS Qfaults database suggests source parameters pertaining to each fault. The earthquake scenarios also use the new Clark County Parcel Map containing 10,721 geotechnical Vs30 shear-velocity measurements, yielding the most realistic models of earthquake ground motion to date. Our seismic wave-propagation modeling covers the 0.1 Hz to 0.5 Hz band, and uses a Gaussian time-history distribution for the low-frequency shaking that would affect the larger structures in the Valley. The E3D wave modeler from Lawrence Livermore National Labs simulates the propagation of the seismic waves through the 3-D ShakeZoning grid, with viscoelastic attenuation but without free-surface topography. The scenarios are visualized through peak ground velocity (PGV) maps and movie simulations of seismic-wave propagation. The ShakeMap statistical approach also provides a PGV map, which allows for comparisons to be made between PGV maps, and comparisons to recorded ground motions. Several scenarios are showing significant differences in patterns of shaking amplification across the valley, when the Next-Level ShakeZoning maps are compared to ShakeMap results. For example, the Frenchman Mountain scenario shows PGV of the two approaches within 15% near the source, but upwards of 200% amplification or de-amplification, depending on location, throughout the Valley.

INTRODUCTION

In and around Las Vegas Valley (LVV), several earthquake faults are classified by the USGS as potentially hazardous. A hazardous fault is defined as any fault believed to be a source of a >M6 earthquake during the Quaternary period. An earthquake of this magnitude in the Valley could cause severe ground shaking, in the band of resonant frequencies for most urban buildings. In a dense urban environment, realistic and accurate models for predicting ground shaking are necessary. A team of undergraduate employees at the Nevada Seismological Laboratory is working to obtain the most accurate, comprehensive set of earthquake scenarios throughout the Las Vegas Valley yet completed. While we primarily use our new ShakeZoning procedures to compute these scenarios, we will also use the USGS ShakeMap product (Worden and others, 2010) to provide an alternate method for scenario calculations and also provide interesting comparisons between the two approaches.
Motivation and objectives

While maintaining a growing urban environment, the challenge of providing safety during a seismic event and keeping construction costs to a minimum is faced by urban planners and engineers constantly. The most effective way to address this challenge is using the most realistic models available for simulation of ground shaking. Clark County, Nevada’s Earthquake Parcel Mapping program, a systematic campaign of shear-velocity measurements throughout Las Vegas Valley, has recently been completed. The Parcel Map provides 10,721 geotechnical shear-velocity (Vs30-averaged Vs from surface to 30 m depth) measurements for ShakeZoning to stitch into a complex grid containing the geotechnical information as well as a dense catalog of geologic measurements including LVV and surround valleys.

Our new ShakeZoning procedure for seismic hazard mapping will properly apply the physics of wave propagation through a geologically complex earth. Our new Parcel Mapping results in LVV represent a revolution in geotechnical characterization, allowing us to predict wave propagation and shaking amplification across terrain that has been measured to an unprecedented degree of detail.

The ShakeZoning process coupled with the vast amount of geologic and geophysical data in the LVV area will provide the community with a means to create probabilistic seismic hazard maps with ease and accuracy, in a short amount of time. Our southern Nevada effort included creating over sixty ShakeZoning scenarios for eight faults, all yielding highly detailed PGV maps and a time-lapse movie representation of the wave propagation through the complex ShakeZoning grid. The total effort took less than two hundred hours of work by undergraduate students, costing only two thousand dollars to complete a comprehensive survey of the potential earthquake hazards to urban Las Vegas. The Next-Level ShakeZoning process will be an invaluable tool for city planners and engineers. The great degree of accuracy and the ability to interpret and utilize sophisticated data sets allows for great adaptability and the ability to easily provide the most current and realistic scenarios for ground shaking in the basin.

Background

Shear-wave velocity in the shallow subsurface is essential for accurately predicting seismic hazards. Because methods for direct measurement of Vs30 have only recently become cost-effective (Louie, 2001), earthquake hazard mapping has to date relied upon extrapolation of statistical averages of a few measurements along geologic-units. However, the site Vs30 measurement cannot be the only guideline for predicting intensities of ground shaking. The earthquake source, wave-propagation path, and site effects must also be taken into consideration to accurately predict seismic shaking.

Las Vegas is subject to earthquake hazards both from below the local LVV basin, and from large earthquake faults up to 200 km away. ShakeZoning computations feed geological and geotechnical results such as the Parcel Map to the E3D code (Larsen and others, 2001) from LLNL for elastic wave-propagation computation. E3D was most recently vetted for ground-shaking prediction at the March 24-25, 2004 Next Generation Attenuation (NGA) Workshop. Such vetting helps to physically and geologically validate ShakeZoning results.

The USGS ShakeMap tool (Wald and others, 1999) is one of the current, comprehensive means of computing scenarios, based on the statistics of relatively sparse recordings of the ground motions of historical earthquakes. Most of these recordings are from California, Japan, and Taiwan. The ShakeMap tool utilizes a statistical approach to predicting earthquake hazards,
as opposed to calculated wave-propagation using physics and geology. The software takes advantage of empirical data collected from historic earthquakes to predict ground shaking and intensity as described by Biasi and Lindquist (2004). The tool was originally created by the USGS as a part of the TriNet project to provide quick information to emergency responders after a serious earthquake in Southern California (Wald and others, 1999). Since then, it has seen use for modeling numerous hypothetical earthquake scenarios throughout the California, the Intermountain West, and elsewhere.

Out of the eight hazardous faults located in and around Las Vegas Valley, the team of undergraduates has constructed ShakeMap and ShakeZoning scenarios for four of the most “dangerous” faults. This categorization was derived from proximity to LVV and the maximum possible seismic moment generated from each individual fault. The source data are taken from the USGS Qfaults database (2010). This paper will attempt to provide analyses of side-by-side comparisons of the four scenarios between the two aforementioned methods of calculating ground shaking in the LVV, while displaying the results of the Next-Level ShakeZoning process for visual analysis.

METHODS

Next-Level ShakeZoning

The Next-Level ShakeZoning tool combines scattered available geologic and geophysical data into a numerical grid to simulate elastic wave propagation as described by Louie (2008). Every scenario compiled by the ShakeZoning process produces an individual grid file allowing for the opportunity to evaluate various data sets and tailor the scenario to the designers’ needs and specifications in the ShakeZoning process. For this project, the five models were each modeled on different grids to ensure the most physically realistic wave propagation through LVV.

For the geologic portion of the grid, two data sets of Neogene basin thickness are roughly stitched together: 1) the Saltus and Jachens (1995) USGS basin gravity inversions for the Basin and Range, including both sedimentary and Tertiary volcanic basins at 2-km resolution; and 2) the Langenheim and others (1998) Las Vegas basin model from gravity, refraction, and a few deep wells, at 0.4-km resolution. Figure 1A shows the composite basin floor depth in shaded relief from an example grid created to simulate the shaking induced by a Mw 6.5 earthquake on the Black Hills fault.

Geophysical datasets are also incorporated into the numerical ShakeZoning grid despite variations in spacing, which can vary from 0.1 km to 3 km or more. The ShakeZoning tool interpolates all of the available geotechnical data onto a single grid using a rule set to determine which data set takes precedence over another in the same region. For all of the models in this effort, the two geotechnical data sets used are: 1) The regional geological map controls the shallow-depth Vs30 default values of 760 m/s in bedrock and 500 m/s in basins; and 2) The 10,721 Vs30 measurements gathered by Clark County’s Earthquake Parcel Mapping program in urbanized Clark County and Henderson. Figure 1B shows the interpolated Vs30 shear-wave velocity map displaying measurements superimposed on default values.
Figure 1: A) Composite basin–floor map for Las Vegas Valley in shaded relief. Note the stitching of the Langenheim (1998) into the Saltus and Jachens (1995) basin models, just inside the orange rectangle. LV = Las Vegas; H = Henderson; BC = Boulder City; FM = Frenchman Mountain. The map extends 103.2 km N-S and 79.8 km E-W.

B) Geotechnical shear-wave velocity map, on the same area as A), developed from the Clark County and Henderson projects. Higher velocities are shaded darker, with Vs30-meter velocities over 1.0 km/sec darker blue.

**ShakeMap**

The statistical approach involved incorporating worldwide statistical data to provide the database from which ShakeMap interpolates ground shaking intensity. ShakeMap augments the sparse observational data with well-documented empirical ground shaking prediction equations.

ShakeMap uses three inputs: 1) recorded instrumental ground-motion data; 2) converted data, based on community intensity observations that are converted using theoretical or empirical relationships; and 3) ground-motion estimates from ground motion prediction equations. These three data inputs are combined using the weighted-average approach of Cua and Wald (2008), stating the estimate of ground shaking at any given point is a weighted sum of the three different types of contributing information (Worden and others, 2010). While pertinent, these three data types neglect the geologic information, particularly the sedimentary and volcanic basins, and the measured Vs30 shear-wave velocity. These are the two major contributing factors for accurately predicting elastic wave-propagation in the Intermountain West. Figure 2 shows the PGV map created from a ShakeMap scenario from a Mw 6.7 event on the western dipping, 18 km long Frenchman Mountain fault.

ShakeMap produces a similar map of peak ground acceleration (PGA), Modified Mercalli Intensity (MMI) and also provides a comprehensive grid file, with all of the information of these calculations. In our scenarios the ShakeMap grids have one data point per minute of arc. To make the ShakeZoning PGV maps comparable to those produced by ShakeMap, the ShakeMap grid file was disaggregated and placed in JRG/Viewmat (crack.seismo.unr,edu/jrg), a tool for
processing seismic and binary data, as well as making the ShakeZoning shaded basin maps and the PGV maps produced from the ShakeZoning process. Each of the models took approximately four hours to run on a quad-core Intel processor.

Figure 2: Topographic map of southern Nevada, output by the Wald and others (1999) USGS ShakeMap program showing PGV estimated for the M6.7 Frenchman Mountain Fault situated in the Las Vegas Valley. The open star marks the epicenter. The thicker black line represents the rupture zone for the Frenchman Mountain M6.7 scenario event. Red lines show principal fault traces from the USGS & NBMG (2010) Qfaults database. White lines are PGV intensity contours in cm/s.
Earthquake ground-shaking predictions

When determining the source characteristics for each of the models, the information in the USGS Qfaults database (2010) was used. All of the faults selected around LVV are assumed to have normal slip, and in the absence of fault geometry a moderate dip for a normal fault of 60 degrees was used. Moment magnitude was calculated using the slip rate and fault length (Anderson and others, 1996) where available:

\[ M = 5.12 + 1.16 \log L - 0.20 \log S \]  \hspace{1cm} (1)

In the event of a fault having no inferred slip rate, the seismic moment was calculated using an estimated fault area and displacement for a single event, provided from fault mapping and scarp information (Qfaults, 2010). A unique Gaussian time-history function is created for each ShakeZoning scenario help provide the most realistic time-history for elastic wave-propagation.

To provide common grounds for comparison, event source information was derived once per fault and applied to each method. All of the finite faults with lengths greater than 15 km were assumed to have a fault-plane width of 15 km, while smaller faults are assumed to be square. The fault is also assumed to rupture with the same slip along the entire fault plane. For all of the faults located in the basin, the Neogene basin thickness data was used to determine the top depth of the faults, as the E3D computation is not accurate for rupture into soft basin sediments. The hypocenter was located at the bottom center of the faults for each scenario. On each ShakeZoning grid, a model of intrinsic seismic attenuation “Q” was developed following Olsen and others (2003).

The four faults selected for modeling in the LVV are, in no particular order of relevance or danger: 1) Frenchman Mountain fault; 2) Black Hills fault; 3) California Wash fault; and 4) Eglington fault. Figure 1 shows a Next-Level ShakeZoning grid for the M6.7 Frenchman Mountain scenario with the aforementioned faults identified and labeled.

Frenchman Mountain fault

The Frenchman Mountain fault is a west-dipping normal fault with an 18 km-long rupture zone with an average strike of N1°E on the eastern edge of LVV butted against the Frenchman Mountains. The slip rate used to calculate the moment magnitude was <0.2 mm/yr. The magnitude calculated for this scenario using Eq. (1) was \( M_w 6.7 \) with a seismic moment of \( 1.38 \times 10^{26} \) dyne/cm (USGS, 2010).

The ShakeZoning grid created for this scenario has a 419 North-South (NS) by 585 East-West (EW) by 81 node deep grid with grid spacing \( dx=dy=dz=0.25 \) km to reduce the grid dispersion artifacts from the 0.5 Hz wave-propagation. Figure 3A shows the ShakeZoning grid for Frenchman Mountain.

Black Hills fault

The Black Hills fault is a southeastern dipping normal fault with a 9 km rupture zone with 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. The magnitude calculated for this scenario using Eq. (1) was \( M_w 6.5 \) with a seismic moment of \( 6.64 \times 10^{25} \) dyne/cm (USGS, 2010). This is probably the largest-magnitude scenario that would be reasonable for such a short fault.
The ShakeZoning grid created for this scenario has a 400 EW by 585 NS by 75 node deep grid with grid spacing $dx=dy=dz$ and a grid spacing of 0.2 km to reduce the amount of grid dispersion artifacts from the 0.5 Hz wave-propagation scenario computed by the Next-Level ShakeZoning process. Figure 3B shows the ShakeZoning grid for the Black Hills fault.

**California Wash fault**

The California Wash fault is a western dipping normal fault with a 32 km rupture zone with an average strike of N15°E that appears to be the boundary between the California Wash basin and the Muddy Mountains on the east. The slip rate used to calculate the moment magnitude was 0.2-1 mm/yr. The magnitude calculated for this scenario using Eq. (1) was $M_w 7.0$ with a seismic moment of $1.38 \times 10^{26}$ dyne/cm (USGS, 2010).

The ShakeZoning grid created for this scenario has a 419 EW by 585 NS by 81 node deep grid with grid spacing $dx=dy=dz$ and a grid spacing of 0.25 km to reduce the amount of grid dispersion artifacts from the 0.5 Hz wave-propagation scenario computed by the Next-Level ShakeZoning process. Figure 3C shows the ShakeZoning grid for the California Wash.

**Eglington fault**

The Eglington fault is an east to southeastward dipping normal fault with an 11 km rupture zone with an average strike of N28°E, situated in the LVV and extending through the northern part of the Las Vegas metropolitan area. The slip rate used to calculate the moment magnitude was 1.5 mm/year. The magnitude calculated for this scenario using Eq. (1) was $M_w 5.6$ with a seismic moment of $2.784 \times 10^{25}$ dyne/cm (USGS, 2010).

The ShakeZoning grid created for this scenario has a 509 EW by 571 NS by 99 node deep grid with grid spacing $dx=dy=dz$ and a grid spacing of 0.2 km to accommodate the 0.5 Hz wave-propagation scenario computed by the Next-Level ShakeZoning process. Figure 3D shows the ShakeZoning grid for the Eglington fault.

*Figure 3A*: Map of southern Nevada showing the ShakeZoning grid for computing a scenario of the magnitude 6.7 Frenchman Mountain earthquake.
**Figure 3B:** Map of LVV showing the ShakeZoning grid for computing a magnitude 6.5 Black Hills earthquake scenario.

**Figure 3C:** Map of LVV showing the ShakeZoning grid for computing a scenario of the California Wash magnitude 7.0 earthquake.
RESULTS

Earthquake ground shaking predictions

The events simulated in our comprehensive survey of seismic hazards in the LVV were carried out at 0.1 and 0.5 Hz to test the sensitivity of Next-Level ShakeZoning results to the 10,721 Vs30 shear-wave velocity measurements made by Clark County and Henderson. The four simulations show drastic differences between the ShakeMap predictions and the physics- and geology-based ShakeZoning predictions. We compare the predicted shaking yielded by ShakeMap against the ShakeZoning predictions in three ways. First, a comparison of the maximum PGV across the maps for the ShakeZoning computations at 0.1 Hz (not shown) yields a simple test of scale similarity between the two prediction techniques. For these low frequency maximum PGV predictions, ShakeZoning produced larger PGV than ShakeMap, but no more than 20% larger. Second, Table 1 compares the maximum PGV predicted by the two methods at 0.5 Hz. Increased trapping of energy within basins at 0.5 Hz compared to 0.1 Hz produces maximum PGV values for ShakeZoning that are 2-3 times larger than the ShakeMap predictions.

Lastly, Figures 4–7 show the PGV map visualizations created from both ShakeZoning simulations at 0.5 Hz and the ShakeMap statistical tool for each fault. Figure 4A shows the PGV map produced from the ShakeZoning calculations for a magnitude 6.7 Frenchman Mountain scenario event. The majority of the wave motion is contained within the Las Vegas basin. The high geotechnical shear-wave velocities in the western part of LVV (blue in Figure 1B) de-amplify the shaking in that area. The de-amplification is more significant in scenarios where the seismic waves propagate from east of the Valley and into the basin. The ShakeMap calculation for maximum PGV is shown in Figure 4B. The wave propagation is sent out radially and none of the energy is trapped in the LVV. Figure 5A shows the maximum PGV for the ShakeZoning Black Hills M6.5 simulation. The most notable feature in the ShakeZoning PGV map for this
event (Figure 5A) is the waveguide effect of the lower-velocity basalt basin fill leading into LVV. The ShakeZoning PGV for the magnitude 7.0 California Wash event (Figure 6A) shows large ground motions in the source basin, California Wash. From there, the waves tunnel into the northeast corner of LVV. Lastly, A notable characteristic of the ShakeZoning Eglington PGV map (Figure 7A) is the seismic wave dispersion through the steep northern edge of the basin.

The differences between the PGV maps come from the radial nature of the ShakeMap empirical ground shaking prediction equations, and the physics and geology taken into consideration for the ShakeZoning calculations. The basin depth in LVV is greater than a quarter wavelength from the 0.5 Hz waves, causing physics to play a more crucial role in wave-propagation calculations than lower frequencies.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max PGV ShakeZoning:</th>
<th>Max PGV ShakeMap:</th>
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<tr>
<td>Frenchman Mountain</td>
<td>144 cm/s</td>
<td>65 cm/s</td>
</tr>
<tr>
<td>Black Hills</td>
<td>167 cm/s</td>
<td>59 cm/s</td>
</tr>
<tr>
<td>California Wash</td>
<td>208 cm/s</td>
<td>88 cm/s</td>
</tr>
<tr>
<td>Eglington</td>
<td>45 cm/s</td>
<td>23 cm/s</td>
</tr>
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</table>

Table 1: Maximum predicted peak ground velocity from the ShakeMap and ShakeZoning methods.

Figure 4: A) PGV map produced from the ShakeZoning calculations of the magnitude 6.7 Frenchman Mountain fault event. B) PGV map from the ShakeMap scenario of the same event, with the same color scale.
Figure 5: A) PGV map produced from the ShakeZoning process for the Black Hills magnitude 6.5 earthquake. B) PGV map produced from the ShakeMap tool for the same event.

Figure 6: A) PGV map of the magnitude 7.0 California Wash scenario. B) PGV map of the ShakeMap predictions for the same scenario.
DISCUSSION AND CONCLUSIONS

The effort to provide a comparison between the physics and geology based Next-Level ShakeZoning, against the statistical approach of ShakeMap, provided some interesting analysis into the effectiveness and differences between them. Using a physics-based scenario will provide a greater degree of realism to predicting ground shaking in the basins. It should prove an invaluable tool for us to help protect Nevada’s population and economy.

Most notably, for every scenario ShakeZoning predicted a systematic amplification (yellowness of maps) of ground motion inside geologic basins, coupled with a systematic de-amplification (blueness of maps) of ground motion outside the basins. This is due to the lower velocity sediments acting as waveguides within the basins. The physics-based scenario correctly keeps most wave energy contained inside the basins, whereas this is not the case with the statistical approach. Rodgers and others (2006) observed this high degree of basin amplification relative to de-amplification outside basins in recordings throughout Clark County of ground motions from earthquakes and Nuclear Test Site explosions, validating the Next-Level ShakeZoning modeling.

The Frenchman Mountain fault trace is entirely contained within LVV. In this M6.7 scenario, the steep northern wall of LVV acts to trap waves, largely preventing them from leaving the valley (Figure 4A). The high velocity regions (western part of LVV) in the Parcel Map (Figure 1B) have a more noticeable effect on ground shaking for this scenario than do the lower-velocity regions. The discrepancies of ground motion prediction between the two methods in this region of the valley are on the order of a factor of ten. In the southeastern part of LVV, a parabolic geometric focusing effect causes a small zone of increased ground shaking. In this

Figure 7: A) PGV map for the ShakeZoning calculation of the magnitude 5.6 Eglington fault earthquake. B) PGV map for the ShakeMap prediction of the same scenario.
model the ShakeZoning grid (Figure 4A) again traps more energy within LVV than ShakeMap (Figure 4B).

In the M6.5 Black Hills event, we see the shallow, basalt-filled volcanic basin at Black Mountain (see Louie and others, this volume, p. 11) channeling the waves from Eldorado Valley to LVV, as the low-velocity volcanic deposits (relative to the underlying granite) act as a waveguide (Figure 5A). The physics-based model correctly applies the directivity of the rupture causing the waves to propagate upwards along the fault plane and trapping more of the seismic energy within the basins.

There is no simple correlation between the 0.5-Hz PGV map (Figure 5A), and LVV basin depth. It is important that the basin depth is more than a quarter of the wavelength. The result is not sensitive to the deeper parts of the basin, between 2 and 4.8 km depth. The much higher PGV predicted by ShakeZoning is due to the wavelength of the waves modeled within the basins being substantially smaller than the width and thickness of the basins, causing more of the energy to become trapped inside the basins. The ShakeMap scenario of the same event (Figure 5B) predicts twice the amplitude of ground movement outside of the basins, compared to ShakeZoning (Figure 5A). This is due to the homogenous, radial nature of the PGV fall-off in ShakeMap, and no physics or geology to provide effects on wave propagation from any basins.

The California Wash fault is located in a large but shallow basin northeast of LVV. There is clear tunneling of wave energy through the boundary between California Wash and LVV, and high PGV near the Apex landfill area (Figure 6A). The tunneling waves travel basin to basin through the bedrock, entering LVV from the northeast. The waves are potentially converted from Love to Rayleigh and back to Love as they are channeled into the basin. Geometric refraction is observed as well in the physics-based propagation, but not from ShakeMap (Figure 6B). In the three scenarios - Frenchman Mountain (Figure 4A), Black Hills (Figure 5A) and California Wash (Figure 6A), the westbound propagation of the waves into the western LVV shows a much greater influence of the Parcel Map than waves propagating southward from the Eglington scenario (Figure 7A).

The M5.6 Eglington scenario rupture is also located completely inside LVV. The shaking in the basin is less severe in the ShakeZoning model (Figure 7A) than in ShakeMap (Figure 7B), because the waves may have reflected off the bottom of the basin and dispersed into the deeper crust. Again in this scenario, we can see the rupture directivity causing the shaking in the basin to have more effect in ShakeZoning (Figure 7A) than in ShakeMap (Figure 7B). The Parcel Map does not have as prominent effect on ground shaking in western LVV as it did for the Black Hills and Frenchman Mountain scenarios, because of the direction of wave propagation through the valley. Interestingly, the geometric effects of the basin edge produce less shaking in the NE corner of LVV with ShakeZoning (Figure 7A) than ShakeMap (Figure 7B). There is some evidence of a geometric focusing effect across the northern basin wall where the waves diffract into the bedrock.

Overall, the ShakeZoning procedures provide a more thorough and realistic representation of wave propagation utilizing physics and geology, than ShakeMap can. Currently, the ShakeMap statistical method for predicting earthquakes can give false areas of amplification and de-amplification, potentially leading to areas of overbuilding and areas without the structural support to withstand some of these scenarios. ShakeZoning is a tool that can be used to provide more realistic predictions of ground shaking scenarios to engineers and city planners than were previously available. For example, the combination of the Parcel Map and the new ShakeZoning predictions suggest that the western side of LVV, with its minimal basin depth and high
geotechnical velocities, will experience much less shaking than was predicted by the prior statistical ShakeMap method (Figures 4A, 5A, and 6A). On the other hand, Next-Level ShakeZoning predicts higher levels of shaking for areas atop thicker parts of the basin than does ShakeMap, especially for earthquake scenarios outside the basin (Figures 5A and B; 6A and B). In effect, ShakeZoning will promote design of more efficient and effective building codes to provide the greatest protection for human life and Nevada’s economy.

REFERENCES


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