Evaluation of Earthquake Hazard for Las Vegas Valley, Nevada Incorporating Probabilistic Hazard Assessment and Non--Linear Site Response

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EVALUATION OF EARTHQUAKE HAZARD FOR LAS VEGAS VALLEY,
NEVADA INCORPORATING PROBABILISTIC HAZARD ASSESSMENT
AND NON-LINEAR SITE RESPONSE

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ABSTRACT

Evaluation of Earthquake Hazard for Las Vegas Valley, Nevada Incorporating Probabilistic Hazard Assessment and Non-linear Site Response

by

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Abstract from Manuscript 1, “An alternative analysis of the probabilistic seismic hazard for Las Vegas Valley, Nevada”: Probabilistic seismic hazard calculations relevant for rock-site conditions in the Las Vegas Valley, Nevada (LVV) have been computed that account for seismic sources that are not included in the current (2008) USGS national seismic hazard model (NSHM) because of insufficient knowledge or documentation, using the commercial software package EZ-FRISK. The LVV is underlain by a system of mapped, active normal faults that comprise the Las Vegas Valley Fault System (LVVFS), with maximum potential earthquakes to M6.8. The 2008 NSHM explicitly includes only one fault of the LVVFS. This analysis includes four more faults of the LVVFS plus four regional faults in addition to those included in the 2008 NSHM, and modifies parameters of two others. As such, this study demonstrates the effect of a significant modification to expectations for seismic sources. These results can be considered as a “what if” scenario for seismic hazard of the LVV. Nominal peak ground acceleration (PGA) and 5% damped spectral acceleration ($S_a$) were calculated for 0.2-s and 1.0-s periods using five ground motion prediction equations (GMPEs). A logic-tree formulation accounted for uncertainty in the GMPEs and source parameters. Hazard values for PGA and $S_a$, computed at ~2.8-km spacing, are comparable to those of the 2008 NSHM on the
margins of the LVV, but are considerably higher in the north-central parts of the LVV near downtown Las Vegas and the city of North Las Vegas. The study provides a rationale for the urgency to conduct deeper investigations of faults in and around the LVV.

Abstract of Manuscript 2, “Evaluating approaches for developing design ground motions and their effects on different sediment columns: A study in Las Vegas Valley, Nevada”: This research investigates the effects of different approaches to generate design earthquake ground motions (GMs; time histories and spectra), including unscaled real GMs, scaled real GMs, and spectrum-matched GMs, on earthquake site response computations; design ground motion can be defined as the ground motion specific to a site predicted at its surface, ready for use in structural design calculations. The GMs are matched to the same target spectrum (uniform hazard spectrum for a 2500-year return period) for a bridge site in Las Vegas Valley (LVV), Nevada, and one-dimensional site response analyses (equivalent-linear and non-linear) are performed. Three soil profile models are tested. The first model (profile 1) is representative of the bridge site and is deep (~400 m depth), and has a simple profile with gradually increasing shear wave velocity (VS) with depth with a VS30 of ~365 m/s. The second (profile 2) is a deep and complex profile, adding a 6-m thick high-velocity layer at ~30 m depth to profile 1. The third (profile 3) is a shallow and simple profile to a depth of ~30 m, which treats the high velocity layer of profile 2 as the model halfspace. Because the modifications to the profiles were made below 30 m, the VS30 (shear wave velocity over the top 30 m) of all three profiles remained constant. Results of the analyses using the three approaches to generate design GMs for the three different models are comparable, although some
differences are notable. The deep profiles (profiles 1 and 2) deamplified the short-period motions while amplifying long-period motions. The shallow profile (profile 3) predicts the highest amplification for all cases, mainly at shorter periods. This outcome indicates that considering only the top 30 m of the sediment can significantly over-predict the response, mainly at shorter periods. In general, amplifications are greater and differences among the three approaches to generate design GMs are greater for the equivalent-linear than for the nonlinear approach.

Abstract of Manuscript 3, “How would the Las Vegas Valley, Nevada sediments respond to strong earthquake shaking?”: One-dimensional site response analysis, equivalent-linear and nonlinear, has been performed for the Las Vegas Valley (LVV), Nevada for two earthquake scenarios – a close-in earthquake on the Eglington fault and a distant earthquake on the Garlock fault. These scenarios were chosen based on deaggregation of seismic hazard from a probabilistic seismic hazard analysis for a hypothetical bedrock outcrop. Site response calculations were performed for 45 target site response grid points (TSRGPs) across the LVV at a spacing of ~5 km. Sediment columns for the TSRGPs were derived from existing 3-D shear wave velocity (VS) and lithology models for the LVV. Spectral ratios at 0.01, 0.2, 0.5, and 1.0 s periods were calculated and contour maps of amplification factors were produced. Results show that there is significant variability in seismic response of the sediments across the LVV, even without considering basin reverberations and near-fault effects. The results show that seismic waves would be amplified in most portions of the LVV basin as they pass through it. Amplifications increase on average with increasing period for both scenarios. Overall, amplifications are highest in the southern and western part of the LVV. For the Eglington
scenario, the patterns of ground motion are similar to the input motion, indicating that the responses of sites to this scenario are overwhelmed by the strong, near-field input motion. For the Garlock earthquake scenario, higher ground motions are observed along the western and southern margins of the Valley, which are dominated by shallow coarse-grained sediments. Amplifications are lower for places dominated by fine-grained sediments with thick sediment columns and higher for places dominated by coarse-grained sediments with relatively thin sediment columns. This result does not correlate well with the pattern of weak ground motions that have been recorded in the LVV during distant earthquakes. This mismatch implies that site response in the LVV is not only a function of sediment properties that can be modeled by 1-D analyses, it is also significantly affected by three-dimensional reverberation of energy and basin-edge effects, which can be expected to further amplify ground motions. There are a number of uncertainties in the analyses presented; perhaps the most significant pertain to the depth to the halfspace and its VS. Still, the research demonstrates that despite the mismatch and the uncertainties, sediment response plays an important role in earthquake site response across the Las Vegas Valley.
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CHAPTER 1
INTRODUCTION

1.1 Purpose of the research

Recent major earthquakes around the globe, for example, 2004 Sumatra earthquake, 2010 Haiti earthquake, 2010 Chile earthquake and 2011 Japan earthquake, showed the destructive nature of earthquakes; in the meantime it has also been observed that preparedness against earthquakes can reduce the loss of life and property. Understanding the nature and characteristic of regional and local seismic hazards can be used to mitigate fatalities and other losses due to earthquakes. Using a sophisticated loss-estimation computer model, HAZUS-MH, developed by the Federal Emergency Management Agency, the Nevada Bureau of Mines and Geology estimated that an earthquake of magnitude 6 occurring in the central east side of the Las Vegas Valley, Nevada (LVV) (epicenter at 36.17°N latitude and 115.12°W longitude) with a depth of 10 km could cause about $7.2 billion of economic losses and about 280 fatalities in the city of Las Vegas, with approximately 15,000 buildings suffering extensive to complete damage (Price et al., 2009). Additional fatalities and damages were estimated in the areas of Henderson and Boulder City due to the earthquake (Price et al., 2009). As such, the city of Las Vegas is ranked highest in the estimated loss due to earthquakes in comparison to other cities in Nevada. It should be noted that according to the U. S. Geological Survey (USGS, http://earthquake.usgs.gov/research/hazmaps, accessed July 2011), the
probability of an earthquake of $M > 6$ within 50 km of Las Vegas in the next fifty years is about 20 to 25 percent. Faults in and around the Valley are capable of earthquakes of magnitude 7.0 and more. Moreover, in every 100 years an earthquake of magnitude 5 or more in the area can be expected (Anderson et al., 2008), and that, according to Price et al. (2009) can produce about 4 fatalities and a total economic loss of about $870 million with 640 buildings facing major damage in Las Vegas.

The USGS has the lead federal responsibility to provide information on earthquakes and earthquake hazards to the U.S. public and professionals working to mitigate seismic hazards, and therefore has produced seismic hazard maps depicting ground shaking parameters for different areas of the U.S. These maps have been the basis for many seismic hazard evaluations in the U.S. and are used in building codes (ASCE, 2010) and American Association of State Highway and Transportation Officials seismic design codes (AASHTO, 2010).

Probabilistic Seismic Hazard Assessment (PSHA) has never been performed for the Las Vegas Valley (LVV) except the one by the USGS, which is included in the National Seismic Hazard Map (NSHM, Petersen et al., 2008). But the current (2008) NSHM model does not explicitly include some active faults in the region, including the Las Vegas Valley Fault System (LVVFS), and therefore is expected to under-predict the hazard for the Valley. The USGS categorizes the faults of the LVVFS (except Eglington) as ‘Class B’ faults which means either that the geologic evidence is not strong enough to classify them as Quaternary faults of tectonic origin or they are not thought to extend deeply enough to be potential sources of significant earthquakes (http://earthquake.usgs.gov/hazards/qfaults/glossary.php, last accessed March 2012).
Recent studies (e.g. dePolo et al., 2006) have found that the faults are tectonic and should be considered a serious seismic hazard. Therefore, in this research an alternative probabilistic seismic hazard model is produced that is based on current understanding of fault sources.

Little is known about the effects of the sediments of the LVV on earthquake ground shaking. This research further evaluates the one-dimensional seismic site response of deep sediment columns in the LVV basin to likely sizeable earthquakes. Two earthquake scenarios are selected based on their major contribution to the seismic hazard of the LVV as indicated by deaggregation of the probabilistic seismic hazard. The site response considered here is limited to a one-dimensional analysis up to a depth of 400 m from the surface and does not include 2-D and 3-D effects that might be equally important and merit further study.

This site response analysis requires input ground motion (acceleration time histories) to be applied at the base of the sediment column. This research investigates different approaches for selecting design ground motions and evaluates effects on site response; design ground motion can be defined as the ground motion specific to a site predicted at its surface, ready for use in structural design calculations. Three main design ground-motion selection approaches are evaluated: unscaled and scaled sets of measured ground motions, and spectrum-matched ground motion.

This dissertation research is a step forward to improve the understanding of earthquake hazards for the LVV by creating hazard maps predicting key ground shaking parameters resulting from credible earthquakes, which incorporate latest understanding of local and regional fault hazards and the effect of deep sediment deposits. Specifically,
this research addresses two main objectives: 1) compute bedrock ground motions that can be expected from capable earthquake sources and 2) compute site-specific ground-surface motions from one-dimensional modeling of sediment columns. As final results, two sets of hazard maps are produced for the LVV. The first set of maps shows the probabilistic seismic hazard across the LVV relevant to rock-site conditions. The second set of maps shows predicted ground-surface motion and associated amplification factors across the LVV for two earthquake scenario events – close-in, moderate magnitude and distant, large magnitude. These sets of maps can lead to improved earthquake safety by providing better understanding of the earthquake hazards and risks in the LVV. The results can lead government agencies to update national seismic hazard maps, revise building codes and re-evaluate loss forecasts.

1.2 Specific research questions

The research first investigates the seismic hazard of the Valley considering alternative seismic source models using a probabilistic seismic hazard model. Then it addresses seismic site response of the deep and shallow sediments of the Valley by exercising a one-dimensional equivalent-linear and a non-linear model across the LVV. The Applied Geophysics Center at UNLV has been involved in testing sediment properties across the Valley over the last decade and has recently produced a comprehensive 3-D model of shear wave velocity (VS) of the sediments to a depth of 100 m or more (Murvosh et al., 2013). This research uses the 3-D VS model and a complementary 3-D lithology model (Taylor et al., 2008) as inputs to the site response model. This research principally answers the following questions:
1. What is the earthquake ground shaking hazard in the Las Vegas Valley, given what we know today about seismic sources in and around the Valley?

The following sub-questions will be addressed to answer the above question:

a. What are the potential seismic sources that could have significant effect on the seismic hazard of the Valley and how are they characterized?

b. Has the seismic hazard of the Valley been previously underestimated given current understanding of local and regional faults? Does the alternative analysis which accounts for recent discoveries produce a significant difference in the seismic hazard?

2. What is the effect of different, credible input ground motions on site response?

The following sub-questions will be addressed to answer the above question:

a. How does the spectrum-matched ground motion compare to suites of unscaled and scaled ground motions in terms of seismic site response? Does a spectrum-matched ground-motion produce bias in site response with respect to an unscaled ground-motion set? Can spectrum-matched ground motion be used reliably instead of an unscaled ground-motion set for calculating site response?

b. How do the choices of approach to developing a design ground motion affect simple, shallow sediment profiles versus complex, deep ones?

3. What are the effects of the sediments of the Valley on one-dimensional earthquake ground motion computations, considering credible earthquake scenarios and our current understanding of the geological, geotechnical and geophysical properties of the sediments?

The following sub-questions will be addressed to answer the above question:
a. How do deep sediment columns affect surface ground motions?

b. Given best understanding of the Valley sediments, what are the 1-D site response patterns of the different sediment columns for the LVV? Do they vary significantly?

1.3 Overall approach

The research includes two main parts: 1) modeling the rock site condition seismic hazard due to credible earthquake scenarios through PSHA; and 2) modeling site response using valley-wide 3-D site parameterizations and equivalent-linear and non-linear 1-D site response. Probabilistic seismic hazard models are produced and hazard calculations are performed. One-dimensional site response analyses are performed at grid nodes across the LVV using the site response models derived from the 3-D VS and sediment lithology models. Other factors that are likely to be important in response to earthquake shaking but are beyond the scope of this research include near-fault effects, basin-edge effects, and three-dimensional effects of reverberation within the basin.

1.4 Organization of the dissertation

This dissertation follows a manuscript format and consists of three journal-style manuscripts, plus appendixes covering supplemental information.

The first objective of this dissertation includes PSHA incorporating current knowledge of local and regional faults, emphasizing the Eglington fault, which is a part of the LVVFS. PSHA is carried out at grid nodes across the LVV and results are produced as seismic hazard maps at different spectral periods for different return periods.
The manuscript in Chapter 2 addresses Research Question 1 and presents the analysis and results of PSHA for the rock-site condition. The manuscript can be taken as a “what if” scenario that analyzes the effect of an alternative seismic source characterization on the seismic hazard of the LVV. The manuscript titled “An Alternative Analysis of the Probabilistic Seismic Hazard for Las Vegas Valley, Nevada” has already been published in the Bulletin of the Seismological Society of America (Lamichhane et al., 2014). Co-authors are Barbara Luke and Wanda Taylor.

A site response analysis requires one input motions in terms of acceleration time histories applied at the base of a sediment column. The input motions are matched to a target spectrum compatible with the seismic hazards at the site. Chapter 3 investigates the effects of different approaches of generating input ground-motion record sets, including unscaled real records, scaled real records, and spectrum-matched records, on site response. This chapter addresses research question 2. Site response analyses are performed using both equivalent-linear and nonlinear methods. This study compares the results mainly in terms of response spectra and investigates whether the scaled record set and spectral-matched record produce bias with respect to the unscaled record set.

The current (2008) U.S. National Seismic Hazard Maps include different maps for different soil-site conditions based on the shear-wave velocity averaged over the top 30 m (VS30); however, it is the user’s responsibility to determine the most relevant VS30 value for their site. The second objective of this research includes conducting a set of 1-D site-specific response analyses, Valley-wide, using a non-linear approach and using site-specific VS profiles and other sediment properties. Chapter 4 contains this study, considering two scenario events. Chapter 4 addresses research question 3.
The figures, tables, and references for each chapter are included at the ends of the respective chapters.

The final chapter (Chapter 5) includes some caveats of this dissertation, recommendations for future research, and makes note of an early outcome of the PSHA.

Appendix A presents results from deaggregation of hazard relevant to a probabilistic seismic hazard analysis for a site in the LVV. The deaggregations are presented for 2500-year return period for spectral periods from 0.01 s to 4.0 s.

Appendix B includes the time histories of the ground motions (unscaled and scaled) used in Chapter 3.

Appendix C tabulates the coordinates of all the target site response grid points used in Chapter 4.

Appendix D contains shear wave velocity profiles developed for all target site response grid points. These profiles were used for the site response analysis performed in Chapter 4.

Appendix E includes a sensitivity study of effects of dynamic soil properties on site response. This analysis supports the choices of dynamic soil properties made for different sediment types in the analyses presented in Chapters 3 and 4.

Appendix F shows response spectra of input and output motion for each of the grid points where site response analyses are performed, as described in Chapter 4. The input motions are matched to the target spectrum, which are also shown in the figures. Site response analyses are performed using equivalent-linear and nonlinear analyses using SHAKE and DMOD programs, respectively. The output motions from these analyses are also shown.
1.5 References


CHAPTER 2
AN ALTERNATIVE ANALYSIS OF THE PROBABILISTIC SEISMIC HAZARD FOR LAS VEGAS VALLEY, NEVADA

Abstract

Probabilistic seismic hazard calculations relevant for rock-site conditions in the Las Vegas Valley, Nevada (LVV) have been computed that account for seismic sources that are not included in the current (2008) USGS national seismic hazard model (NSHM) because of insufficient knowledge or documentation, using the commercial software package EZ-FRISK. The LVV is underlain by a system of mapped, active normal faults that comprise the Las Vegas Valley Fault System (LVVFS), with maximum potential earthquakes to M6.8. The 2008 NSHM explicitly includes only one fault of the LVVFS. This analysis includes four more faults of the LVVFS plus four regional faults in addition to those included in the 2008 NSHM, and modifies parameters of two others. As such, this study demonstrates the effect of a significant modification to expectations for seismic sources. These results can be considered as a “what if” scenario for seismic hazard of the LVV. Nominal peak ground acceleration (PGA) and 5% damped spectral acceleration ($S_a$) were calculated for 0.2-s and 1.0-s periods using five ground motion prediction equations (GMPEs). A logic-tree formulation accounted for uncertainty in the GMPEs and source parameters. Hazard values for PGA and $S_a$, computed at ~2.8-km spacing, are comparable to those of the 2008 NSHM on the margins of the LVV, but are considerably higher in the north-central parts of the LVV near downtown Las Vegas and the city of
North Las Vegas. The study provides a rationale for the urgency to conduct deeper investigations of faults in and around the LVV.

2.1 Introduction

The Las Vegas Valley (LVV) is home to approximately 2 million residents and hosts an average of over 100,000 daily visitors. Although the earthquake hazard in the LVV is not as high as in some other parts of the State of Nevada, its earthquake-derived risk to life and property is large due to the LVV’s population and financial investment in the built environment. Using the loss-estimation computer model HAZUS-MH, Price et al. (2009) estimated that an earthquake of moment magnitude \( M_w \) 6.0 occurring 10 km beneath the Valley (with a near-zero epicentral distance) could cause about 280 fatalities and $7.2 billion of economic losses, with approximately 15,000 buildings suffering extensive to complete damage. To put these potential losses in perspective, according to the U. S. Geological Survey (USGS) the probability of an earthquake of \( M \geq 6 \) within 50 km of Las Vegas in the next 100 years is in the range of 20 to 25 percent; however, the majority of the threat is due to distant events (see Data and Resources section).

While the earthquake hazard in the Las Vegas Valley is known to be significant, it remains insufficiently understood. The U. S. Geological Survey’s (USGS) 2008 national seismic (earthquake ground-shaking) hazard model (NSHM) for rock site conditions in the LVV shows peak ground acceleration (PGA) of about 0.19 g for 2% probability of exceedance (PE) in 50 years (Petersen et al., 2008). For 10% PE in 50 years, the estimated PGA is about 0.08 g. This study calculates the hazard taking into consideration the authors’ current understanding of local and regional faults, most notably the Las
Vegas Valley Fault System (LVVFS) which traverses the LVV. Only one of the faults of this fault system is included in the 2008 NSHM. Our study investigates the extent to which the seismic hazard is affected by following a different interpretation of local and regional faults’ capabilities with respect to the 2008 NSHM. It can be taken as a “what if” investigation by demonstrating the extent to which the modified interpretation influences seismic hazard for the LVV. A finding of significant impact would provide rationale for the urgency to intensify investigations of faults in and around the LVV.

In this research, a probabilistic seismic hazard analysis (PSHA) tool incorporating multiple ground-motion prediction equations (GMPEs) was used to produce a suite of seismic hazard maps for the Las Vegas Valley (roughly 35.9°N to 36.4°N, -114.9°E to -115.4°E). The probabilistic seismic hazard model for this research follows the general methodology described by Kramer (1996), which consists of four steps: (i) characterizing seismic sources, (ii) defining recurrence rates for the seismic sources, (iii) predicting ground motions, and (iv) calculating hazards on a regional map grid. Ground-motion probabilities were forecast for three levels of exceedance, and results were compared to the 2008 NSHM (Peterson et al., 2008).

Ground motions calculated in this study were for the rock site condition and therefore do not account for the potentially significant amplification or deamplification effects of the LVV’s basin-fill sediments, which are deep in some areas and have highly variable stiffness. Site-specific response analyses have demonstrated significant amplification by soft sediments in some parts of the LVV (e.g., Su et al., 1998; Rodgers et al., 2006; Luke and Liu, 2008; Tkalčić et al., 2008). Incorporation of the site-response effects of the near-
surface sediments in the predictions would yield more complex ground-motion maps than those presented here.

2.2 Geologic and seismotectonic settings

The Las Vegas Valley is located near the southern tip of the State of Nevada. The LVV encompasses the cities of Las Vegas, Henderson, and North Las Vegas as well as unincorporated lands that also are developed. The LVV is about 30 km wide and 40 km long and is bounded by mountain ranges. Langenheim et al. (2001) studied the geometry of the basin using gravity and seismic-reflection methods, and reported that the maximum depth of basin-fill sediments over Paleozoic bedrock approaches 5 km. The basin fill contains alluvial deposits sourced primarily from the Spring Mountains, located to the west of the Valley. The shallow fill of the basin consists of Quaternary alluvial-fan deposits and coalescing Cenozoic alluvial and volcanic deposits of varying thickness. The alluvial-fan deposits are composed of clay, silt, sand, and gravel interspersed with carbonate-cemented lenses (Wyman et al., 1993). Sediments generally grade from coarser to finer from west to east toward Frenchman Mountain, which forms the eastern boundary of the LVV, but some coarse-grained sediments lie quite close to Frenchman Mountain. The lithologies of the basin-fill sediments fall into three spatial categories: western, central and eastern (Taylor et al., 2004). The western and eastern regions contain mainly coarse-grained deposits with finer grained matrix, and the central region, which is the largest, predominantly contains clay.

The LVV lies within the central Basin and Range geomorphic province, one of the most seismically active regions in the United States (Lund, 2006). It is characterized by
extensional deformation. Wyman et al. (1993) described the LVV as a prominent, northwest-trending topographic depression. The LVV was formed by right-lateral strike-slip displacement along the NW-striking Las Vegas Valley shear zone and east-west extensional tectonics. Strike-slip and normal faults are characteristic of central Basin and Range extension. Figure 2.1 shows active faults in and around the LVV taken from the USGS Quaternary fault and fold database of the United States (see Data and Resources section). The term ‘active’ is used broadly here to include those faults that have moved within the Quaternary Period, or the past 2.6 million years.

Based on maximum potential magnitude, proximity to the LVV, and level of activity, some close-in faults that pose a seismic threat to the LVV include the LVVFS, which includes the Whitney Mesa, Cashman Field, Valley View, Decatur, Eglington, and West Charleston faults; the Frenchman Mountain fault; the Black Hills fault, to the southeast; the California Wash fault, to the northeast; and the Pahrump fault, about 80 km west of Las Vegas. All are predominantly normal-slip faults except the Pahrump fault, which is predominantly strike-slip. All show most recent activity in the Holocene Epoch (the past 11,700 years), except for the Frenchman Mountain fault, whose most recent activity was in the Late Quaternary, or the past 130,000 years, according to USGS Quaternary fault and fold database (see Data and Resources section). USGS Quaternary folds and faults database places the Eglington fault in the same Late Quaternary category, but for this study we follow recent research that characterizes the Eglington as a younger fault (see Fault seismic sources section). Despite a possibly long dormancy, the Frenchman Mountain fault is considered by some to be the biggest and most active fault in the Las Vegas Valley (Vogel, 2009). Hess and dePolo (2006) chose the Frenchman Mountain
fault for the rupture scenario in their loss-estimation modeling for Las Vegas. This fault was included in developing the 2008 NSHM (Peterson et al., 2008). However, according to Taylor et al. (2008), the LVVFS may be more active than the Frenchman Mountain fault, and thus may pose a greater hazard to Las Vegas. Therefore, most of the faults of the LVVFS are included in the seismic hazard calculations of this study, as discussed below.

A strong earthquake on any of the faults within the LVV would affect the developed areas, particularly those where site amplification effects are strongest. Additionally, the LVV’s deep, sediment-filled basin is expected to amplify long-period motions from distant earthquakes (e.g., Rodgers et al., 2006). The seismicity of neighboring regions—southeastern California, northwestern Arizona, southwestern Utah, and southwestern Nevada—also contributes to seismic hazard in Las Vegas. Distant earthquakes from approximately 150 km and further—such as the 1902 M6 Pine Valley, Utah; the 1916 M6 Death Valley, California; the 1992 M7.3 Landers, California; and 1999 M7.1 Hector Mine, California earthquakes—have been felt in the LVV (Smith et al., 2001). Figure 2.2 shows historic earthquakes that have occurred within 200 km of the LVV. The maximum magnitude ($M_{\text{max}}$) recorded in this area was the $M_w$ 6.5 Manix earthquake, which occurred about 180 km southwest from the LVV on April 10, 1947. Smith et al. (2000, 2001, 2008) provided a summary of the seismicity of the Valley. Smith et al. (2008) pointed out that had seismic monitoring in the LVV been better, more micro-earthquakes would have been recorded. Savage et al. (2013) discussed the inadequacy of the current monitoring system in the LVV and the benefits its improvement would bring, such as
helping to identify and characterize active faults, which will improve understanding of the seismic hazard.

2.3 Seismic source characterization parameters

The source-to-site distance, $M_{\text{max}}$, and activity of an earthquake source are the main contributors of that source to the probabilistic seismic hazard at a site (Stepp et al., 2001). The following addresses each of those contributors for the LVV in sequence and then takes up fault dip angle and depth.

2.3.1 Source-to-site distance

Wong et al. (2002) stated that in seismic hazard analyses for the western U.S., active seismic sources usually are included to a maximum distance of 100 to 200 km from the study site. Stepp et al. (2001), conducting one of the most comprehensive PSHA studies to date, included only faults within 100 km to assess the seismic hazard at Yucca Mountain, the site of a proposed geologic repository for nuclear waste that is located about 120 km northwest of the LVV. Kemnitz (1999) also included only faults within 100 km to analyze the seismic hazard at a radioactive waste landfill located on the Nevada Test site, now called the Nevada National Security Site, which is approximately 90 km northwest of the LVV. In seismic hazard analyses for Salt Lake City (Wong et al., 2002) and for the LVV (Luke and Liu, 2008), seismic sources were considered as far as 150 km from the study site. We considered seismic sources as distant as 200 km.
2.3.2 Maximum magnitude

The maximum magnitude, $M_{\text{max}}$, of a fault source can be estimated from fault parameters. In most cases for this study, the $M_{\text{max}}$ associated with each fault is calculated from the surface rupture length (SRL) (Wells and Coppersmith, 1994):

$$M_{\text{max}} = 5.08 + 1.16 \log_{10}(SRL)$$  \hspace{1cm} (2.1)

where SRL is in km. According to Hanks and Bakun (2002), this relationship underestimates for magnitudes greater than 7. However, since all of the faults relevant to this study except some distant ones in California have $M_{\text{max}}$ of 7 or less and none are larger than 7.2, the relationship by Wells and Coppersmith (1994) is considered acceptable for this study.

For the faults in California that are included in this study, the maximum earthquake magnitudes were based on fault area. For these faults, all parameters used are as given in the database within the commercial seismic hazard program EZ-FRISK (version 7.62; Risk Engineering Inc., 2011). For the California faults, EZ-FRISK follows Petersen et al. (2008) in using two, equally weighted values of magnitude in a logic tree formulation—one based on Hanks and Bakun (2002) and another based on Ellsworth (2003).

2.3.3 Activity

In this study, all fault sources were considered that had activity to the Latest Quaternary, or moved within the last 15,000 years, and that lie at least partially within 200 km of a reference location near the geographic center of the Valley (36.15° N and 115.15° W, the intersection of Las Vegas Boulevard and Sahara Avenue). The Frenchman Mountain fault was also included, for reasons stated earlier. Table 2.1 lists the
faults included in this study along with some of their key parameters. Figure 2.3 illustrates the distribution of fault $M_{\text{max}}$ with respect to distance from the reference location and sense of slip. Most of the faults near the reference location are primarily normal, and most of those that are more than about 120 km distant are primarily strike-slip.

2.3.4 Dip angle

Other key fault parameters to be defined include dip angle and depth. According to Lund (2006), normal faults in the Basin and Range Province have a dip angle of 50° and maximum depth of 15 km; those values are used in the 2008 NSHM. We assigned a dip angle of 50° for normal faults, with some exceptions (see Table 2.1): the faults comprising the LVVFS and the Yucca Mountain faults, western group, were assigned steeper dip angles for reasons explained below. All strike-slip faults were modeled to have a dip of 90°, following the 2008 NSHM.

2.3.5 Maximum depth of rupture

To assign the depth of faults for the LVVFS, historic earthquakes within the Las Vegas Valley (delineated for this purpose by 35.9°N to 36.4°N, -114.9°E to -115.4°E) from 1898 to 2012 were considered in a plot of cumulative frequency with depth (Figure 2.4). About 97% of the earthquakes occurred at depths of 15 km or less. Pancha et al. (2006) found that 98% of earthquakes in Nevada occur at depths less than 17 km. Therefore, in agreement with both Lund (2006) and Pancha et al. (2006), we assigned a
maximum depth of 15 km for the faults of the LVVFS. The same depth was assigned for all other normal faults, following the 2008 NSHM.

Except as stated, where available, fault parameters used in this study were taken from the seismic source database of EZ-FRISK, which incorporates the 2008 NSHM.

2.4 Fault and gridded seismic sources

This section describes our current understanding of fault sources that have the potential to affect the LVV in a future earthquake, from the starting point of the 2008 NSHM database (Petersen et al., 2008). The set of earthquake sources used for this study differs from those in the 2008 NSHM in that eight additional faults are included, consisting of four in the LVVFS plus four regional faults; some properties of two more sources are modified; and faults having activity older than Latest Quaternary are excluded, with the exception of the Frenchman Mountain fault which was discussed earlier (Table 2.1). The additional and modified faults properties were taken from recent research (Anderson et al., 1995; Piety, 1996; Louie et al., 1997; O’Leary, 2000; Slemmons et al., 2001; Fossett et al., 2003; Fossett, 2005; dePolo, 2006; dePolo et al., 2006; Lund, 2006; Guest et al., 2007; Wong et al., 2008; Petersen et al., 2008; Taylor et al., 2010). All eight added faults are listed in the USGS Quaternary fault and fold database (Figure 2.1). These faults include the Cashman, Valley View, Decatur, and Whitney Mesa faults of the LVVFS plus the Rock Valley, West Specter Range, Pahrump, and Yucca Mountain, western group. These faults have $M_{\text{max}}$ ranging from $M_w$ 6.2 to 7.2.

The following addresses the discrete faults and then gridded seismicity.
2.4.1 Fault seismic sources

This section addresses the two faults whose parameters are modified with respect to the NSHM database, followed by the eight newly-included faults.

The Eglington fault, located in the north-western LVV (Figure 2.1b) has an 11-km surface rupture length. According to Taylor et al. (2010) it is one of the youngest in the region, the most recent surface-rupturing event having occurred in late Holocene, a little over 2,000 years ago. In contrast, the USGS Quaternary fault and fold database (see Data and Resources section) indicates most recent prehistoric deformation on the Eglington fault in Late Quaternary. Slip rate estimates vary accordingly. The 2008 NSHM (Petersen et al., 2008) uses a slip rate of 0.1 mm/yr. The USGS Quaternary fault and fold database (see Data and Resources section) assigns a slip rate of <0.2 mm/yr to match expectations for a fault having last deformed in the late Quaternary. dePolo (2006) calculated the slip rates for this fault based on a radiocarbon date of ~22 ky and offset scarp height of 14 m. The calculated slip rate ranged from 0.4 to 1.6 mm/yr with a preferred value of 0.6 mm/yr (dePolo, 2006; Table 2.1, Page 167). Wong et al. (2008) give slip rate in the range 0.5 to > 1 mm/yr; but they do not state the basis for their estimate. Our PSHA addresses uncertainty in fault slip rates by using three values – a preferred value, an upper bound, and a lower bound. (Refer to section, Characterization of uncertainties using logic trees.) For the Eglington fault we followed dePolo (2006) in assigning 0.6 mm/yr as the preferred slip rate, 1.6 mm/yr as the upper bound slip rate, and 0.4 mm/yr as the lower bound slip rate.

The Black Hills fault is a SE-dipping Holocene normal fault, located on the east side of the Black Hills and west of U.S. 95 between the cities of Henderson and Boulder City,
Nevada (Figure 2.1b). This source is capable of generating an earthquake up to $M_w$ 6.9, with a maximum displacement of 0.71-1.96 m, according to paleoseismic fault offsets (Fossett, 2005). This magnitude is significantly higher than the $M_w$ 6.18 used in the 2008 NSHM (Petersen et al., 2008), which was derived using the Wells and Coppersmith (1994) relation based on the surface rupture length of 9 km. The Black Hills fault fits a situation described by Lund (2006) for faults having relatively short rupture lengths but large displacements. Under these conditions, according to Lund (2006), the Wells and Coppersmith (1994) relation underestimates the $M_{\text{max}}$; therefore, displacement information should be used in addition to surface rupture length to estimate the $M_{\text{max}}$. The slip rate for this fault in the 2008 NSHM was given as 0.1 mm/yr (Petersen et al., 2008); Fossett (2005) estimated 0.33 to 0.55 mm/yr based on $^{14}$C dates and heights of colluvial wedges observed in a trench. This study adopts Fossett’s (2005) estimates, using 0.33 and 0.55 mm/yr as bounding values and the average of these values, 0.44 mm/yr, as the preferred slip rate.

The LVVFS is centered within the LVV and includes five principal faults (Figure 2.1b). (Note that the Eglington fault is a part of the LVVFS but has been addressed separately due to its higher rate of activity). From southeast to northwest, the rest of the principal faults of the LVVFS consists of the Whitney Mesa fault, which lies to the south of Whitney Mesa in the City of Henderson; the Cashman fault, which lies in the central LVV near Cashman Field and continues south toward the Whitney Mesa fault; the Valley View fault, trending approximately N-S along Valley View Blvd; the Decatur fault, approximately along Decatur Blvd; and the West Charleston fault, which crosses Charleston Blvd. on the western side of the LVV.
In the USGS Quaternary fault and fold database (see Data and Resources section), all of the principal faults of the LVVFS except the Eglington are considered ‘Class B’ faults, which means either that the geologic evidence is not strong enough to classify them as Quaternary faults of tectonic origin or they are not thought to extend deeply enough to be potential sources of significant earthquakes (see Data and Resources section). All Class B faults, which includes the LVVFS except Eglington fault, are excluded from the NSHM (Petersen et al., 2008), meaning that they are not included explicitly as fault sources (email and verbal communication between S. Lamichhane and Kathleen Haller of the USGS, October 2010).

The faults of the LVVFS, excepting Eglington, were once thought to be created aseismically by hydro-compaction or some other non-tectonic process (Maxey and Jameson, 1948). dePolo et al. (2006) and dePolo (2006) studied and analyzed alternative theories of origin of the LVVFS and concluded that the driving mechanism for the faults was indeed tectonic. The authors stated that these faults should be considered a serious seismic hazard, noting that even a moderate earthquake occurring within the Las Vegas basin could constitute a disaster for the population and built environment.

The tectonic capabilities of the LVVFS are uncertain. Due to insufficient documentation and lack of published, fault-specific studies, this fault system was not explicitly included in the 2008 NSHM. In contrast, this study explicitly includes all the principal faults of the LVVFS, with one exception. We follow Slemmons et al. (2001) in excluding the West Charleston fault as a seismic source due to lack of adequate paleoseismic information, a widely distributed pattern of faulting, and a very low slip rate.
In profile, the surfaces of the normal dip-slip faults of the LVVFS are not planar: they are steep at the ground surface (dip 70° or more) but appear to flatten with depth, as do many faults in the Basin and Range. However, for simplicity in modeling for this study, the Decatur, Valley View, Cashman Field, and Whitney Mesa faults are considered to be planar, with an average dip of 60°, which is consistent with general theory (Anderson, 1951) and our projections of scarp data (Bell, 1981) to offsets in bedrock from gravity data (Langenheim et al., 2001).

The slip rates for the faults of the LVVFS are poorly constrained. The USGS Quaternary fault and fold database website (see Data and Resources section) assigns the slip rate for this fault system in the category of <0.2 mm/yr, in accordance with the late Quaternary characterization of the fault system. dePolo (2006) considered possible slip rates for this system using rough modal heights for offsets and ages. The author calculated strawman slip rates of 0.04 to 0.4 mm/yr based on a composite total offset height of 30 m over 750 ky to 80 ky. According to the Utah Quaternary Fault Parameters Working Group (Lund, 2005), the slip rates of faults in the Basin and Range Province have uncertainty of a factor of two, based on findings from many faults in Utah. In the absence of further guidance, considering the work cited here of USGS faults and folds database, dePolo (2006) and Lund (2005) we chose to assign to the Decatur, Valley View, Cashman Field, and Whitney Mesa faults an upper-bound slip rate of 0.2 mm/yr, a preferred rate of 0.1 mm/yr, which is half of the upper bound, and a lower bound rate of 0.05 mm/yr, which is half of the preferred rate.

The Rock Valley fault lies northwest of the LVV, east of Yucca Mountain (Figure 2.1a). According to Smith et al. (2000), it is an active strike-slip seismic source with a
most-recent prehistoric fault rupture in Latest Quaternary. It has produced small earthquakes (M2 to M4) in the last 20 to 30 years. This source has been studied due to its potential to generate a strong earthquake near Yucca Mountain. The fault is a left-lateral strike-slip fault with a potential maximum earthquake magnitude of 7.0 or greater. O’Leary (2000) gave a slip rate of 0.089 mm/yr. USGS Quaternary fault and fold database (see Data and Resources section) gave a range of 0.02 to 0.1 mm/yr, with the best estimate being 0.02 mm/yr, less than one quarter the rate given by O’Leary (2000). In this study, a conservative value of 0.1 mm/yr was used as the preferred slip rate, with 0.2 mm/yr and 0.05 mm/yr as upper and lower bounds.

The strike-slip Pahrump fault, situated to the west of the LVV on the California-Nevada border between Primm and Amargosa Valley (Figure 2.1a), is a portion of the Stateline fault system, which is a continuous, ~200-km-long zone of active dextral shear, considered by Guest et al. (2007) to be an extension of the Eastern California shear zone. The Pahrump fault, which traverses the south-west edge of Pahrump Valley and the east side of Stewart Valley, is the mostly recently active segment. The Amargosa and Mesquite parts of the Stateline fault system do not have documented activity to the Latest Quaternary, and therefore the entire Stateline fault was not included in this study. The Pahrump fault is the longest seismogenic structure within 100 km of the LVV. According to Louie et al. (1997), this right-lateral strike-slip fault shows Holocene slip greater than 0.1 mm/yr (best estimate; range 0.03 to < 2 mm/yr) and is capable of an earthquake up to $M_{\text{max}}$ of M7.2. We assign $M_{\text{max}}$ of M7.2 and a preferred slip rate of 0.5 mm/yr, which is about half of the midpoint of the range from Louie et al. (1997), with upper and lower bounds of 1.0 and 0.03 mm/yr respectively.
The West Specter Range fault lies south of the main Specter Range, northwest of the LVV (Figure 2.1a). It is a short (9 km) normal fault having most recent significant deformation in Latest Quaternary. Slip rate is estimated at less than 0.2 mm/yr in the USGS Quaternary fault and fold database (see Data and Resources section). Anderson et al. (1995) estimated a slip rate of about 0.004 mm/yr based on displacement of 0.5 m in 113 thousand years. We used that as the preferred rate with upper and lower bounds of 0.008 and 0.002 mm/yr respectively.

The Yucca Mountain faults, western group, is a group of faults west of Yucca Mountain (Figure 2.1a), with a total length of 25 km and most recent movement to latest Quaternary, according to the USGS Quaternary fault and fold database. This group has dip angle of 63° to 73° and slip rate of 0.001 to 0.03 mm/yr (see Data and Resources section). For this fault group we followed the USGS Quaternary fault and fold database by using a higher-than-normal dip angle of 70°, with upper and lower bounds of 73° and 63° respectively. We assigned a preferred slip rate of 0.01 mm/yr with upper and lower bounds of 0.03 and 0.001 mm/yr respectively.

2.4.2 Gridded seismic sources

In addition to mapped faults, there exist other low-activity faults that have not been characterized, and still more faults that have not been mapped or that lack surface expression. The USGS NSHM uses gridded seismic sources to address potential earthquakes that are not linked to specific fault sources and provide a way to recognize low-activity faults that have not been well characterized. Gridded sources are classified as background seismicity and shear zones. Background seismicity addresses random
earthquakes that are not on known faults as well as those that do not cause surface rupture. The 2008 Wells $M_w$ 6.0 earthquake in northeastern Nevada was a background earthquake on a previously unknown fault; this type of earthquake can occur anywhere in Nevada (NESC, 2011). Background earthquakes usually are represented in seismic hazard analyses as gridded sources whose parameters are based on historical seismicity patterns (Petersen et al., 2008); they are incorporated as such in this study. Gridded seismicity is weighted cell-by-cell to reduce its impact near known faults (Petersen et al. 2008). The weights reduce the influence of background source in a cell when the magnitude due to known faults is above the threshold for weights which is set at M6.5.

For the western U.S., Petersen et al. (2008) considered historic earthquakes with $M \geq 4.0$ to describe background seismicity. The gridded sources used in this study are all as given in the EZ-FRISK database, v. 7.62, which is taken from the work of Petersen et al. (2008). Gridded seismicity is smoothed over a radius of ~50 km (Petersen et al., 2008). The minimum and maximum magnitudes for gridded sources (Extensional Gridded Zones) are M5 and M7 respectively. These sources were treated as finite faults with two fault mechanisms equally possible, strike-slip and normal, and having random strike. Shear zones in the PSHA (so-called “C Zones”) account for earthquakes in zones of distributed shear where geodetic data indicate elevated shear strain (Petersen et al., 2008). Both Petersen et al. (2008) and this study include the Mojave shear zone (in eastern California) as a gridded source, with minimum and maximum magnitude set at M6.5 and M7.6 respectively. This zone was treated as having a fixed strike with a fault mechanism of strike-slip.
2.5 Recurrence rates for seismic sources

Each seismic source is described by a recurrence relationship that indicates the probability that an earthquake of a given magnitude will occur during a specified period of time. For gridded sources, the recurrence model usually is based on historical seismicity (Reiter, 1990). For a fault source, geologic data – for example, slip rate – are used.

Two earthquake recurrence models were applied in this study: the exponential model (Gutenberg and Richter, 1954), and the characteristic model (Youngs and Coppersmith, 1985). The characteristic model used here, which is in accordance with Petersen et al. (2008), represents the magnitude of an event with a normal distribution of characteristic magnitudes about the mean that is truncated at set minimum and maximum values.

The exponential model is more appropriate for gridded sources (Wesnousky, 1994; SSHAC, 1997; Wong and Olig, 1998). In this model, the earthquake occurrence rate increases logarithmically as earthquake magnitude decreases: \[ \log_{10} N = a - bM, \]
where \( N \) is frequency of earthquakes greater than \( M \). The constant ‘\( a \)’ represents the baseline activity rate (\( 10^a \) is the rate of events having \( M \geq 0 \)) and ‘\( b \)’ describes how the number of earthquakes varies with magnitude. A low \( b \)-value corresponds to a relatively high frequency of large events (as compared to small events). According to Youngs and Coppersmith (1985), a characteristic earthquake occurs with greater frequency than predicted by the exponential model; the frequency \( (N) \) increases exponentially as the magnitude \( (M) \) decreases, resulting in a nonlinear \( N-M \) relation.

In EZ-FRISK, the magnitude recurrence model is defined by minimum and maximum magnitude, the parameter \( \beta \), where \( \beta = b \cdot \ln 10 \), and earthquake rate. For all discrete faults
except those in California, the $b$-value was assigned to be 1.0 ($\beta = 2.3$) for the characteristic model and 0.8 ($\beta = 1.842$) for the exponential model. For all gridded sources, the exponential model was used with $b$-value of 0.8 ($\beta = 1.842$). In EZ-FRISK, the fault slip rate is converted to activity rate during calculations, using relationships defined by Youngs and Coppersmith (1985) (Risk Engineering Inc., 2011). For those faults whose properties were not modified from those given by the 2008 NSHM, the activity rate in EZ-FRISK was used directly. For the rest of the sources, the earthquake rate was defined in EZ-FRISK by slip rate. This is the process used in the 2008 NSHM (Petersen et al., 2008). Figure 2.5 shows activity rate for those ten sources that are added in this study or modified with respect to the 2008 NSHM.

For the exponential model, the minimum magnitude was set at M6.5 for all cases following Petersen et al. (2008), and the $M_{\text{max}}$ was set as stated in Table 2.1. Following the 2008 NSHM, for the characteristic earthquake model the magnitude range was set as $M_{\text{max}} \pm 0.24$ which represents two standard deviations using a normal distribution (Petersen et al., 2008). The distribution is truncated at these minimum and maximum values. Thus, for a fault whose characteristic magnitude was less than or equal to minimum magnitude (M6.5), the exponential model was not used (only the characteristic model was used).

2.6 Ground motion prediction

In this study we computed the free-field horizontal component of the PGA and 5% damped spectral acceleration for a reference rock outcrop site, using multiple ground-motion prediction equations (GMPEs). The reference rock outcrop is described as the B/C boundary rock site condition in the National Earthquake Hazards Reduction Program.
(NEHRP; Building Safety Council, 2000), having a $V_{S30}$ (shear wave velocity averaged over the top 30 m) of 760 m/s. The GMPEs compute ground motion at a specific location with respect to earthquake magnitude, distance, and other factors, including path and site characteristics for all relevant sources (Kramer, 1996). Douglas (2003) presents a comprehensive review of GMPEs, and Seyhan and Stewart (2012) present a review of the GMPEs from the Next Generation Attenuation (NGA) suite of models for the Western U.S.

No GMPE exists specifically for the Las Vegas region. Therefore, five different GMPEs were used in this study. Three are the models used in the 2008 NSHM: Boore and Atkinson (2008; BA08), Campbell and Bozorgnia (2008; CB08), and Chiou and Youngs (2008; CY08). The fourth is the model by Abrahamson and Silva (2008, AS08); all of these are part of the Next Generation Attenuation (NGA) suite of models for the Western U.S. Only about 8% of the data in the NGA database flat file are from extensional tectonics or normal faulting; most are from reverse faulting or strike-slip faulting, many from California earthquakes. Different styles of faulting generate different ground motions and, hence, different ground motion prediction models (Bommer et al., 2003). Although all of the NGA models include a style-of-faulting factor, a GMPE of Spudich et al. (1999; SEA99), although older, is included because it was developed from earthquakes occurring in extensional tectonic regimes, where most of the faults are normal or strike-slip. Figure 2.6 shows median ground motion with distance for M6.0 and 7.5 events using the five selected GMPEs for a normal fault. Although the NGA models have capabilities to address the effect of overburden on the calculated ground motion, that feature was not exercised in this study.
The four NGA models are applicable to both discrete and gridded sources within 200 km of the site and for earthquakes ranging in magnitude from 5 to 8. The SEA99 model is more limited. It is applicable to discrete faults only, for magnitude range 5 to 7.7, and to a maximum distance of 100 km (Figure 2.6).

2.7 Characterization of uncertainties using logic trees

The PSHA provides a framework to identify, quantify, and combine the uncertainties associated with earthquake hazard models. Aleatory uncertainties – those that are due to the randomness and variability of the phenomenon itself – are accounted for in the computation of the seismic hazard, for example, by representing it as a Poisson model (McGuire, 2008). Some epistemic uncertainties – those that relate to uncertainty in the model, due to a lack of knowledge and understanding – are addressed by applying the logic tree formulation.

The logic tree integrates uncertainty for each of the input parameters by considering a range of possible values. Each node of the tree accommodates branches, each of which represents a different value for a parameter (an alternative choice). Each of the values is assigned a weight that represents the degree of confidence in the value. The logic tree was used to address uncertainties in the GMPE and in source parameters including fault dip, $M_{max}$, fault slip rate, and magnitude recurrence model. An excerpt from a branch of the logic tree for a single fault is shown in Figure 2.7.

The NGA models, which used the same database, have differences that are indicative of the epistemic uncertainty in GMPEs for the Western U.S. The use of multiple models in concert arguably reduces the degree of uncertainty in seismic hazard projections. In
this study, each of the five GMPEs was weighted equally, considering analyses by Sabetta et al. (2005) which demonstrated that when using four or more GMPEs, the effect of relative weights on the PSHA is minor, barring a case of extreme bias.

The fault parameters in the logic tree are assigned three values: a preferred or most likely value, flanked by upper and lower bounds. These parameters are assumed to have a continuous normal distribution, and are therefore weighted 0.185, 0.630, and 0.185, to represent the 5th, 50th, and 95th percentiles, respectively, of the distribution (e.g., Keefer and Bodily, 1983). For fault dip, the preferred dip as stated above and as tabulated in Table 2.1 is augmented and decremented by 10 degrees, with the exception of the Yucca Mountain faults, western group as discussed earlier. For Nevada faults, the epistemic uncertainty in earthquake magnitude is addressed with $M_{\text{max}}$ (the characteristic earthquake magnitude), as given in Table 2.1, augmented and decremented by 0.2, as done in the 2008 NSHM. For California faults, as noted earlier, we address magnitude uncertainty by using two estimates that are based on fault area, weighted equally.

As noted earlier, according to Lund (2005), the slip-rate estimate for faults in the Basin and Range Province has an uncertainty of a factor of two. In the absence of more specific guidance, we assigned the upper and lower bound slip rates as double and half of the preferred value, respectively.

To model the recurrence rates of earthquakes, we applied the characteristic and exponential models with weights of 0.7 and 0.3 respectively. The weights differed slightly from the 2008 NSHM which used weights of 0.667 and 0.333, respectively. This minor difference in weighting is expected to be insignificant; however, that expectation was not tested analytically.
Besides the factors whose uncertainties are discussed above, researchers have identified others that might affect PSHA outcomes. Some factors whose uncertainties have been included in logic trees by others (e.g., Stepp et al., 2001; Wong et al., 2002) but are not included in our analysis comprise fault segmentation, seismogenic depth, and $b$-value. Fault segmentation is not included because segmentation is neither easily identified nor well documented for most of the faults that were included in this study and the surface rupture length of some faults, including all of those in the LVVFS, is too short to justify segments. However, the exponential model does allow for partial fault rupture on all faults during seismic hazard calculation. Regarding seismogenic depth and $b$-value, a sensitivity analysis on these factors was conducted by Ghanat (2008) for the region centered on Phoenix, Arizona, which also lies within the Basin and Range province, about 500 km southeast of Las Vegas. The author found that neither parameter had a significant effect on the ground motion calculations. Hence, the uncertainties associated with those factors were not taken into consideration in this study.

2.8 Probabilistic ground motion hazard analysis and results

Using the previously described input parameters, probabilistic ground motion hazard analysis was performed using the seismic hazard analysis software EZ-FRISK, version 7.62 (Risk Engineering Inc., 2011), which is based on the standard Cornell-McGuire approach (Cornell, 1968; McGuire, 1976). The seismic hazard analysis integrates the effects of all earthquakes of different magnitudes – occurring at different locations on different earthquake sources at different probabilities of occurrence – into a single curve to estimate a desired ground motion parameter, for example PGA or spectral acceleration,
$S_a$, at a particular period of interest. The curve represents the probability that selected values of the particular ground motion parameter will be exceeded at the site during a specified period of time. The results apply to the rock-site condition, as previously described.

Annual frequencies of exceedance are calculated for different amplitudes of acceleration ranging from 0.0001 g to 3 g to produce a Total Hazard Curve (THC). Figure 2.8 shows THCs for PGA for the reference location, apportioned into contributions from discrete fault sources and gridded sources. The nominal PGA is taken as $S_a$ at approximately 0.01 s. The figure shows that the contribution from gridded seismicity is greater up to PGA of ~0.1g while for higher PGA, contribution from discrete fault sources is greater. The ratio of contributions from gridded sources to fault sources for a PGA of 0.05 g is about 1.9, and for PGA of 0.5 g is 0.25. THCs for periods of 0.01 s (the nominal PGA), 0.2 s, and 1.0 s are shown in Figure 2.9.

From the total hazard curve for PGA and spectral accelerations at periods of interest for a specified probability of exceedance, a Uniform Hazard Spectrum (UHS) can be produced. We computed UHSs for three spectral periods: PGA, 0.2, and 1.0 s. Figure 2.10 presents UHSs for 10%, 5%, and 2% probability of exceedance (PE) in 50 years, which correspond to return periods of approximately 500, 1000, and 2500 years, respectively. At the reference location, this study estimates PGAs of 0.32 g and 0.11 g for 2% and 10% PE in 50 years, respectively. A comparison between acceleration projections for the reference location by this study and by the 2008 NSHM is presented in Table 2.2. This study yields higher estimates in every case, by about 70% and 38% for 2% and 10% PE in 50 years, respectively. Deaggregation of hazard was carried out for
the reference location for 5% PE in 50 years; the result is not shown for the sake of brevity. For PGA and amplitude 0.2 g, the deaggregation showed that contributions Most of the contributions are observed from events of magnitude 6.25 to 6.95 at a distance of about 9 km, producing a mean magnitude of 6.35 and mean distance of 11.5 km from the reference location. Most of the contributions at PGA are observed from events of magnitude 6.25 to 6.95 at a distance of between 1 and 20 km, producing a mean magnitude of 6.4 and mean distance of 9 km from the reference location.

To explore spatial variation in ground-motion prediction, the PSHA was performed for gridded points across the LVV. Depending on the application, grid spacings from other regional seismic hazard maps range from a few meters (e.g., Wong et al., 2002) to kilometers (e.g., Cramer et al., 2004; Ghanat, 2008). For the LVV, analyses were conducted for 441 locations at a grid spacing of 0.025 degrees in latitude and longitude, which is equivalent to approximately 2.8 km in both directions (Figure 2.11). Results are presented in the form of contour plots that were created using the kriging interpolation algorithm in the software program ArcGIS v. 10.1.

Figure 2.12 shows a sample contour map for nominal PGA at 2% PE in 50 years. Higher ground motions are observed near the Eglington fault in the north-central part of the LVV; this is expected due to the higher slip rate assigned to this fault with respect to the rest of the LVVFS. The overall increase in hazard across the LVV is due also to contributions from the other faults of the LVVFS and the Black Hills fault. The PGA ranges from 0.18 g in the southwest portion of the Valley to 0.52 g in the north-central portion. Figures 2.13, 2.14, and 2.15 present seismic hazard maps for PGA, 0.2 s and 1.0 s $S_a$, at 2%, 5%, and 10% PE in 50 years, respectively. The hazard maps for different
values of $S_a$ display similar patterns. The patterns persist for all probabilities of exceedance evaluated for all three ground motion parameters. Overall, accelerations are larger to the north, which reflects the locations and orientations of close-in seismic sources. Locally, the highest amplitudes appear in the north-central part of the Valley, near downtown Las Vegas and the western part of the city of North Las Vegas (Figure 2.12). This pattern is attributable to the high-slip-rate Eglington fault compounded by influence of the other LVVFS faults, the Black Hills fault and the Frenchman Mountain fault. Extreme values of ground motion parameters for 2%, 5%, and 10% PE in 50 years are summarized by histogram in Figure 2.16. The maximum values are approximately double the minimum values.

When compared to the 2008 NSHM, this analysis showed consistently higher PGAs, with increases up to about 150% and 45% for 2% and 10% PE in 50 years, respectively. The differences are largest toward the center of the LVV, where the hazard is highest, and smaller on the edges. The smallest differences are observed at the south edge of the model space.

2.9 Discussion

Risk Engineering Inc. performed tests at various locations including Las Vegas to compare ground motions calculated by EZ-FRISK to those calculated by the 2008 NSHM, given the same input data. The tests showed that for Las Vegas, the difference in the results was, at most, 1.4% (see Data and Resources section). This finding validates the capability to compare results from the two modeling approaches.
To investigate whether the differences in results between the two analyses could be attributed to causes other than differences in the seismic source database, we considered the following:

1. Five GMPEs were used in this study, while the 2008 NSHM used three (BA08, CB08 and CY08). We tested the effects of incorporating the two GMPEs in addition to those used in the 2008 NSHM (results not shown here for brevity) and found a maximum difference in results of approximately 10%.

2. This study considers uncertainty in fault slip rates using the logic tree while the 2008 NSHM does not consider uncertainty in slip rate. Our tests (results not shown here for brevity) showed that incorporating slip-rate uncertainty in the seismic hazard model produced a minor increase in the ground motions with respect to using the most preferred rate only.

This analysis predicted ground-motion values that significantly exceed the 2008 NSHM predictions (Petersen et al., 2008) in many cases (Table 2.2). The computed PGA and $S_a$ values were comparable to those of the 2008 NSHM on the fringes of the LVV, but considerably higher than the 2008 NSHM (by a factor approaching 2) in the north-central parts of the LVV near downtown Las Vegas and the city of North Las Vegas, where this study’s acceleration values were the highest.

The fault set studied here differs from that of the 2008 NSHM in part because of new discoveries over the intervening years but also because of insufficient documentation of fault sources. Omission of fault sources having insufficient documentation fits with our understanding that the USGS’ data inclusion policy is cautious, with the intent of not needlessly or carelessly impacting communities (e.g., building codes, emergency
response planning). We conclude that the observed differences between the results from this “what if” study and the 2008 NSHM are primarily due to the higher slip rate assigned to the Eglington fault, and are also impacted by higher magnitude and slip rate for the Black Hills fault and by the four added fault sources of the LVVFS. Therefore more detailed studies of the LVV’s local faults, particularly the Eglington fault, are warranted. We understand that research is underway to understand discrepancies between slip rates determined geodetically and geologically, both individually and system-wide and to better understand the phenomena of shear strain accumulation and release as they apply to earthquakes.

Some fault parameters applied in this study have large uncertainty or are not yet rigorously documented. This study demonstrates some consequences of the uncertainty involved in computing seismic hazard; specifically, those attributable to faults characterization. It provides a strong argument for continuing investigation of the faults in and around the LVV.

2.10 Conclusions

This study analyzed the ground-shaking hazard in the Las Vegas Valley for rock site conditions, using probabilistic analysis techniques that are comparable to those used in the 2008 NSHM. Fault sources consisted of twenty-nine discrete faults that had Latest Quaternary activity, one fault with most recent activity in Late Quaternary. Gridded sources that encompass background seismicity and a shear zone were also included. Eight of the 30 faults were not included in the 2008 NSHM, and key properties of two others were adjusted in this study with respect to the 2008 NSHM. Analyses yielded
significantly higher ground motions, with respect to the 2008 NSHM in some urbanized parts of the LVV. The most significant driver appears to be an elevated slip rate for the Eglington fault.

This study illustrates the considerable effect that potentially significant local fault sources can have on hazard projections. These results are not intended to be applied in design; rather they provide an urgent rationale for conducting detailed investigations of the LVVFS and nearby faults, to determine how they are best addressed in future versions of the NSHM (Lamichhane et al., 2013). The results also add impetus to improving earthquake monitoring and earthquake preparedness in the LVV.

2.11 Data and resources

The probability of an earthquake of M ≥ 6 within 50 km of Las Vegas in the next 100 years was calculated from U. S. Geological Survey (USGS, https://geohazards.usgs.gov/eqprob/2009/index.php, last accessed November 2011). GIS shape files for active faults in and around the Las Vegas Valley (LVV) as shown in Figure 2.1 were obtained from USGS (http://earthquake.usgs.gov/hazards/qfaults/, last accessed October 2011). The data for faults in and around the LVV, including data for Rock Valley, Yucca Mountain, West Spectra Range, Frenchman Mountain, Las Vegas Valley, and Eglington faults, were obtained from the USGS Quaternary fault and fold database website (http://earthquake.usgs.gov/hazards/qfaults/, last accessed June 2010). The earthquake data shown in Figure 2.2 were downloaded from the Advanced National Seismic System (ANSS; http://www.ncedc.org/anss/catalog-search.html, last accessed February 2013). The earthquake data used in the Figure 2.4 are also based on the ANSS
website, plus data provided by Nevada Seismological Laboratory (Kenneth D. Smith, personal comm., 2011). Definition of different fault classes are based on USGS (http://earthquake.usgs.gov/hazards/qfaults/glossary.php, last accessed March 2012). The NGA Flatfile ground motion data that were used to develop the NGA models were downloaded from Pacific Earthquake Engineering Research Center (PEER; http://peer.berkeley.edu/nga/flatfile.html, last accessed August 2011). The report on the PSHA results for different cities (including Las Vegas) from EZ-FRISK, used in this study as software validation, is available from EZ-FRISK (http://www.ez-frisk.com/Website%20Summary%20EZ-FRISK%20ver.%207.3.pdf, last accessed August 2010). All other data used in this paper came from published sources listed in the references. Charts and data calculations were performed using Microsoft Excel (2007). Figures were plotted using ArcGIS (v. 9.3). Seismic hazard computations were performed using the computer program EZFRISK (v. 7.62) and contour maps were created using ArcGIS (v. 9.3).

2.12 Paper-specific acknowledgements

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### 2.13 Tables

Table 2.1  Fault sources considered in this study, sorted by distance.

<table>
<thead>
<tr>
<th>No.</th>
<th>Fault Name</th>
<th>Distance (km)</th>
<th>Maximum magnitude ((M_w))</th>
<th>Slip Sense</th>
<th>Dip angle</th>
<th>Slip rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cashman†,‡</td>
<td>2</td>
<td>6.81</td>
<td>Normal</td>
<td>60°</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>Valley View†,‡</td>
<td>4</td>
<td>6.81</td>
<td>Normal</td>
<td>60°</td>
<td>0.1</td>
</tr>
<tr>
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<td>Strike-Slip</td>
<td>90°</td>
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</table>

*Approximate straight-line distance of the nearest point of the surface trace of the fault from the reference location at the approximate geographic center of the Las Vegas Valley.
†These faults, plus the West Charleston fault, form the Las Vegas Valley Fault System.
‡These faults are not included in the 2008 National Seismic Hazard Model (NSHM; Petersen et al., 2008).
§Some of the parameters for these faults have been modified with respect to the NSHM as discussed in the text.
Table 2.2 Comparison of accelerations computed by this study and by the National Seismic Hazard Model (NSHM) for the reference location (36.15° N and 115.15° W).

<table>
<thead>
<tr>
<th>Spectral period (s)</th>
<th>Acceleration for 2% PE in 50 years (g)</th>
<th>Acceleration for 10% PE in 50 years (g)</th>
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<td>NSHM</td>
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<td>0.01(PGA)</td>
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<td>0.2</td>
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<td>1.0</td>
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Figure 2.1 a) Selected faults around the Las Vegas Valley (LVV), characterized by activity, taken from the USGS Quaternary fault and fold database; the four added regional faults are identified. b) Faults inside or near the LVV; the added four Las Vegas Valley Fault System (LVVFS) faults are identified: WMF – Whitney Mesa Fault, VVF – Valley View Fault, CF – Cashman Fault, and DF – Decatur Fault. “Class B” faults are those of the LVVFS that were not included in the 2008 USGS model.
Figure 2.2 Seismic activity (≥ M4.0) within 200 km of the Las Vegas Valley during the period 1898 to December, 2012. The circle represents the region within 200 km of the Las Vegas Valley.
Figure 2.3 The maximum magnitude of the faults included in this study as a function of distance from the reference location. Faults included in the 2008 NSHM (squares) are distinguished from those that have been added in this study (diamonds). The symbols with heavy outlines represent strike-slip faults; the rest represent normal faults.
Figure 2.4 Cumulative frequency of depth distribution of all earthquakes $M \geq 0.4$ (1898-2012) in the Las Vegas Valley (boundary delineated for this purpose by $35.9^\circ$N to $36.4^\circ$N, $-114.9^\circ$E to $-115.4^\circ$E). Earthquake data are from ANSS and Nevada Seismological Laboratory.
Figure 2.5 Earthquake activity rate for the eight faults that were added and the two faults properties were modified with respect to the 2008 NSHM.
Figure 2.6 Attenuation of peak horizontal acceleration with distance, predicted for a hypothetical rock site condition with VS(30) of 760 m/s, for M 7.5 (solid lines) and M 6 (dashed lines) for a normal fault. Five ground motion prediction equations (GMPEs) were used: AS08, BA08, CB08, CY08, and SEA99. The heavier, black curves represent the geometric means of the five GMPEs.
Figure 2.7 Excerpt from the logic tree used to seed the Probabilistic Seismic Hazard Analysis (PSHA) computations, using the Cashman fault as an example. Values in parentheses represent the weights given to a particular branch.
Figure 2.8 Total hazard curves applicable to the reference location for nominal peak ground acceleration (PGA; ~0.01 s $S_a$), showing contributions from fault sources and gridded sources.
Figure 2.9 Total hazard curves applicable to the reference location for spectral acceleration ($S_a$) at nominal peak ground acceleration (PGA), 0.2 s, and 1.0 s. Values for 2% and 10% PE in 50 years are identified.
Figure 2.10 Uniform hazard spectra for the reference location. The discrete points represent values predicted by the 2008 USGS NSHM.
Figure 2.11 Grid points where PSHA was computed across the LVV. The reference location is indicated by the solid square.
Figure 2.12 PSHA results for nominal PGA at 2% PE in 50 years. The reference location is indicated by the black solid square. Faults, per USGS Quaternary fault and fold database, are also identified. The faults identified are as defined in Figure 2.1b.
Figure 2.13 PGA at (a) 2%, (b) 5%, and (c) 10% PE in 50 years. The faults identified are as defined in Figure 12.
Figure 2.14 0.2-s spectral acceleration at (a) 2% (b) 5% and (c) 10% PE in 50 years. The faults identified are as defined in Figure 12.
Figure 2.15 1.0-s spectral acceleration at (a) 2% (b) 5% and (c) 10% PE in 50 years. The faults identified are as defined in Figure 12.
Figure 2.16 Computed maximum and minimum acceleration values within the boundary of the Las Vegas Valley computed for 2%, 5%, and 10% PE in 50 years.
2.15 References


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CHAPTER 3

EVALUATING APPROACHES FOR DEVELOPING DESIGN GROUND MOTIONS AND THEIR EFFECTS ON DIFFERENT SEDIMENT COLUMNS: A STUDY IN LAS VEGAS VALLEY, NEVADA

Abstract

This research investigates the effects of different approaches to generate design earthquake ground motions (GMs; time histories and spectra), including unscaled real GMs, scaled real GMs, and spectrum-matched GMs, on earthquake site response computations; design ground motion can be defined as the ground motion specific to a site predicted at its surface, ready for use in structural design calculations. The GMs are matched to the same target spectrum (uniform hazard spectrum for a 2500-year return period) for a bridge site in Las Vegas Valley (LVV), Nevada, and one-dimensional site response analyses (equivalent-linear and non-linear) are performed. Three soil profile models are tested. The first model (profile 1) is representative of the bridge site and is deep (~400 m depth), and has a simple profile with gradually increasing shear wave velocity (VS) with depth with a VS30 of ~365 m/s. The second (profile 2) is a deep and complex profile, adding a 6-m thick high-velocity layer at ~30 m depth to profile 1. The third (profile 3) is a shallow and simple profile to a depth of ~30 m, which treats the high velocity layer of profile 2 as the model halfspace. Because the modifications to the profiles were made below 30 m, the VS30 (shear wave velocity over the top 30 m) of all three profiles remained constant. Results of the analyses using the three approaches to
generate design GMs for the three different models are comparable, although some differences are notable. The deep profiles (profiles 1 and 2) deamplified the short-period motions while amplifying long-period motions. The shallow profile (profile 3) predicts the highest amplification for all cases, mainly at shorter periods. This outcome indicates that considering only the top 30 m of the sediment can significantly over-predict the response, mainly at shorter periods. In general, amplifications are greater and differences among the three approaches to generate design GMs are greater for the equivalent-linear than for the nonlinear approach.

3.1 Introduction

This study evaluates the effects of three approaches to generate input earthquake ground-motion (GM; time histories and spectra) – unscaled real GMs set, scaled real GMs set, and spectrum-matched wavelet-adjusted GM – on one-dimensional geotechnical site response analyses. In this chapter the GM represents the time histories (acceleration, velocity and displacement) and their respective response spectra. Nonlinear dynamic analysis of structures is used to study their seismic response. This kind of analysis requires seismic ground-motion input, not just in terms of peak ground accelerations but also in the form of acceleration time histories that are representative of a target spectrum that is compatible with the combined effect of the seismic hazard and site conditions.

Several options are available to obtain GMs that match the target spectrum: set (suite) of unscaled real GMs, a set of scaled real GMs, one or more synthetically created/artificial GMs, and one or more spectrum-matched wavelet-adjusted GMs. Much research has been conducted to study the application of these different approaches to
structural response, primarily in terms of bias of response spectra from different approaches to generate GMs with respect to an unscaled record set (for example, Iervolino et al., 2006; Luco and Bazzurro, 2007; Hancock et al., 2008, Iervolino et al., 2010; Heo et al., 2011). However, little research has been conducted to understand the effects of these different approaches on geotechnical site response. This study does not look into the effects of these GMs on structural response, but rather looks into their effects on site response. This study investigates effects of three approaches of generating design GMs – unscaled real GM set, scaled GM set and a single, spectrum-matched wavelet-adjusted GM – on one-dimensional site response. (This research does not address fully synthetic / artificial GMs.) Focusing on a bridge site in Las Vegas Valley (LVV), Nevada, this research assesses whether or not the spectrum-matched GM is suitable for the purpose of site response analysis. Site response analyses in this study are performed using both equivalent-linear and nonlinear methods. This study compares approaches mainly in terms of response spectra with respect to the unscaled GM set for the study site. As a sensitivity study of effects on different site profiles, two hypothetical profiles, related to the site profile, were produced and the responses on all three profiles were analyzed. The outcome of this chapter guides the approach to produce design ground motions used in Chapter 4.

Seismic codes for different countries advise similar general guidelines. Most suggest selection of ground motions based on spectral compatibility with a design spectrum (Watson-Lamprey, 2007). ASCE 7-10 (ASCE, 2010) allows use of either recorded or simulated ground motions as long as they are compatible with the design spectrum. AASTHO LRFD bridge design specification (AASHTO, 2010) allows recorded,
simulated, and time-domain spectrum-matched ground motions that are compatible with the target spectrum. A summary of different design codes for the U.S. can be found in NIST (2011).

A conventional method to produce a site-specific GM includes the following processes: 1) seismic hazard analysis to predict bedrock motions, 2) producing a target (bedrock) response spectrum, 3) computing or selecting input GMs compatible with the target spectrum, and 4) 1-D site-specific response analysis to account for energy transmission from bedrock through the sediment column, which produces surface GMs. Each step of this process is discussed in detail in this chapter. Surface GMs are produced, using the three approaches mentioned earlier, for the site of an existing bridge (G-953) in the LVV. These surface GMs are intended to be used by structural engineers at the University of Nevada Las Vegas and Nevada Department of Transportation in nonlinear analyses of structural performance of the bridge, Therefore, they are referred to hereafter as “design GMs”.

Bridge G-953 is located at the crossing of W Carey Avenue (overpass) and I-15 (underpass; latitude 36.2034083 and longitude -115.1347167). This bridge is one of 20 considered to be at high risk in Clark County, Nevada, based on seismic risk assessment with weighted components of vulnerability and importance (Ebrahimpour et al. 2007). It has a risk score of 0.843, risk score 1 being the highest risk. The bridge is ~150 m long and is curved in both horizontal and vertical directions (Saad, 2009). More information on the bridge can be found in Saad (2009). Saad (2009) analyzed five bridges including bridge G-953 using a non-linear static procedure, also called "pushover analysis".
3.2 Methodology

Design response spectra are produced to represent the anticipated earthquake load within a certain period of time; for example, a return period of 2,500 years. Basically, two main approaches have been followed for decades (e.g. Kalkan and Chopra, 2010) – deterministic seismic hazard approach (DSHA) and probabilistic seismic hazard approach (PSHA). In DSHA, given earthquake magnitude (M) and distance from the study site (R) for discrete events, ground motion parameters are estimated. The M-R pair that estimates the most severe ground motion is selected as the design scenario event and is used in the selection of the ground motions. In PSHA, uniform hazard spectra (UHS) are produced based on all relevant combinations of multiple M-R pairs for the period of interest. For this study, the latter approach of PSHA was implemented.

3.2.1 Seismic hazard analysis

The PSHA was performed using EZ-FRISK v. 7.43. The inputs are the same as used by Lamichhane et al. (2014). PSHA was performed to produce results for 2% probability of exceedance (PE) in 50 years, which is equivalent to 2,500-year return period. The peak ground acceleration (PGA) for the site was calculated to be 0.41g (Figure 3.1). Unlike DSHA, PSHA does not address a single earthquake in terms of magnitude and distance. Therefore, deaggregation of the hazard was performed to identify the mean M and R of the controlling earthquake. The deaggregation displays the relative contribution to the seismic hazard of different seismic sources, primarily in terms of M, R, and epsilon (ε) (Bazzurro and Cornell, 1999); where ε is the deviation of the probabilistic response spectrum from the median ground motion in terms of standard deviation. Deaggregation
allows the identification of scenario earthquakes to approximate the probabilistic hazard. The deaggregation of the hazard at short period (0.01 s) showed that most of the contributions were from events of ~M6.25 to ~M6.75 at distances between ~5 and ~15 km, with mean M of 6.45 and a mean R of 6.4 km (Figure 3.2a). Deaggregation at long period (4.0 s; Figure 3.2b) also showed the highest contribution from nearby earthquakes, and in addition it showed a contribution from strong, distant events. At both short and long periods, the highest contribution was from the Eglington fault. The Eglington fault is a southeast-dipping normal fault located in the northwestern part of the LVV that has potential to generate an earthquake up to M6.5 (Taylor et al., 2010).

The PSHA results provide ground motion parameters (e.g., PGA, spectral acceleration [Sa] ordinates) predicted at a hypothetical bedrock outcrop that has an averaged shear wave velocity within the top 30 m (VS30) of 760 m/s, which corresponds to the boundary between B “Rock” and C “Very dense soil and soft rock” site conditions per the National Earthquake Hazard Reduction Program (NEHRP) provision (Building Seismic Safety Council, 2003). These results do not account for ground conditions where bedrock does not outcrop and therefore a site-response analysis is required, subsequent to selection/computation of bedrock (“input”) earthquake ground-motions, to account for the effect of the sediments at the site.

3.2.2 Target spectrum

A target spectrum (sometimes referred as design response spectrum) can be derived from a scenario event using one or more ground motion prediction equations (GMPEs), from PSHA by computing the UHS for a particular return period (essentially by
considering a full suite of scenario events), or by adopting a design spectrum from a code provision (Kottke and Rathje, 2008). The scenario event can be taken as the controlling earthquake from deaggregation of the hazard. UHS from PSHA is the most commonly used target spectrum (Jayaram et al., 2011); this represents a spectrum of accelerations with respect to period that are exceeded at a particular rate. The UHS factors weighted contributions from all earthquakes thought to be relevant, and thus different parts of the UHS will be controlled by different earthquakes. Therefore, no single earthquake’s spectrum will match the UHS. In this study, spectra were produced from two methods – UHS from PSHA and GMPEs applied to a scenario earthquake. Based on the deaggregation of the hazard, a M6.5 earthquake on the Eglington fault (distance ~7 km) was selected as the deterministic scenario case. For GMPEs, the same set of GMPEs that was used to produce the PSHA presented in Lamichhane et al. (2014) was used. Results are shown in Fig. 3.3. The UHS was selected as our target spectrum for conservatism, as UHS produced a higher hazard than did the mean from the deterministic scenario. This outcome is not unexpected because a spectrum from a deterministic scenario is due to a single event while a spectrum from PSHA is from multiple events, including the one modeled in the deterministic scenario.

### 3.3 Selection of input ground motions

Idriss (1993) listed some procedures or methods used to select and develop input earthquake GMs. The first method uses motions previously recorded at the site during similar size earthquakes and at distances comparable to those under consideration. But this method is impractical because of the lack of needed recorded motions at the site. The
second method uses simulation, starting with the source and propagating the appropriate waveforms through an earth model to generate an acceleration time history; this is called an artificial or synthetic GM. The third method includes estimation of a target spectrum and then selection of GMs whose spectral ordinates are comparable to those of the design target spectrum in the period range of interest. This method has been the most used by far, and as such it has been included in the ASCE 7-10 (ASCE, 2010) and is also being used in this study. The selected GM(s) can be either recorded (natural) or synthetic. The use of natural GMs is preferred over synthetic ones because synthetic ones tend to have an excessive number of cycles of strong motion, thereby presenting unreasonably high energy content (Hancock et al., 2006). Additionally, artificial ground motions tend to be unrealistic when the UHS is strongly influenced by more than one source of seismicity (Bommer and Acevedo, 2004).

A suite of GM records is selected such that the mean matches the target spectrum. The required minimum number of GM records in the suite is important but is not well standardized. Idriss (1993) and FEMA-356 (ASCE, 2000) suggest using at least three, while ASCE 7-10 provisions (ASCE, 2010) requires at least seven. UBC (1994) requires that if less than seven GMs are used then the maximum response must be used; otherwise, the average-response may be used. Hancock et al. (2008) analyzed the response of an 8-story multiple-degree-of-freedom reinforced-concrete structure using five different scaling and matching procedures. They concluded that the required number of GM varies among the damage measures and scaling methods. In our study, suites of seven GMs were used. The following defines different GM characteristics that could affect the GM selection, and then briefly discusses the factors that affect those characteristics.
3.3.1 Ground-motion parameters relevant to selection of ground motions

Many parameters are used to characterize strong ground motion. Three that are important for engineering purposes are amplitude, frequency content, and duration (Kramer, 1996). Kavazanjian et al. (1998) pointed out that energy content is also useful in selecting time histories for geotechnical analysis, and is also important for seismic deformation analysis. Among various measures of energy content available, Arias Intensity (AI) is the most widely used (Hancock, 2006). AI is defined as the integral of the square of the amplitude of ground acceleration over the duration. AI is usually plotted as a function of time to form the Husid plot. The slope of the Husid plot describes the rate at which energy is released. The level of damage of structures has been related to the total energy of the GM and the rate at which it is released: Bommer et al. (1997) considered two earthquakes in El Salvador occurring four years apart that released almost the same amount of energy but had very different effects, and found that the one that caused much more destruction and damage than the other had a higher rate of energy release.

3.3.1.1 Amplitude of ground motion

Peak ground acceleration (PGA) is the most common index used to represent the amplitude of the strong motion. However, peak ground velocity (PGV) and peak ground displacement (PGD) are also important. PGA is the absolute maximum amplitude of acceleration in an acceleration time history. The maximum equivalent lateral force applied to a very stiff, short-period structure is equal to PGA times the mass of the structure. PGA alone generally does not directly depict degree of damage because a high-frequency short-duration GM and a low-frequency long-duration GM having the same
PGA could produce very different responses, and therefore other amplitude parameters must be considered as well (Acevedo, 2003).

Given the acceleration time history, the velocity time history can be calculated by integration of the acceleration time history. Further integration will produce the displacement time history. Figure 3.4 shows an arbitrarily selected, measured acceleration time history, with corresponding, computed velocity and displacement time histories. PGA is generally associated with higher frequency components of the ground motion. PGV is less sensitive to the higher frequency components of an earthquake motion and therefore is suited to characterize intermediate frequency motion. PGD controls the low-frequency or long-period component of the motion (Kramer, 1996). PGD controls structural displacements at long periods and hence is related to damage.

3.3.1.2 Frequency content (spectral response)

The dynamic response of a geotechnical site or a structure is highly dependent upon the frequency content of earthquake motion. When the frequency of the ground motion approaches the natural frequency of the site/structure, the site/structure will resonate, resulting in amplification of the motion. A response spectrum represents the peak response (acceleration, velocity or displacement) of a single-degree-of-freedom system to a particular input motion as function of natural frequency for a given damping ratio; a 5% damping ratio was used throughout this study. The acceleration response spectrum is most often used. The frequency content is generally described by the shape and amplitude of the response spectrum. The shape of a response spectrum is strongly controlled by earthquake magnitude. A small magnitude event produces a narrow spectrum, while a
strong magnitude event produces a wider spectrum. Dynamic responses of structures depend on the frequency content of the motion. Mexico City suffered huge damage due to the 1985 Michoacán earthquake (M8.1), ~360 km away, due to long period (1- to 2-s) ground motions that resonated with 10 to 20-story buildings and the basin sediments, causing collapse of buildings and claiming thousands of lives (Kramer, 1996).

3.3.1.3 Duration

The moment magnitude of an earthquake is directly proportional to the area of the fault rupture (Kramer, 1996). The larger the rupture area, the more time it requires for rupture, and hence the longer the duration of the GM. Thus, duration is related to the magnitude of an event. Duration also depends on distance between source and site because of spatial differences in wave propagation velocities and scattering, but the dependence is much less (Bommer and Acevedo, 2004). According to Bommer and Acevedo (2004), in general, duration increases by about 0.6 s for every 10 km distance.

Many different definitions of ground-motion duration are used (Bommer and Martínez-Pereira, 1999) and a brief view of some of them is presented here. “Bracketed duration” is defined as the time elapsed between the first and last excursions of a specified threshold level of acceleration; therefore, bracketed duration depends on the specified threshold acceleration. Similar to bracketed duration, “uniform duration” is the sum of time intervals when the ground motion exceeds that threshold. “Significant duration” is defined as the time interval over which some proportion, for example 5-95% of the total energy (usually represented in terms of AI) of the GM is accumulated.
As was discussed earlier, seismic response is not only dependent on the amplitude but also on the duration of the GM. For example, a structure may show more damage from a medium amplitude-long duration GM than a high amplitude-short duration GM. Duration determines the number of cyclic loads during shaking, and plays a vital role in building up strains in the sediments. Additionally, the sediment stiffness and strength decrease and the material damping increase as the duration increases. Duration of motion is responsible for the generation of cyclic pore pressure in saturated sediments and is therefore related to the liquefaction susceptibility of the site (Kramer, 1996).

Duration is considered as a secondary criterion for selection of GMs for response analysis because it is directly controlled by magnitude and distance which are already taken as criteria (Katsanos et al., 2010). Duration of a GM is not readily captured by a response spectrum. Therefore magnitude and distance, from a DSHA or from a deaggregation of the PSHA, are used to find an appropriate duration. A reasonable estimate of duration can be calculated as a function of magnitude, distance and fault mechanism using GMPEs, for example see Bommer et al. (2009).

3.3.2 Factors that influence earthquake ground motions at a site

Proper selection of GM is critical. Thousands of recorded GMs are available. Selection of GMs includes screening many available records, selecting realistic GMs by considering key ground motion parameters, and comparing / matching them to a target spectrum. The ground-motion parameters used for this purpose in this research are: earthquake magnitude (M), source-to-site distance (R), PGA, and rupture mechanism. The following discusses the factors that affect the ground motion parameters, thereby
affecting and guiding the selection of the ground motions. The main factors that influence the ground motion parameters are the source, the path, and the site. (These are the key variables in GMPEs; e.g., Abrahamson and Silva, 2008.) For this research, these three factors are considered to quantify the parameters that are used to select input GMs.

3.3.2.1 Source

Source characteristics to consider for selection of ground-motion include magnitude, rupture mechanism, and directivity. The higher the magnitude, the higher the ground motion amplitude, and the longer the duration. Magnitude has a direct effect on the spectral shape of a ground motion (Bommer and Acevedo, 2004). Larger magnitude events yield wider response spectra, as stated earlier, and shift the predominant period to higher values (Kalkan and Chopra, 2010); where predominant period is the period corresponding to the peak spectral acceleration in an acceleration response spectrum. Strong earthquakes produce more low-frequency motions than small-magnitude events (Kramer, 1996).

Rupture mechanism addresses sense of slip – mainly strike-slip, dip-slip (normal or reverse) or a combination of both, oblique-slip. According to Bommer et al. (2003), ground motions from different rupture mechanisms differ mainly in terms of stress drop and radiation pattern. The authors argue that reverse-faulting events produce higher amplitudes of motion than strike-slip, especially at short and intermediate periods, while differences between ground motions from strike-slip and normal-faulting events are small, with the latter producing slightly lower amplitudes. The use of style-of-faulting in ground motion prediction equations remains a subject of debate (Bommer et al, 2003).
Rupture directivity can be important for the near-fault region. A forward directivity effect occurs when the direction of slip of the fault is aligned with the site and the rupture front propagates toward the site, and a backward directivity effect occurs when the front propagates away from the site (Somerville et al., 1997). For a given earthquake, the forward-directivity zone should experience a relatively short-duration, large-amplitude motion with a broad response spectrum, with respect to the backward-directivity zone which should experience a relatively long-duration, low-amplitude motion with a narrow response spectrum (Hancock, 2006; Somerville et al., 1997). A wise and practical design should consider rupture directivity effect for any site near a strike-slip fault.

3.3.2.2 Path

The path effect is governed by distance and regional tectonics. It describes attenuation of seismic waves as they propagate from source to site. A close-in site experiences relatively large-amplitude motion, while a distant site (with similar site condition) experiences low-amplitude motion. Bommer and Acevedo (2004) found that the source-to-site distance is less sensitive to the spectral shape than earthquake magnitude, but they also warned of the distance criterion being critical when GMs are selected from soft soil sites. The spectral shape can be modified at soft soil sites. Additionally, near-source rupture directivity has to be considered when the distance of the site to the source is small (Somerville et al., 1997). Source-to-site distance also affects the predominant period of the ground motion. Similar to magnitude, increasing the distance of the source to site shifts the predominant period of the spectral shape to longer values (Kalkan and Chopra, 2010). Regional tectonics affects the ground motions in
terms of GM attenuation, mainly because of stiffness and continuity of the bedrock crustal structure; for example, in general, ground motion in the western U.S. attenuates faster than it does in the eastern U.S. because the bedrock beneath the eastern US is stronger and more intact than in the western US (http://www.usgs.gov/newsroom/article.asp?ID=3447, last accessed December 2013).

3.3.2.3 Site

The third and final factor that could affect the selection of ground motion is site effect, which is governed by local geology and local sediment properties. The site is often represented in terms of VS30. The predominant period of a soil site is generally higher than that for a rock site, i.e. the predominant period increases with decreasing VS30 (Kalkan and Chopra, 2010). The local geology tends to alter GMs as they pass from bedrock to surface, in terms of amplitude and frequency content. Topography could also affect the GMs. A site near the edge of a valley could observe basin-edge effects. Some sites could observe reverberation effects, similar to those observed during the 1995 Kobe earthquake (Pitarka et al., 1998). Thickness of basin-fill sediment can also affect seismic response. Ghanat and Kavazanjian (2011) analyzed the Phoenix basin in Arizona using equivalent-linear and non-linear approaches and compared results to ground motion values established using the national seismic hazard map for reference rock-site conditions and NEHRP site factors. (NEHRP site factors are factors used to adjust for local site conditions based on VS30.) They found that site factors were not suitable to predict the response of either deep basin or shallow bedrock sites. For deep profiles, the response spectra using NEHRP site factors over-predict response at short periods because
the deep sediments filter the short period motions, and under-predict responses at long periods. Conversely, for shallow profiles (60 m thickness or less), the response spectra using NEHRP site factors under-predicted long period motions.

3.4 Unscaled real ground motion

This section discusses the selection of real unscaled GMs for the study site. The response spectral crests and troughs of real GMs can affect the nonlinear response of a structure. Therefore, ideally, unmodified real GMs should be used. As discussed earlier, the GMs are selected based on the design earthquake scenario including the effects of earthquake source, path, and site conditions. Considering all these, the Pacific Earthquake Engineering Research Center (PEER) database of strong motions (http://peer.berkeley.edu/smcat/search.html, last accessed March 2013) was searched for appropriate GMs. The GMs were selected based on the following four criteria: earthquake magnitude (M), source-to-site distance (R), PGA, and rupture mechanism. The deaggregation results (discussed in Section 3.2.1) were used to specify controlling magnitude and distance. The effectiveness of the use of M-R pair for selecting GMs for structural response has been questioned by some (for example, Iervolino and Cornell, 2005; Baker and Cornell, 2005). Nevertheless, the M-R pair has been widely used as the main criterion for selection of ground motions (e.g. Watson-Lamprey and Abrahamson, 2006). Ideally, ground motions selected should be from an earthquake of a magnitude that closely matches the scenario earthquake. Bommer and Acevedo (2004) proposed that the match between the record and the scenario magnitude be within 0.2 magnitude units. Haselton et al. (2009) studied effects of ground motion selection and modification
methods on response of buildings. The author provided examples where magnitude windows from ±0.2 to ±0.7 were accepted during selection of ground motion.

PGA and rupture mechanism can be considered for further refinement of the ground motions, provided an adequate number of records are identified that meet the criteria for M and R. Because the objective is to select GMs that match the target spectrum without scaling, the amplitude (either PGA or spectral acceleration) is key. The GM searches were narrowed down by defining a PGA window of mean ± 0.2 g, mean PGA being 0.42 g based on the UHS (Figure 3.1). As discussed earlier, different rupture mechanisms can produce different GMs. Almost no records from normal faults that fit our M-R and PGA criteria were available; therefore records from the western US for any fault mechanism were searched. Ground motions recorded in orthogonal directions at the same station during the same event are generated by the same wave field. Therefore, Kottke and Rathje (2008) recommend use of only one component of motion from one station for one event, and thus multiple ground motions from the same station and earthquake were not used. Few records were found where all of these criteria were met. Because of this, the magnitude window and the distance window were increased to ±0.5 and ±20 km, respectively. With these criteria, a GM library of about 70 GMs was formed.

The final level of screening was based on compatibility of the response spectra of the selected ground motions with the target spectrum so that the geometric mean response of the selected GM suite was well-matched to the target spectrum. After all the screenings, seven ground motion records were selected. Every possible combination of the 70 GMs that were compatible with the selection criteria was not checked, rather, the search ended when a combination that acceptably met the conditions was selected. Table 3.1 lists the
selected ground motions with descriptions. Appendix B shows the time histories (recorded acceleration plus computed velocity and displacement). The response spectra of the selected GMs are plotted in Figure 3.5 with respect to the target spectrum. Figure 3.6 shows the geometric mean response spectra of the seven selected GMs with respect to the target spectrum. The mean response spectrum of the selected GMs compares reasonably to the target spectrum, especially for periods 0.5 s and below; the maximum difference in that range is ~10% (at 0.1 s). The mean fits less well to the target spectrum at longer periods; a maximum difference of ~25% occurs at 0.75 s. Overall, the root-mean-square error is ~0.07. The 5-95% significant duration for the selected unscaled records ranged from 3.3 to 10.3 s and averaged ~7.7 s, whereas the significant duration for the Eglington fault scenario at the study site (M6.5, R~10 km) is ~8 s according to the GMPE of Bommer et al. (2009).

3.5    Scaled ground motion (using SigmaSpectra)

Scaling of a GM to match it to the target spectrum has been widely exercised among researchers and practitioners and is still being used. According to ASCE 7-10 (ASCE, 2010) for 2-D analysis of a structure, the average value of the 5% damped elastic response spectra of a scaled suite of ground motion should not be less than the design response spectra for periods between 0.2T and 1.5T where T is the fundamental period of the structure. Because of data sparsity, it is not always possible to get a good match for a GM set without scaling, and that is one important reason that scaling of GMs is still in use. Linear scaling methods apply a constant multiplier either to the amplitude or to the time step of a GM, thereby changing its amplitude or duration/frequency content,
respectively (Kramer, 1996). Because one important principle is that the scaled GM should retain the characteristics of a real GM, linear scaling to time axis of GM is discouraged, as it changes the frequency content and duration without altering the number of cycles and might produce an unrealistic motion (Bommer and Acevedo, 2004).

Scaling can be done in terms of different GM parameters. Scaling to PGA, PGV, a spectral acceleration and AI are some of them and each has pros and cons. Many studies have investigated whether linear scaling produces bias in structural response (e.g., Shome et al., 1998). Shome et al. (1998) modeled a five-degree-of-freedom steel structure to analyze the effect of scaling. They observed that scaling a ground motion such that the spectral acceleration at the fundamental period of the structure is equal to the target does not introduce bias when compared to suites of unscaled ground motions with the same average response spectra. Luco and Bazzurro (2007), analyzing expected nonlinear structural drift response of both single-degree-of-freedom and multi-degree-of-freedom buildings, demonstrated that scaling can introduce bias in the nonlinear response of structures and the bias increases with the degree of scaling / scale factor. The bias was quantified with respect to the response to unscaled records at the spectral acceleration of interest. They found that the bias depends on the fundamental period of the structure, the overall strength of the structure, and the characteristics of the earthquake GMs. ASCE 7-10 does not specify a limit for the scale factor, however it states that it is desirable that the scale factor be close to unity. Bommer and Acevedo (2004) recommended that the maximum scaling factor should range from 2 to 4, while Luco and Bazzurro (2007) stated that a scaling factor up to 10 is acceptable.
Different algorithms are available to select and scale GMs, for example Naeim et al. (2004) and Wang (2011). The approach used in this study is the method developed by Kottke and Rathje (2008) as embedded in the computer program “SigmaSpectra”. The method selects a suite of earthquake GMs from a library such that the median of the scaled suite matches a target response spectrum at all user-specified periods, and then the scaling factor is adjusted such that the standard deviation of the scaled suite agrees with the target standard deviation. To produce the GM library for SigmaSpectra, GMs that were compatible with the criteria presented above were selected. For scaling purposes, the PGA window is not a required criterion. But to keep the scaling factor close to 1, a PGA window was used as well, and because of this, the same GM library, consisting of 70 GMs, that was produced for the selection of unscaled GMs was used. During selection and scaling, the software was allowed to select multiple GMs from the same earthquake, but not from the same station. Figure 3.7 shows the response spectra of the GMs that were selected, after scaling to match the target spectrum. The matching was done over the entire range of periods shown (0.01 s to 10 s). Table 3.2 lists the selected ground motions for scaling with descriptions. The table also specifies the scaling factors (scaled linearly in amplitude). Appendix B includes the unscaled time histories (recorded acceleration plus computed velocity and displacement). The 5-95% significant duration for the selected scaled records ranged from 5.6 to 12.5 s (averaging about 9 s); compare to ~8 s, the significant duration for the Eglington fault scenario at the study site derived from the GMPE equation of Bommer et al. (2009). Figure 3.8 shows the mean response spectrum of the seven selected and scaled GMs, with respect to the target spectrum. The mean of
the scaled GM set matches closely to the target spectrum over the entire range of periods. The match is distinctly better than the match for the mean of unscaled GMs.

3.6   Wavelet-adjusted ground motion (using RspMatch2005)

An alternative to using multiple scaled or unscaled GMs to match a specified target spectrum is using a single spectral-matched GM. This approach has become commonly used among researchers (e.g. Grant, 2011; Heo et al., 2011). Methods of spectral matching in the frequency domain by adjustment to Fourier amplitude spectra are also available (for example, RASCAL [Silva, 1987]), but according to Hancock et al. (2006), this process can add unrealistically high energy content to the GMs. Although the frequency domain method can produce adequately matched time histories, it lacks good convergence, mainly for spectrum matched for more than one damping ratio (Takhirov et al., 2005); where convergence means matching of the adjusted ground motion within the requested tolerance. For instance, NIST (2011) considered convergence as a criterion for the selection of GMs and noted that GMs of longer duration may converge more easily and may require less modification. Hancock et al. (2006) claim that using multiple, scaled ground motions (to preserve the characteristics of real ground motions) is not required if the target spectrum is obtained from PSHA, for example a UHS, because the ground motion variability has already been incorporated into the PSHA-produced target spectrum. While the wavelet-adjusted approach to developing design GMs adds less energy to the seed GM than does the frequency-domain spectral-matching approach, it is advisable to check whether excessive modification has been made to the seed GM in any case (Hancock et al., 2006).
A widely used approach to computing spectral-matched GMs is the methodology proposed by Hancock et al. (2006) which is applied in the computer software RspMatch2005 (Ordóñez, 2012a). RspMatch2005 adds wave packages to parts of the time series at frequencies where there is a mismatch between the seed GM and target spectrum. It adds wavelets to the acceleration time history in the time domain, such that the frequency content and phasing of the real (seed) ground motion are altered to closely resemble the smooth target spectrum (Hancock et al., 2006). The spectrum-matched GM allows fewer records to be used to attain a robust estimate of the inelastic response (Hancock et al., 2008), but unlike scaled and unscaled GMs, a spectral-matched GM might alter frequency content and phase, which are fundamental physical characteristics of recorded motions. Hancock et al. (2008) claim that wavelet-adjusted spectrally matched ground motion using RspMatch2005 provides an effective compromise between use of a suite of unscaled, measured ground motions and a completely artificial, fully spectrum-compatible record to represent a target spectrum.

RspMatch2005 modifies a single “seed” acceleration time history so that its frequency spectrum nearly matches the target spectrum for a specified range of periods and for multiple, user-specified damping values. For this study, the seed GM was matched to the target spectrum over the entire period range of the spectrum (0.01s – 10s) for a single damping value of 5%. Different forms of wavelet adjustment are available. RspMatch2005 uses “sinusoidal corrected wavelets” that are added to the acceleration time history (Hancock et al., 2006). As recommended in the documentation for RspMatch2005 (Ordóñez, 2012a), further, “sinusoidal corrected displacement compatible wavelet” was specified, which ideally ensures that the final displacement does not add a
displacement drift; however, if there is not enough time at the end of the wavelet to apply a sinusoidal correction, the wavelet is baseline corrected (Hancock et al., 2006). The seed GM used to produce the spectral-matched GM was selected with a similar consideration as was discussed in Section 3.4. The seed GM, selected somewhat arbitrarily from the library described earlier, is from the Whittier Narrows earthquake (October 1, 1987 14:42), magnitude- M6.0, distance – ~12 km, downloaded from PEER database (WHITTIER/A-GRV330; Garvey Res. - Control Bldg., 330 [USGS Station 709]) with a peak acceleration of 0.46 g and ~25 s total duration time history. This is the first GM given in Table 3.1. Figure 3.9 shows the response spectra of the seed ground motion, target, and spectral-matched GM. Original (seed) and modified (spectral-matched) time histories of acceleration, velocity, and displacement are compared in Figure 3.10. The modified time histories do not look unrealistic and do not require baseline correction. The displacement time history of the modified GM however has high amplitudes with respect to the seed GM and might be important to displacement analysis for example for analysis of earth slope stability under seismic loading. The Husid plot permits comparing energy distribution (Fig. 3.11). The energy distribution within the adjusted GM is similar to the seed GM (within ~10 %); excessive energy has not been added. The maximum difference in Arias intensity between the GMs before and after the spectral matching was found to be about 10%. Also the bracketed duration of the GM did not undergo much change (~5% [6.3 s for seed and 6.6 s for modified]); however, the 5-95% significant duration increased by ~30%.

The seed GM for spectral matching was selected from a group of six, based on visual comparison of spectral-matched GM to seed GM in the time domain, the Husid plot, the
match of the spectral-matched GM to the target spectrum, and convergence. (One of the six GMs considered did not converge.)

3.7 Site response analysis

Ground surface motions on sediment are always different from those for bedrock. This is because sediments interact with the ground motion to amplify, or in some cases deamplify, the motion (e.g., Kramer, 1996). The main soil characteristics that affect the ground motion are: depth-dependent shear wave velocity (VS), density ($\rho$) and Poisson’s ratio ($\nu$); depth to the reference rock (thickness of the sediment column); and pressure/depth- and strain-dependent shear modulus (G) reduction and damping ($\xi$). A 1-D site response analysis uses these parameters and an anticipated bedrock ground motion as an input motion to simulate wave propagation through the sediment layers and calculate motion at the surface. So once the input ground motions are selected as described above, they are used as input motions in the site response models and GMs at the surface are computed. For suites of GMs, each GM is run through the site response analysis, and for spectrum-matched, only one analysis is performed.

Two approaches for site response analysis are commonly used: the frequency-domain equivalent-linear approach and the time-domain non-linear approach. The differences in theory behind these approaches can be found in many text books (for example, Kramer, 1996). The equivalent linear approach accounts for the non-linearity of soil response at large strains to some extent, but the non-linear approach more accurately simulates the cyclic stress-strain behavior of sediment under severe earthquake loading where induced strains are large (Hashash and Park, 2001). In this study, both equivalent linear analyses
using SHAKE2000 (Ordóñez, 2012b) and non-linear analyses using D-MOD2000 (Matasovic and Ordóñez, 2012) were carried out. Both were one-dimensional analyses. Due to complexity in defining different parameters for non-linear analysis, equivalent-linear (SHAKE) analysis is, arguably, more vetted in the research community than any non-linear analysis software. However, of the software programs for nonlinear earthquake site response analysis, DMOD is one of the most widely used (Hashash et al. 2010). All selected GMs – unscaled suite, scaled suite, and spectral-matched – were used as “within” input motions in SHAKE and DMOD, which means that the record will be applied at the base of the sediment column as-it-is and will not be modified, as opposed to “outcrop” motion in which deconvolution is performed to account for site conditions where it was recorded before applying it to the base of the sediment column (Ordóñez, 2012b). Any impacts of not deconvolving the GMs are not investigated here and are suggested for future study. The responses from the two approaches for the study site are compared. Development of the site response model for the study site is discussed in following section.

3.7.1 Study site parameterization

The VS profile for the site was derived based on the VS profiles from the nearby grid points of a three dimensional shear wave velocity model developed by the Applied Geophysics Center (AGC) at the University of Nevada Las Vegas (Murvosh et al., 2013). The model has VS values at grid spacing of 195 m east-west, 180 m north-south, and 1.35 m vertically across the LVV. To produce a VS profile for the study site, all the VS profiles from the model within 300 m of the site were considered; this distance is in
agreement with the “correlation distance” for VS to lithology used by Murvosh et al. (2013) to interpolate VS values in creating the model. Chapter 4 (section 4.4) will present in detail the procedure to produce the site response model, including VS profile, sediment lithology profile, dynamic material properties, depth to halfspace and density profile. Figure 3.12 shows “Profile 1”, the profile for the study site, having a VS30 of ~355 m/s and depth to halfspace of ~400 m. Figure 3.12 also shows unit weight, maximum shear modulus, and lithology profile of Profile 1. The "atm" and "ft" given in the lithology are the overburden pressure and depth to the middle of the layer, respectively, which were used to assign the dynamic material properties (modulus reduction and damping). Where the depth to the middle of the sediment layer is more than the maximum depth of the sediment for which dynamic curves exist, the dynamic curves for the greatest depth available were used. For example, the dynamic properties for sand for layers 4 and 5 are the same because the depths to the middle of the layer for both layers are more than the maximum depth of the dynamic curves used for sand.

As a sensitivity study of different VS profiles, two hypothetical profiles were produced and site response analyses were performed on them too. The second profile (Profile 2) is the same as Profile 1 except that a 6-m thick layer representing caliche was added at ~30 m depth below the second layer (Figure 3.13). To maintain the depth of the halfspace of Profile 2 the same as for Profile 1, the thickness of the layer below the caliche was decreased by 6 m. This hypothetical profile was produced because caliche is ubiquitous in the Las Vegas Valley. Caliche is cemented sediment and has high VS which occurs in lenses, thereby creating a velocity inversion. Analyses have shown that a velocity inversion can have significant effect on site response (for example, Di Giacomo
et al., 2005; Bordoni et al., 2011). We wanted to test whether the site response analyses would produce similar results for quite different profiles having the same VS30. The third profile – Profile 3 – has a shallow halfspace. The caliche layer of Profile 2 was made the model halfspace for Profile 3 and therefore the total depth to halfspace for this profile was only about ~30 m (Figure 3.14). The VS30 remains the same for all three profiles because the profiles vary only below 30 m. To summarize, three different profiles were analyzed -- a simple but deep profile (Profile 1), a complex and deep profile (Profile 2) and a simple shallow profile (Profile 3).

3.8 Results and discussion

The effects of the different approaches for generating design GMs on site response were compared in terms of the geometric mean of the spectral responses of each GM in the unscaled GM set and likewise for the scaled GM set, and spectral response of the single, spectrum-matched GM. The following discusses the results for the three approaches to generate design GMs, for the three profiles. Figures 3.15, 3.16, and 3.17 show the response spectra from the three approaches after 1-D site response analyses, both equivalent-linear (SHAKE2000) and nonlinear (DMOD2000), for Profiles 1, 2, and 3, respectively. In general, amplifications were greater for equivalent-linear than nonlinear analyses. Considering nonlinear response (Figures 3.15b, 3.16b and 3.17b), the design GMs from the three approaches produce fairly comparable results for all three profiles. But for equivalent-linear response (Figures 3.15a, 3.16a, and 3.17a), the design GMs from the three approaches produce somewhat different results: there is bias towards over-prediction of response from the spectral-matched GM approach with respect to the
other two approaches. (For comparisons, the response from the unscaled GM set is taken as the baseline.) In general, the scaled GM set over-predicts ground motions with respect to the unscaled set and the spectrum-matched GM over-predicts the ground motion even further.

In every case the unscaled GM set gives higher accelerations at long periods. The geometric mean of the unscaled GM set has consistently higher spectral ordinates than the target spectrum at long periods (Figure 3.6) whereas the match is good for the other two approaches (Figs. 3.8 and 3.9). The higher acceleration in the geometric mean of the unscaled GM set with respect to the target spectrum explains higher spectral acceleration in the design ground motions. Overall, for the study site, it seems to be acceptable to use any of the three approaches to generate design GMs for the purposes of site response.

For Profile 1 (simple deep profile), long-period motions were amplified and short-period motions (<~0.2s) were deamplified when analyzed using the nonlinear approach; when analyzed using the equivalent-linear approach, some amplifications were also observed at short periods (<~0.03s) including PGA (Fig. 3.15). For both analysis approaches, the peak spectral acceleration is shifted to a higher period. The same general observations apply for Profile 2 (complex deep profile), the main change being that both deamplification at short periods (0.01s – 0.2s) and amplification at long periods (>~0.5s) are stronger. In general, Profile 2 yielded higher peak acceleration than Profile 1. Profile 3 demonstrated much higher ground motion than the other two. The short-period motions, except at 0.05 s to 0.15 s, were amplified, which is in contrast to the results from the other two profiles. Similar to the results for profiles 1 and 2, the period corresponding to the peak spectral acceleration is shifted higher. For Profile 3 for all approaches to
generate GMs, the maximum spectral acceleration occurs at ~0.3 s, which is comparable to the predominant period of the site (~ 4H/VS = 120/VS30), which is as expected.

Figures 3.18, 3.19 and 3.20 show the same results as Figures 3.15, 3.16 and 3.17 but they are grouped according to approach for generating input GMs. These figures demonstrate that Profile 3 showed the highest peak spectral acceleration and PGA in all cases. This result is attributed to the relatively high VS and shallow depth of its halfspace (Figs. 3.12 through 3.14). The amount of energy reflected or transmitted at an interface depends on the impedance ratio of the materials on the either side of the interface, where impedance is the product of density and shear wave velocity. With a high impedance contrast at the halfspace, more energy is reflected and less is transmitted (Kramer, 1996). For a stiff layer, the upward-moving incoming energy might be reflected downward and never reach the surface (implying a potentially beneficial role of caliche in mitigating surface ground motions). But for a stiff halfspace, transmitted energy, having no opportunity for reflection, can get trapped above the stiff layer and reverberate. Profile 3 significantly amplified the short period motions (<0.5 s), while the longer period motions are slightly lower than from the other two profiles. In this case, considering only the top 30 m of the “true” sediment column (Profile 1) significantly over-predicts the response at periods to ~0.6 s. The peak spectral acceleration for Profile 3 was at least twice that of the input motion for equivalent-linear analysis. The smallest amplification in Profile 3 occurred with the unscaled GM set. Overall, the spectrum-matched GM showed lower amplification than the scaled GM set but slightly higher amplification than the unscaled GM set.
There are no major differences between results for profiles 1 and 2 for the equivalent-linear response analysis (Figures 3.18a, 3.19a, and 3.20a). However, for the non-linear response analysis, accelerations are lower for Profile 2 at short periods (<~0.5 s; Figures 3.18b, 3.19b, and 3.20b), indicating that insertion of the high-velocity layer at relatively shallow depth reduced ground motions for short periods. It appears that if high frequency response is significant, then a stiff layer at depth even shallower than 30 m could have a stronger impact than the one tested. This finding is consistent with Liu (2006) and Maresh et al. (2006), who found that cemented inclusions particularly affect high-frequency (short-period) response. Luke and Liu (2007) also observed that the impact of the cemented inclusion is depth-dependent and can deamplify or slightly amplify the surface motion.

The deep profiles (profiles 1 and 2) deamplified most of the short-period motions but amplified the long-period motions. This deamplification is expected as deeper sediments tend to filter the high-frequency components of ground motions. This finding is consistent with Toro and Silva (2001) who observed that thin soil columns strongly amplify high-frequency motions, while thick soil columns attenuate the high-frequency components of the ground motion and amplify the low-frequency motions. Ni et al. (1997) also found that shallow soil deposits produced larger surface amplification than did a deep soil deposit. On the other hand, the shallow profile (Profile 3) amplified the short-period motions in addition to the long-period motions. At long periods (>~0.6 s), all three profiles showed similar results for all input GMs. The variation of the results for the three profiles shows the effects the different profiles (mainly differences in VS) have in site response. Additionally, the fact that the three profiles have the same VS30 but
different ground surface motions demonstrates that using only the top 30 m of a profile could misrepresent the site response.

3.9 Conclusions

A comparison of site responses was performed using three approaches to generate design GMs, as inputs to the site-response analyses. One approach was based on selecting a set of real, unscaled GMs to match a target spectrum. Another was based on selecting a set of real GMs, then scaling them to match the target spectrum (using the program SigmaSpectra). Both of these sets contain seven GMs. The other approach is a single, wavelet-adjusted spectrum-matched ground motion (using the program RspMatch2005). GMs from the three approaches were matched to the same target spectrum, the uniform hazard spectrum for 2% PE in 50 years predicted at the study site. A bridge site in Las Vegas Valley, Nevada was studied. Deaggregation of the hazard from PSHA provided the magnitude and distance for the controlling event, which, in this case, was on the Eglington fault.

A best-representation of the study site (Profile 1) and two related, hypothetical profiles were analyzed. Profile 1 is deep (depth to halfspace ~400 m), with VS gradually increasing with depth. Profile 2 is similar to Profile 1 except that it models a 6-m thick caliche layer at ~30 m depth. Profile 3 is shallow, having its halfspace at the top of caliche layer of Profile 2. Because the modifications to the profiles were made below 30 m, the VS30 of all three profiles was identical. All of the GMs from the three approaches were used as input into site response analyses of all three profiles. Site response analyses were performed using a 1-D equivalent-linear approach and a 1-D non-linear approach.
The resulting response spectra indicated fairly comparable results for nonlinear response. The main difference was in the spectral-matched GM that slightly over-predicted the ground motion for equivalent-linear response with respect to the other two. Based on the results, applicable to a particular site in the LVV and two related hypothetical profiles, it seems acceptable to use any of the three approaches to generate input ground motion considered in this study. Thus, considering time saved and ease of conducting the spectral matching, it may be a feasible choice to use spectral matched ground motion for site response analyses.

Profile 3 predicted the highest spectral acceleration by far in all cases, which implies that considering only the top 30 m of the sediment column for Profile 1 or 2 could significantly over-predict response. Profiles 2 and 3 showed similar results for equivalent-linear analysis, but for non-linear response analysis, Profile 2 showed lower spectral ordinates, meaning that insertion of a high-velocity layer at a relatively shallow depth (~30 m) decreased ground-motion amplification, mainly at short periods. Both the deep profiles (Profiles 1 and 2) deamplified short-period motions. Significant differences between results from the three profiles demonstrate that VS30 does not always adequately represent site response.

The analyses presented herein are for a single set of ground motions. Different input ground motions that have a similar response spectrum may still produce different responses (Kramer et al., 2012). Additionally, a different choice of GM for spectral matching might produce a different conclusion. Further studies are recommended to compare the findings of this study to other choices of ground motions and for other profiles.
### Table 3.1  Unscaled ground motion properties

<table>
<thead>
<tr>
<th>Name</th>
<th>Magnitude</th>
<th>Distance (km)</th>
<th>PGA (g)</th>
<th>Event and Recording Station</th>
</tr>
</thead>
<tbody>
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<td>A-GRV330</td>
<td>6.0</td>
<td>12.1</td>
<td>0.456</td>
<td>Whittier Narrows 10/01/87 14:42; Garvey Res. - Control Bldg., 330 (USGS Station 709)</td>
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<tr>
<td>A-ZAK360</td>
<td>6.2</td>
<td>18.7</td>
<td>0.400</td>
<td>Chalfant Valley 07/21/1986 14:42; Zack Brothers Ranch, 360 (CDMG Station 54428)</td>
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<tr>
<td>B-PTS225</td>
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<td>D-OLC360</td>
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<td>Coalinga 7/22/1983 02:39; Oil City, 360 (USGS Station 1604)</td>
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<tr>
<td>H-E06230</td>
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<td>1.0</td>
<td>0.438</td>
<td>Imperial Valley 10/15/1979 23:16; El Centro Array#6, 230 (CDMG Station 942)</td>
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<tr>
<td>I-CVK180</td>
<td>6.3</td>
<td>9.0</td>
<td>0.441</td>
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<tr>
<td>STG000</td>
<td>6.9</td>
<td>13.0</td>
<td>0.512</td>
<td>Loma Prieta 10/18/1989 00:05; Saratoga -Aloha Ave, 000 (CDMG 58065)</td>
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</table>

### Table 3.2  Scaled ground motion properties and scale factors applied

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<tr>
<th>Name</th>
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<th>PGA (g)</th>
<th>Scale factor</th>
<th>Event and Recording Station</th>
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<td>H-E06140</td>
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<td>LOB000</td>
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<td>STG090</td>
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<td>Loma Prieta 10/18/89 00:05; Saratoga Aloha Ave, 090 (CDMG Station 58065)</td>
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CHAPTER 4

HOW WOULD THE LAS VEGAS VALLEY, NEVADA SEDIMENTS RESPOND TO STRONG EARTHQUAKE SHAKING?

Abstract

One-dimensional site response analysis, equivalent-linear and nonlinear, has been performed for the Las Vegas Valley (LVV), Nevada for two earthquake scenarios – a close-in earthquake on the Eglington fault and a distant earthquake on the Garlock fault. These scenarios were chosen based on deaggregation of seismic hazard from a probabilistic seismic hazard analysis for a hypothetical bedrock outcrop. Site response calculations were performed for 45 target site response grid points (TSRGP) across the LVV at a spacing of ~5 km. Sediment columns for the TSRGPs were derived from existing 3-D shear wave velocity (VS) and lithology models for the LVV. Spectral ratios at 0.01, 0.2, 0.5, and 1.0 s periods were calculated and contour maps of amplification factors were produced. Results show that there is significant variability in seismic response of the sediments across the LVV, even without considering basin reverberations and near-fault effects. The results show that seismic waves would be amplified in most portions of the LVV basin as they pass through it. Amplifications increase on average with increasing period for both scenarios. Overall, amplifications are highest in the southern and western part of the LVV. For the Eglington scenario, the patterns of ground motion are similar to the input motion, indicating that the responses of sites to this scenario are overwhelmed by the strong, near-field input motion. For the Garlock
earthquake scenario, higher ground motions are observed along the western and southern margins of the Valley, which are dominated by shallow coarse-grained sediments. Amplifications are lower for places dominated by fine-grained sediments with thick sediment columns and higher for places dominated by coarse-grained sediments with relatively thin sediment columns. This result does not correlate well with the pattern of weak ground motions that have been recorded in the LVV during distant earthquakes. This mismatch implies that site response in the LVV is not only a function of sediment properties that can be modeled by 1-D analyses, it is also significantly affected by three-dimensional reverberation of energy and basin-edge effects, which can be expected to further amplify ground motions. There are a number of uncertainties in the analyses presented; perhaps the most significant pertain to the depth to the halfspace and its VS. Still, the research demonstrates that despite the mismatch and the uncertainties, sediment response plays an important role in earthquake site response across the Las Vegas Valley.

4.1 Introduction

It has long been recognized that earthquake ground motions can be significantly amplified by sediment deposits, with large amplification occurring where layers of low shear wave velocity (VS) overlie material with high VS, i.e. where soft sediments cover bedrock or stiff soils. The soil deposit, according to its properties, amplifies energy at some frequencies, deamplifies at others or may not affect energy at all at some frequencies. In most cases, the spectral amplitude of the earthquake motion at bedrock is modified as the energy travels through the sediment layers and reaches the surface, a process which is called site response. Amplification of ground motions is usually caused by two phenomena: impedance and resonance. Impedance causes amplification due to a
decrease in VS as the ground motion passes from a high stiffness material, such as rock, to a low stiffness material, such as clay. Resonance is observed when the natural period of a soil deposit is similar to the predominant period of the ground motion. The nonlinear characteristics of sediment tend to cause decrease in stiffness (causing amplification) and increase in damping (causing deamplification) with increasing strain; the overall effect might sometime cause amplification and other times cause deamplification. The process of building a model to characterize the site and analyzing its response (primarily 1-D) is used to predict ground motion given a specific input motion at the base of a sediment column (typically at the bedrock surface; Kramer, 1996). Other factors that can be important in earthquake site response include near-fault effects and three-dimensional effects such as those caused by reverberation of energy around a basin.

This research is specific to 1-D site response analyses for the Las Vegas Valley, Nevada, which is situated atop a deep, sediment-filled basin. Energy diffracted from the edge of a basin can interfere constructively with the primary S-wave propagating upward from the bottom of the basin, a phenomenon called basin-edge effect, thereby amplifying ground motions (Pitarka et al. 1998). Another factor that is important in earthquake site response in a sediment-filled basin is trapping of body waves in the basin sediments, causing some incident body waves to scatter and propagate through the sediment as surface waves, thereby producing stronger shaking at the surface and a longer duration of motion (Kramer, 1996). The amplification pattern observed during the 1995 Kobe, Japan earthquake (M6.9) is an example of the combined effects of response through the sediment column and basin-edge scattering, which resulted in the loss of over 6400 lives. The basin-edge effect is most pronounced for earthquakes on faults that form an edge of a
basin (Pitarka et al., 1998). The LVV is at risk for both threats. 1-D response of sediment columns is investigated in this study but phenomena that require 2-D and 3-D analyses are beyond the scope of this study.

The Las Vegas Valley (LVV) is located near the southern tip of the State of Nevada and is the setting of the cities of Las Vegas, Henderson, and North Las Vegas as well as unincorporated lands that are also developed. Considering the potential for significant life and financial losses due to earthquakes in an urban area that houses ~2 million people, understanding the seismic response of the LVV is important. Recent research shows that there are at least five Quaternary faults within the LVV basin that are capable of producing earthquakes of magnitude up to ~M6.5 to 6.8 (the Eglington, Cashman, Decatur, Whitney Mesa, and Valley View faults, which are referred to jointly as the Las Vegas Valley fault system) (dePolo, 2006).

Distant strong earthquakes on large faults in southern California, primarily the Death Valley and Garlock faults, also threaten the LVV. Distant earthquakes can cause tremendous damage in certain situations. The 1985 Michoacán earthquake (M8.1), although it originated nearly 360 km away from Mexico City, Mexico incurred extensive losses there due to long period (1 to 2 s) ground motions that resonated with 10 to 20-story buildings and the soft lakebed sediments, causing many buildings to collapse and claiming thousands of lives (Kramer, 1996).

4.2 Background and previous studies

Analyses from previous nearby earthquakes and explosions have helped researchers study seismic response of the LVV. Murphy and Hewlett (1975) performed a preliminary seismic microzonation of the LVV. They investigated seismic responses observed during
six historical underground nuclear test events conducted about 120 km away at the Nevada Test Site, now called the Nevada National Security Site. Considering ground motions recorded at 26 different locations in the LVV, they produced contour maps of spectral ratios in 12 different frequency bands covering the period range from 0.16 to 6.0 s, where spectral ratio is defined as the ratio of amplitude of the response spectrum of the motion observed on a soil site with respect to the motion on bedrock. They found that most parts of the basin amplified ground motions by a factor of 2 with respect to a reference site, over a frequency range of 0.2 to 1 Hz. The reference site is ideally an intact rock site but theirs was well within the basin, not on bedrock, and therefore, the amplification factors might be underestimated. The authors demonstrated a correlation between long-period seismic response and sediment thickness in the LVV. They made note that measured response might have been affected by surface waves that were reflected back from the Valley boundaries, at the base of the surrounding mountain ranges.

Su et al. (1998) investigated site response across the LVV by examining ground motion data recorded during the 1992 Little Skull Mountain earthquake (LSM; ~M5.6) which occurred about 100 km northwest of the LVV. They reported an average amplification factor of 5 with respect to a representative near-rock motion, over 0.5 to 2 Hz. The representative near-rock motion was calculated as an average of responses recorded at two near-rock sites, one each on the eastern and western edges of the LVV. They found that the duration of strong shaking was significantly increased in sediment sites with respect to rock sites, and they attributed this to basin-induced reverberation of surface waves. Using synthetic ground motions, they predicted that an M7.4 earthquake
on the Death Valley fault system, about 150 km from LVV, would produce average peak accelerations from 0.058 to 0.13 g at rock sites and from 0.051 to 0.22 g at alluvium sites. As would be expected, the predicted amplification factors for this larger, more distant event were lower than values observed for the LSM earthquake.

McCallen et al. (2003) used historical recordings of nuclear explosions and the LSM earthquake to calculate amplification factors in the LVV. They found band-averaged amplifications in some locations with respect to a reference rock outcrop recording up to a factor of ten over 0.2 to 2 Hz. They found higher amplification factors where the basin is deep. As will be discussed later, “basin depth” refers to the depth to Mesozoic or Paleozoic rock (Figure 4.1); this depth is greatest in the north-central part of the LVV and much less in the western LVV.

Similarly, Rodgers et al. (2006) studied historical ground motion datasets from nuclear explosions and earthquakes in the LVV, and carried out two-dimensional elastic finite difference modeling to study site response. They found variable ground motion amplification across the Valley with site-averaged amplification factors up to 10 at some frequencies. They found higher amplifications correlated with greater basin depth (> 1 km; this covers the central and northern part of the LVV; Figure 4.1) and lower amplifications where basin depth was less than 1 km, which covers the western part of the LVV.

Luke and Liu (2007, 2008) developed an earthquake microzonation map of the LVV based on site response projections that were performed using a lithologic and shear wave velocity database and 1-D equivalent-linear analyses using the computer program SHAKE. The authors selected the 10 known Latest Quaternary faults (moved in the past
15,000 years) within 150 km of the Valley as potential seismic sources and performed multiple deterministic seismic hazard analyses. Their analyses showed amplification factors for deep soil sites over the period range 0.3 to 5 s as high as 10. Their study also showed that site response projections based on VS30 (VS averaged over the upper 30 meters) can underestimate the surface motion; inclusion of strata below 30 m can significantly affect the accuracy of the response predictions. The authors demonstrated that the 1-D equivalent-linear model adequately captured the response of higher frequency ground motions (> 5 Hz); however, it did not accurately model low frequency response.

Tkalčić et al. (2008) studied teleseismic data from 12 earthquakes around the world to analyze differential travel-time of seismic waves across the LVV. They reported site response from the teleseismic earthquakes and compared it with published results from regional earthquakes. They observed no significant variation across the LVV. They reported spectral peaks between 0.4 and 0.5 Hz, meaning that the LVV basin's resonance frequency is in this range. They found good agreement between the two results (teleseismic vs. regional) within the frequency band 0.2-1.0 Hz. They therefore concluded that ground-surface amplification is independent of the nature of incident energy (horizontally propagating regional waves vs. vertically propagating teleseismic waves).

Flinchum et al. (2014) used a finite-difference code to compute wave propagation through a spatially extensive 3-D earth model of the LVV and its surroundings. They used an extensive dataset of VS measurements across the LVV (>10,000 measurements, also considered in this research; discussed in more detail later) as input into their model
in addition to the detailed basin-floor depth model of the LVV (Figure 4.1). They simulated the LSM earthquake and compared predicted results to observed data. At 0.1 Hz, predicted and measured peak ground velocities matched within a factor of two. However, duration of the shaking was not matched.

The approach in this study is to produce site-response models for a number of gridded sites in the LVV (where “site-response model” is defined as the set of geotechnical, geophysical and geological characteristics of a site that are used to analyze the response of the site to earthquake ground motions), based on current understanding of the lithology and VS of the LVV sediments, and apply them in computations to simulate response to a nearby (in-basin) moderate earthquake and a distant strong earthquake.

4.3 Geological setting of the basin underlying the Las Vegas Valley

The LVV, bounded by mountain ranges, is about 30 km wide (E-W) and 40 km long (N-S). Langenheim et al. (2001) studied the geometry of the LVV basin using gravity and seismic-reflection methods, and reported that the basin is deep and complex in shape. They found that the maximum depth of basin-fill sediments over bedrock (Paleozoic or Mesozoic, 145 million years and older) approaches 5 km, with the deepest part occurring in the northeast quadrant of the basin, approximately 5 km west of Frenchman Mountain which bounds the LVV on the east (Figure 4.1). Shallow bedrock occurs around the margins of the basin. Bedrock gradients are smallest (bedrock is shallowest) to the west and south in the LVV, and highest to the east.

Taylor et al. (2008) developed a 3-D sediment-lithology geometric model of the basin stratigraphy and structure from a database of approximately 1400 well logs, averaging
171 m deep, primarily from Nevada Division of Water Resources archives, supplemented with data from air photos, maps and direct field observations. The lithology model was developed under the auspices of the Applied Geophysics Center (AGC) at the University of Nevada Las Vegas (UNLV). The bedrock surface forming the basin is mostly Paleozoic in age, but some parts are Mesozoic (Figure 4.1); in this research, the term "bedrock" applies to this Paleozoic/Mesozoic surface, even though stiff, indurated sediments can occur above this surface. In the model, the LVV basin fill (above bedrock) is divided into two sub-basins – upper and lower.

Figure 4.2 shows a model of the upper surface of the lower basin. The lower basin fill consists of sedimentary rock (e.g. limestone, sandstone) and volcanic units that correlate to the Horse Springs formation and the Muddy Creek formation, of Oligocene- and Miocene-age, deposited 5.3 to 33.9 million years ago (Taylor et al., 2008). The volcanic units most likely were erupted from local source areas in the River Mountains and McCullough Range or are air fall tuffs (wind-blown ash) from more distant sources. Such indurated sediments would be considered rock for engineering purposes.

The upper basin consists of Quaternary and Pliocene sediments deposited within the last 2.6 million years and extends as deep as 1 km (Taylor et al., 2008; Figure 4.3). Deeper sediments of the upper basin (> ~ 400 m) have high VS (1100 m/s according to Murvosh et al., 2013), again constituting “rock” for engineering purposes. The 3-D lithology model demonstrated that coarse and mixed grain-size deposits dominate the shallower, western part of the basin fill, while clay sediments dominate the deeper, central and south parts. Coarse and fine grained deposits interfinger at their interfaces. Lenses of heavily carbonate-cemented fines, sand and/or gravel, locally called caliche,
occur at various depths and can have thickness of up to 2 m or more (Taylor et al., 2008). Caliche constitutes “rock” for engineering purposes, with VS exceeding 1500 m/s in some cases (Tecle et al., 2003). The stiffness contrast and velocity inversion due to the presence of high-velocity caliche between layers of soft sediments is shown to impact site response (Luke and Liu, 2007).

Louie et al. (2012) measured VS30 in much of the developed parts of the Las Vegas Valley. Most of the VS30 values fit National Earthquake Hazard Reduction Program (NEHRP) site classes C (“very dense soil and soft rock”) and D (“stiff soil”). The authors introduced a “C+” class for sites with Class B (“rock”) average velocities (VS30 = 760 m/s) but soft surface soil. The boundary is complex between site classes “C” and “D”, but it is clear between “C” and “C+”, along the western boundary of the LVV, apparently conforming to alluvial fan edges.

4.4 Site-response models

The characteristics of sediments that govern their response to seismic loading are shear stiffness, damping ratio and mass density. The dynamic behavior of sediment subjected to strong shaking is nonlinear; both the stiffness and damping vary nonlinearly with shear strain. A key component in site response analysis is proper selection of the site-response model parameters for each layer. A sediment profile is described by layers based on sediment type, VS, density and dynamic curves. Another factor that affects the site response is the profile depth to halfspace, which fixes the bottom of the sediment profile and is the depth where the input motion for the 1-D analysis is applied.
Input motion is the ground motion (amplitude of acceleration with respect to time) expected at the halfspace of the site (often considered to be bedrock). Chapter 3 discussed and evaluated approaches to select design ground motions from real ground motions measured elsewhere, including (1) a suite of unscaled ground motions, (2) a suite of scaled ground motions, and (3) a single, spectrum-matched ground motion. For the cases tested, it was found that the wavelet-adjusted spectrum-matched ground motion resulted in acceleration response spectra that are reasonably comparable to the unscaled and scaled ground motion suites. Considering this finding and the time saved by adopting the spectral-matching methodology, in this study the input motion is developed using a wavelet-adjusted spectrum matching procedure using the commercial software RspMatch2005 (Ordóñez, 2012). In this procedure, the acceleration-response spectrum of a single ground motion was modified to match the target spectrum. The target spectrum is developed based primarily on the magnitude and distance of the scenario earthquake to the site (discussed more in Section 4.5).

The following sub-sections discuss development of 1-D site-response models for the sites to be analyzed, which include layer geometry and shear wave velocity, density, lithology and dynamic properties (strain-dependent shear modulus and damping functions) for each layer.

4.4.1 Depth to halfspace

The sediment thickness or the depth to halfspace (modeled as bedrock) used in a site-response model affects the response of a site. A deep sediment column can amplify long-period ground motions more than short-period motions. In general, the predominant period increases with increasing sediment-column depth (e.g. Toro and Silva, 2001), and
therefore selecting a too-shallow halfspace depth can mistakenly provide a shorter predominant period. Ideally, the depth to halfspace is the depth to bedrock. For the LVV, the depth to bedrock is poorly understood, though it is known to be large in places (Luke and Liu, 2007). Therefore, for the LVV, selection of depth to the halfspace is a challenging task. This sub-section discusses the effects of depth to halfspace on site response and then describes assignment of depths and VS values for halfspaces used in this study.

For hypothetical sediment columns with thicknesses of 20, 50, 100 and 200 m, using a 1-D nonlinear approach (DESRA2), Ni et al. (1997) observed that the depth to the bedrock halfspace significantly affects the resonant frequency of the site, but the amplitudes of acceleration response spectra did not change much for deeper deposits (100 m vs. 200 m). The authors found lower surface amplification in the deep soil deposits than in the shallow deposits. They also found, for a 100 m sediment column, that stronger shaking at the base of the sediment column produces larger deamplification and a lower resonant frequency than does weaker shaking.

In a study of seismic hazard and site response in Saint Louis, Missouri and Memphis, Tennessee, Toro and Silva (2001) found that thin soil columns (< ~30 m) amplify high-frequency motions, while thick soil columns (to ~ 900 m) attenuate high-frequency motions and amplify low-frequency motions. Consistent with Ni et al. (1997), they found that for a shallow profile, increasing the shaking levels from weaker to stronger shifts the site resonance to a lower frequency. They concluded that the thickness of the soil column has a significant effect on the site response.
Hashash and Park (2001) used nonlinear 1-D analysis to estimate ground-motion amplification and attenuation for deep sediments of the Mississippi embayment. They analyzed three soil columns, 100, 500 and 1000 m deep, using depth-dependent modulus and damping properties for the sediments (accounting for the influence of confining pressure). Their analysis of amplification factors for the different depth models showed that deeper soil columns show greater amplification of long-period components, which is consistent with the findings of Toro and Silva (2001) and Ni et al. (1997). They concluded that long-period waves are developed at greater depths and therefore, cutting off the sediment column above bedrock might produce less long-period amplification than is realistic and yield a too-short predominant period. Therefore, the authors recommended using the entire depth of the soil column in the model. Luke and Liu (2007) pointed out that using the entire depth of the soil column as recommended by Hashash and Park (2001) is challenging for the LVV model because of variable sediment lithology to great depths and poorly constrained dynamic properties (including VS) at depth.

Luke et al. (2001) studied site response for sandy soil deposits to ~350 m depth, and found that for soil profiles much deeper than 100 m, setting the halfspace at the bedrock surface would cause excessive attenuation and unrealistic shifts to longer periods. For the cases studied, the authors recommended that the halfspace be placed within the soil profile, well above the bedrock interface. They investigated the influence of shallow sediments on site response for a 1-km-deep alluvial column in the LVV, subjected to weak ground motions. From this study they recommended that the depth to halfspace be selected so that the projected peak ground acceleration (PGA) matches its target.
Using an equivalent-linear approach, Luke and Liu (2007) tested three models to place the depth to halfspace for two sites in the LVV: placing the halfspace: 1) at the estimated soil-bedrock interface; 2) at the "engineering bedrock" interface, based on a threshold VS of 760 m/s; and 3) within the sediment column by matching characteristics of projected surface response to measured data or expectations (the approach recommended by Luke et al. (2001)). They considered different metrics when comparing ground motions including PGA, peak spectral acceleration (Sa), predominant period, and acceleration spectrum intensity (ASI). The authors considered weak (low amplitude, small strain) input ground motions recorded on the study sites from four nuclear test events at Nevada Test Site/Nevada National Security Site (event yields from 20 to 150 kt, corresponding to body wave magnitudes of 5.0 – 5.9) with a maximum PGA in the LVV of ~1 cm/s² (~0.001 g). Based on matching the one-dimensional, small-strain parametric computations of the ground shaking to the weak-motion recordings, the preferred depth-to-model-halfspace was found to be ~400 m. For the cases tested, option 3 produced better results than the other two.

Current code-based practices, for example the NEHRP Provisions (Building Seismic Safety Council, 2003), use VS30 as a criterion for seismic site classification, which, in turn, is a predictor for site amplification. VS30 is also used in the Next Generation Attenuation (NGA) ground-motion prediction equations (e.g., Boore and Atkinson, 2008) to incorporate site effects. Some NGA models additionally use depth criteria. For example, Abrahamson and Silva (2008) use depth to "engineering bedrock", defined as the depth where VS reaches 1,000 m/s, to distinguish between "shallow soil sites" with engineering bedrock depth < 200 m and "deep soil sites" otherwise. The site response
computations presented in Chapter 3 demonstrated that site response can vary significantly for different profiles having the same VS30 and subjected to the same input ground motion. In this study, 1-D site response analyses for deep sediments use halfspace defined to intermediate depth, following recommendations of Luke and Liu (2007), rather than full depth.

In conjunction with the 3-D model of sediment lithology, Murvosh et al. (2013) developed a 3-D model of VS for the Las Vegas Valley, under the auspices of the AGC at UNLV (Figure 4.4; discussed further in Section 4.4.2). VS profiles for this research are derived from that 3-D VS model. Murvosh et al. (2013) use the same boundaries for Paleozoic/Mesozoic bedrock and Oligocene/Miocene lower basin that were described earlier. The authors divided the upper basin into shallow and intermediate zones (Figure 4.3). The shallow zone extends to a maximum depth of 370 m (shallower if bedrock is encountered above that depth) and the intermediate zone from 370 m to the top of the lower basin, a maximum depth of 1 km. The VS is modeled in 3-D only in the shallow zone. The maximum depth of the shallow zone is set based on data availability (Murvosh et al., 2013) and approximates the 400-m depth to halfspace for 1-D earthquake site response analyses recommended by Luke and Liu (2007). The intermediate zone, lower basin and bedrock are assigned constant VS values of 1100, 1500 and 2600 m/s, respectively; note that 1500 m/s is the site class A/B boundary per the NEHRP provisions, and 1100 m/s is close to the midpoint VS for Site Class B per the NEHRP provisions (1130 m/s; Building Seismic Safety Council, 2003).

Neither the intermediate zone nor the lower basin extends Valley-wide (Figure 4.3). In this research, for grid points where the sediment column thickness is less than 370 m,
the halfspace was fixed at its base, and the VS of the halfspace was assigned as 1500 m/s for sites where the lower basin was present and 2600 m/s (representing Mesozoic/Paleozoic bedrock) otherwise. For grid points where sediment columns were thicker than 370 m, the halfspace was placed at 370 m (top of the intermediate zone) with VS = 1100 m/s.

Figure 4.5 shows a contoured map of depth to halfspace used in this study, based on values assigned at each grid point. Numerous points around the perimeter of the grid have thin sediment columns (depth < 30 m). At places with thin sediment columns, the VS30 can be high due to effect of bedrock. For sites having VS30 > 760 m/s (NEHRP site class B, “rock”) (Appendix C, Table C.1; Figure 4.5), the effect of the sediment was considered to be negligible and those sites were excluded from site response analysis; amplification factors for ground surface motions with respect to bedrock were fixed at 1 for all frequencies.

4.4.2 Shear-wave velocity profiles

The 3-D VS model has VS data at grid spacings of 195 m east-west, 180 m north-south, and 1.35 m vertically (Figure 4.6). The shallow zone, the only part of the VS model that has velocities interpolated in 3-D, is expected to have the most significant effect on the response of a site to earthquake ground shaking. The VS for the shallow zone is based on more than 200 measured VS profiles (Figure 4.7a) and 1400 lithologic well logs (Figure 4.7b); the lithology well logs are the same that were used to create the complementary 3-D sediment lithology model. The VS was interpolated across the model using depth-dependent correlations of VS with sediment type (Luke et al., 2009). A
characteristic VS profile for each of five sediment units – clay, sand, gravel, mixed, and cemented – was produced. To better inform the VS interpolation, at each well location, sediment units were correlated to the characteristic VS value at the appropriate depth (Murvosh et al., 2013). A view of the model’s surface demonstrates strong lateral variability in VS (Figure 4.4); therefore variability in site response is anticipated.

The 3-D VS model was used to produce a GIS database of VS for use in the site response analyses. To facilitate computations and because the shallow zone (where VS varies in 3-D) ends at 370 m, the VS profiles were truncated at 400 m depth below ground surface.

The grid contains 80 points (hereafter called target site response grid points - TSRGPs). It is anchored at the mid-valley reference location described in Chapter 2. Grid points are spaced at 0.05 degrees, ~5 km. This study analyzed site response at 45 of the grid points. (Appendix C, Table C.1 and Figure 4.5 identify the 35 TSRGPs where site response analysis was not performed.) These TSRGPs were ranked as primary, secondary and tertiary; the ranks were created to prioritize analyses. Primary TSRGPs are located around the center of the LVV (covering the deeper sediment deposits), secondary TSRGPs are in the outer portions of the LVV (covering shallow to intermediate-depth sediment deposits), and tertiary TSRGPs are at the edges, with very shallow sediments (Figure 4.5). The TSRGPs for which no analysis was conducted are unranked. Appendix C presents the coordinates of all TSRGPs.

The 3-D VS model has some limitations that affect VS profiles for the TSRGPs. The data coverage is not spatially uniform; density is lowest in the western and northeastern part of the LVV due to lack of both VS measurements and catalogued lithology data.
(Figure 4.7). Additionally, most VS profiles used to create the model are shallower than 100 m; therefore, model accuracy decreases with depth along with the decrease in data density. On the other hand, the tendency for lateral variation in VS logically decreases at greater depth, because different sediments at greater depths tend to be subjected to the same high confining pressures. Other limitations of the model relate to uncertainty associated with correlating VS to lithology, and uncertainty in the VS measurements and lithology interpretations. Murvosh et al. (2013) pointed out that surface-wave measurements, which were used to generate most of the VS profiles used to create the model, could overestimate VS at the Valley fringes due to the influence of shallow bedrock. This potential problem is most relevant in the western part of the Valley where the dip of the bedrock is shallowest.

Another set of VS data available was an extensive dataset of VS30, herein called the Optim dataset, after the company Optim SDS which was contracted by local government entities to determine seismic site class over about 1300 square kilometers including much of the developed portions of the Las Vegas Valley and beyond (Figure 4.8; Louie et al., 2012). The dataset consists of over 10,000 VS profiles, at a density of one per 36 acres (0.146 km$^2$), created using the Refraction Microtremor (ReMi) technique. This technique uses passive source energy (ambient noise) collected along linear arrays. The city of North Las Vegas is not covered by the Optim data. Only VS30 values from the Optim dataset were available at the time this research was started, although the full VS profiles became publically available later.

The following sub-sections describe the procedure that was used to produce the VS profiles for the TSRGPs. Section 4.4.2.1 discusses how VS profiles were derived from
the 3-D VS model. Section 4.4.2.2 discusses comparison of the VS profiles with the Optim data. Section 4.4.2.3 discusses the procedure for revision of VS profiles to honor the VS30 data, where necessary.

4.4.2.1 Producing VS profiles from the 3-D VS model

The following discussion pertains only to the subset of 45 TSRGPs for which site response analyses were conducted. The TSRGPs do not coincide with the 3-D models’ (VS and sediment lithology) grid. To produce a VS profile for a TSRGP, all VS profiles from the 3-D VS model within 300 m of the TSRGP were considered. This distance is in agreement with the correlation distance for VS to lithology used by Murvosh et al. (2013) in creating the 3-D VS model. The 3-D lithology model was also used in producing the VS models, to identify layer boundaries and assign sediment lithologies to layers. The lithology profile for each TSRGP was provided to the author by Jeff Wagoner (Lawrence Livermore National Laboratory) by extraction from the 3-D sediment lithology model (Taylor et al., 2008). Because of the lack of alignment of the two grids, TSRGPs 73-76, along the southern boundary, were more than 300 m from any VS or sediment-lithology data (Figure 4.6), so the search range for VS profiles and lithology was extended to 900 m and 500 m respectively.

A simplified stepped VS profile (hereafter called Stepped-VS) was produced for each TSRGP based on all nearby VS profiles from the 3-D VS model. “Stepped” refers to a profile having discrete layers, each with single-valued VS. The Stepped-VS profile for each site was selected visually from the arithmetic average of all the nearby VS profiles from the 3-D model (about 8), balancing the areas between the arithmetic average curve
and the stepped-VS profile on either side of the stepped-VS profile. The following points were also considered:

1) Because the resolution for VS decreases with depth, layer thickness increased with increasing depth.

2) Where VS increased consistently with depth, layer boundaries were chosen such that the difference in VS between adjacent layers was ~ 50 m/s.

3) In some cases, it was found that the depth to the Paleozoic/Mesozoic bedrock in the 3-D VS model did not match that of the 3-D sediment-lithology model. In such cases, the sediment-lithology profile was used to select the depth to halfspace.

4) The VS30 for the stepped-VS profile was calculated and compared to the VS30 from the 3-D VS model and the Optim data within 300 m. Similar VS30 from all sources would lend confidence to the Stepped-VS model.

An example is presented for TSRGP 25. Figure 4.9 shows the eight VS profiles from the 3-D VS model that are within 300 m of the site; their locations are shown in 4.10. The curve labeled “Average” in Figure 4.9 is the arithmetic average of the eight nearby VS profiles from the 3-D VS model, from which the “Stepped-VS” profile is derived. VS30 values from the Stepped-VS profile, the average from the 3-D VS model, and the average from the two Optim measurements that are within 300 m of the TSRGP are 570, 530 and 520 m/s, respectively. The VS30 value from the average of the Optim measurements differs by ~10% from that of the Stepped-VS, and ~2% from that of the 3-D VS model average.
The 3-D VS model contains a large, broad velocity inversion at great depth (VS ~ 400 m/s over ~ 50 m, at > ~ 250 m depth). This condition appears in the deeper sediments (TSRGPs 18, 21, 22, 23, 26, 27 and 46; Figure 4.5). TSRGP 46 illustrates (Figure 4.11). At such depths it is unrealistic and unreasonable to have such a low VS. The local sediment-lithology and measured VS profiles that were used to create the 3-D lithology and VS models were checked but the cause for inversion was not apparent. This irregularity in the 3-D VS model remains to be investigated. Therefore, the deep velocity inversion was deemed implausible and the affected Stepped-VS profiles were revised to bypass the VS inversion by extending the VS of the overlying layer down to the next layer having higher VS (Figure 4.11).

4.4.2.2 Comparison of VS30 values from 3-D VS model against Optim dataset

To compare VS30 values from the 3-D VS model with the Optim dataset, a contour map showing differences in percentage was produced (Figure 4.12). Contour maps for VS30 of the Optim data and the 3-D VS model were first produced separately and then the difference in percentage between the two was computed using the "Raster Calculator" tool in the Geostatistical Analyst Toolbox of ArcGIS v. 10.1. Figure 4.12 also identifies the lithology wells and measured VS locations used in the 3-D VS model according to measurement method – crosshole, downhole, REMI or SASW. Figure 4.12 also shows the TSRGPs. Differences are low (generally less than 25%) where VS measurements were incorporated in the 3-D VS model, except in the northwest part of the Valley. Differences are small in much of the area, however, the 3-D VS model predicts higher
VS30 than the Optim data show in much of the north and east, and the opposite is true in the west.

Significant discrepancies, defined as where the 3-D model produced VS30 more than 50% higher than Optim data, are observed at 9 TSRGPs (TSRGPs 6, 7, 12, 14, 20, 23, 24, 27, and 30). The Stepped-VS profiles for those nine TSRGPs were revised, as explained next. (There was no TSRGP where the 3-D model produced VS30 more than 50% lower than Optim data.)

4.4.2.3 Revision of nine VS profiles to honor VS30 measurements

For the nine TSRGPs having too-high VS30 with respect to measurements, VS values in the upper 30 m were scaled by a constant factor so that VS30 of the VS profile matched the average of all VS30 values measured within 300 m of the TSRGP (usually two).

To transition back to the original Stepped-VS model, the scaling factor was adjusted in the 30 - 60 m depth range, in two, ~15-m thick increments. Existing layer boundaries close to a transition depth (within ~2 m of 30, 45 or 60 m depths) were honored. In general, the scaling factors were increased equally in the two transition layers. The scaling factors by which VS was increased in each layer with respect to the Stepped VS were 0.6 for 5 of the revised TSRGPs, 0.75 for two TSRGPs, and 0.55 and 0.7 for one each TSRGP. The smaller the scaling factor, the greater the difference between the measured data and the model.

This methodology is illustrated using TSRGP 7, which has the highest difference between data and model among all the TSRGPs. TSRGP 7 is located in the northwest
(Figure 4.5). Figure 4.13 shows the surroundings of TSRGP 7, including VS30 values from the 3-D VS model and the Optim dataset. No measured VS from the VS model or lithology log locations exist within 300 m, but both exist within 600 m. Figure 4.14 shows the surrounding VS profiles (1 through 7 and nearest) from the 3-D VS model and Optim VS30 values (Optim1 through Optim4), all within 300 m. The VS profile “Average” and “Stepped-VS” are as defined earlier and the “Final VS” is the revised (scaled) profile. The VS30 from the Stepped-VS profile was 668 m/s, approximately equal to the average VS30 from the 3-D model, whereas the Optim VS30 values measured nearby average ~80% lower, 374 m/s. To accommodate this discrepancy, all layer velocities in the upper 30 m of the “Final VS” profile are scaled by 0.55 to reach VS30 of 374 m/s. One layer was added to form two transition layers between 30 - 60 m, the layer boundary being at mid-depth, 45 m. The scaling factor increased to 0.7 for the 30-45 m transition layer and to 0.85 for the 45-60 m layer. The Stepped-VS profile is honored below 60 m.

The VS profile for the nearest VS measurement used in the 3-D VS model (Station LMNVSS1; Murvosh, 2011, Table A.5, Page 153) is also shown in Figure 4.14. The VS30 of this profile, which is from an SASW measurement, is 371 m/s, which is consistent with Optim data in the area. This situation indicates a possible error in computation of the 3-D VS model, which remains to be investigated. A comparison of “LMNVSS1 VS” and “Final VS” profiles supports the claim that the latter is a reasonable VS profile for this area except in the upper 10 m. The cause and effect of the difference has not yet been investigated.
Appendix D shows the VS profiles produced for all the TSRGPs for which site response analyses were conducted. The profiles are grouped into primary, secondary and tertiary TSRGPs. Note that the primary TSRGPs are deeper than the other two and secondary TSRGPs are deeper than tertiary TSRGPs.

4.4.3 Density profiles (density-versus-depth models)

Density (ρ) and VS define the maximum shear stiffness \( G_{\text{max}} \) of a sediment \( G_{\text{max}} = \rho V_S^2 \). The shear stiffness affects the response of the sediment to earthquake ground motion. Therefore, density of the sediment is a relevant parameter in the site-response model, although the effect of VS is more pronounced than that of density. In cases where density data are not readily available, different studies have used different approaches.

Some researchers have applied constant values for density based on similar local sediments. Luke et al. (2001) reviewed different density values available for alluvium at a landfill site within Yucca Flat of the Nevada Test Site/Nevada National Security Site, which is located ~90 km NW of Las Vegas. The authors used a constant density of 1680 kg/m\(^3\) for the upper 97 m of alluvium and 1770 kg/m\(^3\) below 97 m to bedrock at a depth of ~400 m. In a site response study of the LVV, Liu (2006) used a constant value of 1700 kg/m\(^3\) for density of sediments (clay, sand and gravel, dry and wet), which is approximately the average of what Luke et al. (2001) used for the Yucca Flat site. Liu used a density of 2200 kg/m\(^3\) for cemented material (caliche).

Some researchers calculated density from relationships of density to VS or compression wave velocity (VP) published in the literature (for example, Kaklamanos et al., 2013, Boore and Joyner, 1997; Gardner et al., 1974; and Brocher, 2005).
In the absence of site-specific field geotechnical data for the Valley basin-fill sediments for TSRGs, VS-to-density relations recommended by Boore (2007) were used for this study.

The process is as follows (Boore, 2007):

- For VS < 0.3 km/s, $\rho = 1.93 \text{ g/cm}^3$
- For VS between 0.3 km/s and 3.55 km/s:
  - Compute VP from VS (Brocher, 2005):
    \[
    VP = 0.9409 + 2.0947VS - 0.8206(VS)^2 + 0.2683(VS)^3 - 0.0251(VS)^4,
    \]
    where VP and VS are in (km/s); and
  - Then compute density from VP (Gardner et al., 1974):
    \[
    \rho = 1.74 (VP)^{0.25}, \text{ where } \rho \text{ is density in g/cm}^3.
    \]

Densities calculated following Boore (2007) were consistently higher (~15%) than those used by Liu (2006). For the reference location (TSRGP 18), the calculated densities varied from 2040 kg/m$^3$ at the surface (VS = 560 m/s) to 2200 kg/m$^3$ for the halfspace (VS = 1100 m/s).

4.4.4 Dynamic sediment properties

The ideal approach to produce dynamic sediment properties for a site response analysis is to measure them in the laboratory on site-specific samples. But in the absence of site-specific dynamic properties, published dynamic property curves according to sediment type (for example, EPRI, 1993; Darendeli, 2001) are used.

The following shear modulus reduction and damping curves were chosen:
• Clay: Shear modulus reduction and damping curves by Darendeli (2001) were used to represent the dynamic properties of clay (Figure 4.15). Dynamic properties of clay vary according to many factors such as the plasticity index (PI) and confining pressure. Darendeli (2001) produced dynamic curves for clays with different PI (0%, 15%, 30%, 50% and 100%) and also for different confining pressures (0.25, 1, 4 and 16 atm). The soil samples that the author tested were mostly (~76%) from California, and from a depth range of 3 to 300 m. Clay of mild plasticity (15%) was chosen to represent the clay sediment in the LVV, based on statistical analysis of a limited dataset (312 measurements irrespective of location within the LVV or depth) from the Clark County, Nevada Electronic Submission of Geotechnical Investigation database (obtained indirectly from Jonathan Bahr; Figure 4.16). Luke and Liu (2007) used PI = 15 for clayey deposits of the LVV when modeling site response of deep sediments. Pressure-dependent dynamic curves appropriate to confining pressure computed at the middles of individual layers were selected. For all cases where the confining pressure is more than 16 atm, the curves for 16 atm were used. The maximum confining pressure calculated for clay in the site-response models developed in this study was ~70 atm at a depth of ~350 m, which is ~4 times that at 16 atm. This lack of well-suited dynamic curves is a shortcoming of this research which remains for further study.

• Sand: Depth-dependent curves from EPRI (1993) for “cohesionless soil” were used to represent dynamic properties of sand (Figure 4.17a). The authors tested material at pressures representative of different depths (0-6, 6-15, 15-36, 36-75,
and 75-150 m). Therefore, similar to clay, pressure-dependent dynamic curves appropriate to confining pressure computed at the middles of layers were used in this research. For cases where the calculated depth to the middle of the layer is more than 150 m, the curves for 75-150 m were used. The maximum depth calculated for sand in the site-response models developed in this study was ~320 m. Ni et al. (1997) analyzed the effects of depth-dependency of dynamic curves on site response of sand columns varying in thickness from 20 m to 200 m and found that use of depth-dependent curves yields larger amplitude surface response than use of stress-independent curves.

- **Gravel:** The author is not aware of any depth/pressure-dependent curves for gravel. Comparison of depth/pressure-independent dynamic curves for gravel from Seed et al. (1986) and Rollins et al. (1998) shows higher shear modulus and lower damping for the latter (Figure 4.17b). A sensitivity analysis was performed to determine the effect of choice of curves on the spectral response (presented in Appendix E). Results indicated that curves from Rollins et al. (1998) predicted higher spectral acceleration than those from Seed et al. (1986). Therefore, for conservatism, dynamic curves by Rollins et al. (1998) were used for gravel sediments.

- **Rock:** EPRI (1993) produced dynamic curves for rock at different depths (0-6, 6-15, 15-36, 36-75, 75-150, 150-300, 300-600, and 600-1500 m). A sensitivity analysis (see Appendix E) comparing the effects of choice of dynamic curves by EPRI (1993) and Schnabel (1973) on spectral response showed that results were not very sensitive to the selection. Therefore, depth-independent dynamic
properties by Schnabel (1973) were used for simplicity (Figure 4.17c). The rock
curves were used for bedrock in every profile and for caliche.

4.5 Site response analysis for scenario earthquakes

As discussed in Chapter 2 (Lamichhane et al., 2014), several seismic sources have the
potential to cause considerable ground motion in the LVV. It is believed that close-in
earthquakes of magnitude M>6 could occur on any of the faults of the Las Vegas Valley
fault system (LVVFS) except the West Charleston fault, or the Frenchman Mountain
fault. Slemmons et al. (2001) excluded the West Charleston fault as a potential seismic
source due to lack of adequate paleoseismic information, a widely distributed pattern of
faulting, and a very low slip rate. Additionally, the LVV could be shaken by distant
strong earthquakes of magnitude M>7 on the Garlock fault or the Death Valley fault.
Probabilistic Seismic Hazard Analysis (PSHA) was conducted to take into account the
ground-shaking potential in the LVV of all of these active faults. The PSHA results are
usually presented in terms of a total hazard curve or uniform hazard spectrum (UHS).
The UHS gives spectral amplitudes with respect to period having equal probability of
exceedance. The UHS includes weighted contributions from several different
earthquakes, and thus, different parts of the UHS are controlled by different earthquakes.
It is highly unlikely that two events will occur at the same time and therefore it is usual
practice to treat each event as different earthquake scenario.

PSHA was carried out at a reference location near the geographic center of the LVV
(666428.6 Easting and 4002171.2 Northing, the intersection of Las Vegas Boulevard and
Sahara Avenue; TSRGP 18), following procedures given in Chapter 2 (Lamichhane et al.,
Figure 4.18 shows the UHS for the reference location. To identify the controlling earthquakes, deaggregation of the hazard was performed for short period (0.01 s, nominal PGA) and long period (4.0 s), at 2% probability of exceedance in 50 years (Figure 4.19). Most of the contributions at short period are from nearby moderate-sized earthquakes (~5-15 km and M6.25-M6.75), with highest contributions from the Eglington fault. Additional contributions are from the faults of the LVVFS, and gridded seismicity (Figure 4.19a). The contributions at long periods are also from nearby moderate-sized earthquakes but additionally from distant, strong earthquakes (Figure 4.19b). The moderate-sized earthquake sources are the same as stated earlier, with the highest contribution from the Eglington fault. The distant strong earthquakes are of about M7.5-M8.0 from a distance of about 115-135 km, with most contributions from the Garlock and Death Valley faults. Therefore, two scenario events were considered in this study – one, a local event of moderate magnitude on the Eglington fault, and the other, a distant strong event on the Garlock fault. The Eglington fault is a relatively short normal fault with maximum surface rupture length of 11 km and having potential for an earthquake of magnitude up to M6.5, and the Garlock fault is a much longer strike-slip fault with a maximum magnitude up to M7.9 (Chapter 2).

Site response analyses were performed separately for each scenario and each TSRGP. To produce the input motion for each TSRGP and for each scenario event, first, the shortest distance from the TSRGP to the surface rupture of the fault was calculated (Figure 4.20; Appendix C, Table C.2). Then, target spectra were produced based on distance and magnitude of the scenario event using a set of five ground-motion prediction equations; The set of ground motion prediction equations is same as used in Chapter 2.
Wavelet-adjusted spectrum-matched ground motions were then created, using the software RspMatch2005.

The method to select the seed ground motion and produce a spectrum-matched ground motion from it is as described in Chapter 3. Tables 4.1 and 4.2 tabulate the seed ground motions with their properties used for producing input motion for Eglington and Garlock scenarios, respectively. The Imperial Valley earthquake (1979, M6.5) dominates the list for the Eglington fault scenario, and the Landers earthquake (1992, M7.4) dominates the list for the Garlock fault scenario.

An equivalent-linear and a nonlinear analysis were conducted using the programs SHAKE2000 and DMOD2000, respectively. Hashash et al. (2010) recommend conducting equivalent-linear analyses in parallel with nonlinear analyses to compare the two to identify any potential pitfalls in the nonlinear analyses. After the analysis, response spectra corresponding to the output (ground surface) motion were produced and amplification factors were calculated by computing the ratio of the spectral intensities of output (ground surface) to input motions (accelerations):

$$A_{i,j,k} = \frac{(SA_{i,j,k})_{output\ motion}}{(SA_{i,j,k})_{input\ motion}}$$  \hspace{1cm} (4.1)

where $A$ and $SA$ are the amplification factor and spectral acceleration, respectively for a particular grid number ($i$), scenario event ($j$), and spectral period ($k$).

Amplification factors were calculated for four spectral periods – 0.01 s (~PGA), 0.2 s, 0.5 s, and 1.0 s. Longer period ground motions (0.5-s and 1.0-s SA) affect mid-sized to tall (multi-story) buildings and bridges, while shorter period motions (PGA and 0.5-s SA) affect shorter structures, for example 1- to 3-story buildings. A flowchart of the process
for a single TSRGP is presented in Figure 4.21. Once all surface ground motions and amplification factors were calculated, contour maps were plotted.

4.6 Results

Following the flowchart on Figure 4.21, a sample analysis for TSRGP 18, which is coincident with the reference location, is shown in Figures 4.22 through 4.26. Figure 4.22 shows the target spectra computed using multiple ground motion prediction equations (as discussed earlier) for the two scenarios. Figure 4.23 shows the time histories of the seed and wavelet-adjusted spectral-matched motion for both scenarios. Figure 4.24 shows the corresponding response spectra (5% damping). Figure 4.25 (produced by the software SHAKE2000) and Table 4.3 show the VS profile and other site characteristics. The spectrum-matched ground motions shown in Figures 4.23 and 4.24 are input at the top of the halfspace of the sediment column (Figure 4.25). Figure 4.26 shows the response spectra of the input (at halfspace) and output (at surface) motions using equivalent-linear (SHAKE) and non-linear (DMOD) approaches. Equivalent-linear analysis predicts higher ground motions than non-linear analysis, for periods up to ~1 s for the Eglington fault scenario and up to ~0.5 s for the Garlock fault scenario. For longer periods, the analyses for the two scenarios predict similar ground motions. Comparing output to input motions, the equivalent-linear analyses predicted amplification at almost all periods for both scenarios, while non-linear analysis predicted deamplification of periods of up to ~0.3 s (Eglington; Figure 4.26a) or ~0.2 s (Garlock; Figure 4.26b) and amplification otherwise.

Appendix F shows results from the same analyses for all TSRGPs. To analyze spatial variation of ground motions across the LVV, color contour maps were produced; contour plots were created using the kriging interpolation algorithm in the software program.
ArcGIS v. 10.1. Figures 4.27 and 4.28 show PGA (for a hypothetical bedrock outcrop) of input motions for the Eglington and Garlock fault earthquake scenarios, respectively. In general, the ground motion from Eglington scenario is higher than for Garlock scenario as can be expected. Figures 4.29 through 4.32 show surface motions at nominal PGA, 0.2, 0.5 and 1.0 second spectral periods from nonlinear analyses (DMOD); (contour plot produced with ArcGIS v. 10.1 software). For the scenario earthquake on the Eglington fault, the highest PGA is ~0.5 g and the highest acceleration is ~1.4 g, at 0.2-s spectral period (affecting smaller buildings). For the scenario earthquake on the Garlock fault, the highest PGA is ~0.1 g and the highest spectral acceleration is ~0.23 g, at 0.5-s spectral period (affecting mid-sized buildings).

For the Garlock event scenario, the highest long-period (1.0-s SA) ground motions, those that can affect tall buildings, are > 0.15 g; this information is important because, even though the corresponding value for the Eglington fault scenario is larger, an earthquake is more likely to occur on the Garlock fault (due to higher slip rate) than on the Eglington fault. This predicted acceleration is slightly lower than those projected by Su et al. (1998), who predicted an average peak ground acceleration range of 0.051 to 0.22 g across the LVV for an earthquake on the Death Valley fault system, which is about 150 km from LVV. For the Eglington fault scenario (close-in event; Figures 4.29a, 4.30a, 4.31a and 4.32a), the patterns of ground motion are similar to the input motion (Figure 4.27), which suggests that the response of the sediments is over-ridden by the close-in input motion. For the Garlock scenario, accelerations are higher along the western and southern margins of the Valley, which have shallow, coarse-grained sediments.
Figures 4.33 through 4.36 show contoured maps of amplification factors across the LVV for the two scenario events based on nonlinear analysis. For PGA, amplification factors vary from 0.7 to 1.6 and from 0.97 to 1.8 for the Eglington and Garlock fault scenarios, respectively. For 0.2-s SA, amplification factors vary from 0.7 to 1.7 and from 1 to 1.9 for earthquake scenarios on the Eglington and Garlock faults, respectively. For 0.5-s SA, no deamplification is observed; amplification factors vary from 1 to 2.4 and from 1 to 2.5 for the Eglington and the Garlock scenarios, respectively. For long period (1.0-s) spectral acceleration, the amplification factors vary from 0.98 to 2.5 and 1 to 3 for the Eglington and Garlock scenarios, respectively. Amplification increases with increasing period. Amplification factors for the Garlock scenario are slightly higher with respect to the Eglington scenario. This is expected because of higher amplitudes of input motion from the Eglington than from the Garlock scenario: higher amplification factors are expected for lower amplitude inputs than for higher amplitude inputs (Cramer et al. 2004). Unlike for acceleration values, the amplification factors do not show a particular pattern for each scenario. This suggests that the sediments have significant effects on the site response of the LVV, supporting the hypothesis for significant variability of ground surface response across the LVV, based on variabilities in the VS model (Murvosh et al. 2013, Figure 4.4).

4.7 Discussion

This section first addresses the results of the analyses across the LVV in terms of predicted ground motions and amplification factors. The section then addresses some possible reasons for fundamental differences between results of this study for the distant earthquake scenario and observations made during a distant earthquake. It then addresses
results for three example sites – one each composed predominantly of clay, gravel, and sand in the upper 30 m, the purpose being to generalize how the different sediment types respond to the earthquake scenarios.

The results of the site response analyses show that significant variability exists in seismic response in the LVV, even when considering only sediment characteristics; without considering basin reverberations and near-fault effects. The results show that the sediment column would amplify seismic waves in most portions of the LVV as they pass through it. Ground-surface accelerations could be up to two times higher on sediments than in bedrock when the earthquake source is close-in. Amplification could be slightly higher when the earthquake source is distant, for example on the Garlock fault. Highest amplifications are observed for the distant earthquake for long-period motions (1.0 s) but note that the amplitudes for the distant earthquake are smaller than for the close-in earthquake. Amplification factors increase on average with increasing period for both earthquake scenarios. However, for the distant earthquake scenario, at some points in the southern LVV, amplifications higher than two occur for PGA. The highest amplifications overall occur in the southern and western parts of the LVV.

The results are compared to long-period ground motions by Murphy and Hewlett (1975), discussed earlier, who studied seismic responses observed during six historical underground nuclear test events (very weak motion) conducted about 120 km away at the Nevada Test Site/ Nevada National Security Site. They observed a strong correlation between very-long-period seismic response (3.33 to 4.48 s) and alluvial thickness; a much longer-period than what was considered for this study. In this study, long-period amplifications (1.0 s) are not highest where the basin-fill sediments are thickest with
respect to the Paleozoic/Mesozoic bedrock (Figure 4.1) as observed by Rodgers et al. (2006) but instead they occur in the shallow portion of the LVV (west side). For the period band 0.16 to 0.22 s, Murphy and Hewlett (1975; Figure 3) showed higher amplifications at the northern and southern edges and relatively lower amplifications in the deepest part of the basin (Figure 4.2). The authors’ observation is consistent with results of this study for the Garlock earthquake scenario for 0.2-s SA. For the period band 0.74 to 1.00 s, the authors showed highest amplifications in the mid-western part of the LVV, decreasing toward the outer edges (Murphy and Hewlett, 1975, Figure 8, radial component). The authors’ observation is consistent with the results of this study for the Garlock earthquake scenario for amplification at 1.0 s SA.

Distant earthquakes are occasionally felt in the LVV. Recordings display strong variability of ground shaking across the LVV. Figure 4.37 shows ground motions recorded in the LVV during the Chino Hills earthquake (M5.4, ~300 km distant). Ground motions were larger in the north-central part of the LVV and smaller to the south and west. Similarly, larger amplifications have been observed during distant earthquakes in the zones of fine-grained sediments (clay) that exist in the deeper, northeast part of the LVV (Rodgers et al. 2006). Figure 4.38 shows selected ground acceleration predictions from this study for the distant fault scenario. Higher ground motions are predicted in the western part of the LVV and relatively lower ground motions are predicted in the north-central LVV. These predictions do not correlate well with the pattern of recorded ground motions shown in Figure 4.37. As stated earlier, in this study, amplifications are largest along the western and southern margin of the Valley, where sands and gravels overlie relatively shallow bedrock. Larger amplifications might be anticipated for fine-grained
sediments with respect to coarse-grained sediments because fine-grained sediments have relatively low VS (and therefore low stiffness in shear); however, fine-grained sediments have higher damping than coarse-grained sediments, which might produce deamplification.

The following may be reasons for the fundamental differences between results of this study for the distant earthquake scenario and observations made during a distant earthquake:

- Higher amplifications are predicted at the edges of the LVV than in the center. This pattern can in part be attributed to differences in depth to the halfspace and the impedance contrast due to the halfspace VS. In the inner portion, mainly in places with greatest upper-basin thickness, the VS of the model halfspace is set at the top of the intermediate zone, with VS of 1100 m/s. In outer regions, with shallower bedrock, the sediment column ends at the top of the lower basin, so the model halfspace is assigned VS of 1500 m/s. At Valley margins (near the edges of the outer regions), the Paleozoic/Mesozoic bedrock occurs at relatively shallow depths (Figure 4.3 and 4.4), and therefore the sediment columns are short and the VS of the model halfspace is high (2600 m/s). Higher stiffness bedrock is expected to produce higher amplification than lower stiffness bedrock for equivalent soil conditions (Kramer, 1996). Additionally, shallow soil deposits are expected to produce higher surface amplification than deep deposits (Ni et al., 1997). In summary, amplification factors are influenced by the depth of the halfspace and its stiffness with respect to the sediment column (impedance contrast); in this research, the impedance contrast of bedrock to sediment
(halfspace to bottom layer) is higher at the edges than in inner regions, and occurs at shallower depths, contributing to higher amplifications there. Further study is needed to isolate and identify the effects of these two factors (depth to halfspace and halfspace VS) on 1-D site response analysis projections for the LVV.

- The maps produced in this study are for four discrete spectral accelerations, which do not always capture peak values (Appendix F).
- Due to interfingering of sediments, results of seismic response analyses might be highly variable over short distances. Further analyses, beyond those conducted in this research (Appendix F), are needed to understand the impact that choice of dynamic material properties can have on results.
- Site response in the LVV is not only a function of sediment properties that can be modeled by 1-D site response analysis; it is also affected by three-dimensional reverberation of energy and basin-edge effects, which are expected to add significant amplification. As noted earlier, the greatest depth to Paleozoic/Mesozoic bedrock in the LVV occurs in the north-central part of the Valley (Figure 4.1), about 5 km west of Frenchman Mountain, which is close to the eastern edge of the LVV basin. Tkalčić et al. (2008) noted that the basin edge of the LVV is probably formed by Frenchman Mountain, and this proximity will result in stronger ground motion Valley-wide during an earthquake. Stewart et al. (2002) recommend using 2-D and 3-D models instead of 1-D for sites near a steeply sloping basin edge. 2-D or 3-D site response analyses that take into account the complexities of the basin boundary are warranted for the LVV. Bakir et al. (2002) investigated basin edge effects of an alluvial basin, to ~ 100 m deep,
in Southeast Anatolia, Turkey due to the 1995 Dinar, Turkey earthquake using 1-D and 2-D finite element analyses and found that the 1-D analyses considerably underestimated the response at basin edges. The discrepancy between responses from 1-D and 2-D analysis decreased as distance from the basin edge increased. The fact that consideration of 2-D and 3-D effects could cause even greater amplification of ground motions is important to consider for the LVV because results from this 1-D analysis already show larger amplifications on basin margins (on the western side of the LVV).

- Bedrock ground-motion amplitudes in the LVV from the Chino Hills earthquake were smaller than those expected for the Garlock earthquake scenario. Therefore, as stated earlier, because higher amplification can be expected for weaker ground motions than for stronger ground motion, the Chino Hills earthquake would be expected to show higher amplifications.

The following addresses results of the site response analyses in terms of characteristic response for sites predominated by clay, gravel and sand. Predominance is defined here by the most prevalent sediment type in the top 30 m depth. Most of the TSRGPs have a predominant sediment of gravel.

- Figure 4.39 shows VS profile and response spectra (input and output) for TSRGP 26, which is located in the north-east part of the Valley. The site has more than 300 m of clay above the halfspace (lower basin - VS = 1500 m/s). The VS30 is ~470 m/s, which is close to (~8% higher than) VS30 for the characteristic VS profile developed for clay in the LVV (Murvosh et al. 2013). For the close-in earthquake (Eglington) scenario for nonlinear analysis, ground motion is
deamplified at short periods and amplified at periods longer than ~0.2 s. For the
distant earthquake (Garlock) scenario, ground motion is amplified at almost all
periods and highly amplified at long periods (about double the input motion for
periods > ~ 0.2 s). A similar result is observed for TSRGP 17 which is also a clay
site (Appendix F). In general, ground motion predictions for clay sites show
amplifications at long periods (low frequency).

This clay site has a thick sediment column, ~350 m above halfspace. In this
research, for such deep sediment columns, long period accelerations were
amplified and short period accelerations were deamplified. This result is
consistent with general findings that thick sediment columns attenuate high-
frequency ground motion and amplify low-frequency motion (e.g. Toro and Silva,
2001). For both TSRGPs 26 and 17, at long periods (>~0.5 s) the nonlinear and
equivalent-linear analyses showed similar results. Regarding the deamplification
at short periods for the close-in scenario, one explanation might be the higher
damping that is characteristic of strong ground motion at high strains (as in the
Eglington scenario) (Figure 4.15).

- Figure 4.40 shows VS profile and response spectra (input and output) for TSRGP
40, which is located in the southwest part of the Valley. The site has 128 m of
gravel above the halfspace (Paleozoic/Mesozoic bedrock - VS = 2600 m/s). The
VS30 is ~590 m/s, which is close to (~3% higher than) the VS30 of the
characteristic VS profile for gravel (Murvosh et al. 2013) and significantly higher
than the VS30 values reported for the example clay site. For both earthquake
scenarios the ground motions are significantly amplified over almost the entire
period range, with amplification factors exceeding 2 from 0.1 to 1 s. As discussed earlier, the amplification can be attributed to the site being relatively shallow with a high impedance contrast at the halfspace. This result is consistent with the finding in chapter 3, where sensitivity analyses demonstrated higher amplifications for a shallow profile with high bedrock VS than deeper profiles with lower bedrock VS.

- Figure 4.41 shows VS profile and response spectra (input and output) for TSRGP 42, which is located in the northwest part of the Valley. This site has 107 m of sand above the halfspace (lower basin - VS = 1500 m/s). The sediment column is thin in comparison to both clay and gravel sites discussed above. The VS30 is ~330 m/s, which is ~30% lower than the VS30 of the characteristic VS profile for sand (Murvosh et al. 2013). Note that VS30 for this sand site is ~30% lower than that for the clay site and ~45% lower than that for the gravel site cited above. The higher VS for sand than for clay is different from general expectations (e.g., Lin et al., 2014). Only a few of the TSRGPS are predominantly sand. Also, the characteristic profile for sand in Murvosh et al. (2013) is based on a relatively small dataset, therefore the uncertainty in the characteristic profile for sand is higher than for clay and gravel. The amplification pattern for this site should be considered in light of the sediment column being relatively shallow, with relatively low VS in the top 65 m and moderately high VS in the halfspace. For the Eglington scenario, the ground motions are significantly deamplified at shorter periods (< ~0.3 s) and slightly amplified at higher periods. For the Garlock scenario, the ground motions are significantly amplified over almost the entire
period range, with amplification factors exceeding 2 from 0.2 to 2 s. This pattern is similar to the response discussed for the clay site. Most of the TSRGPs that have sand predominant in the top 30 m have alternating layers of either clay or gravel. For example, TSRGP 8 has alternating layers of sand and gravel. TSRGP 6 has 22 m of sand at the top but ~180 m of gravel below it to the halfspace. Both TSRGPs 8 and 6 amplified ground motions at all periods for both scenarios. Amplifications were higher at long periods. Small deamplifications are observed between 0.07 – 0.1 s. The response pattern of TSRGP 6 is similar to that of the gravel site discussed above, which can be expected as the sediment for TSRGP 6 contains mostly gravel and only the top 22 m is sand. (See Appendix F for the results.)

In general it was observed that clay tends to deamplify the short-period motions and amplify the long-period motions. Gravel tends to amplify ground motions in its entire period range. And sand shows a mixed behavior, amplifying and deamplifying ground motions at different frequencies.

4.8 Conclusion

Contour maps of amplification factors from 1-D nonlinear site response analyses at 0.01-s (nominal PGA), 0.2-s, 0.5-s and 1.0-s periods showed significant variability in seismic response across the LVV, even without considering 2-D and 3-D effects which are expected to impart further lateral variability. Results showed that seismic waves would be amplified in most portions of the LVV as they travel from bedrock to sediment surface. Amplifications increase on average with increasing period. Overall,
amplifications are highest in the southern and western part of the LVV. Amplifications are lower on sediment columns dominated by fine-grained sediments with thick sediment columns and higher on places dominated by coarse-grained sediments with relatively thin sediment columns. This result does not correlate with the pattern of weak ground motions that have been recorded in the LVV during distant earthquakes. There are a number of uncertainties in the analyses presented here; in the author’s opinion the most significant pertain to the depth to the halfspace and its VS. Still, the mismatch between patterns of predicted and observed ground motion implies that site response in the LVV is significantly affected by two-dimensional and three-dimensional effects such as reverberation of energy and basin-edge effects. Considering one-dimensional analysis alone cannot sufficiently capture the site response of the LVV; however, the research demonstrates that sediment response plays an important role in earthquake site response across the Las Vegas Valley.
Table 4.1  Seed ground motions and their properties, used for Eglington scenario

<table>
<thead>
<tr>
<th>Name</th>
<th>Magnitude</th>
<th>Distance (km)</th>
<th>PGA (g)</th>
<th>Event and Recording Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-BRA225</td>
<td>6.5</td>
<td>8.5</td>
<td>0.16</td>
<td>Imperial Valley 1979/10/15 23:16; 5060 Brawley Airport station (USGS)</td>
</tr>
<tr>
<td>SG3261</td>
<td>6.9</td>
<td>35</td>
<td>0.07</td>
<td>Loma Prieta 1989/10/18 00:05; 47189 SAGO South - Surface (CDMG)</td>
</tr>
<tr>
<td>H-ECC092</td>
<td>6.5</td>
<td>7.6</td>
<td>0.235</td>
<td>Imperial Valley 1979/10/15 23:16; 5154 EC County Center FF (CDMG)</td>
</tr>
<tr>
<td>H-E06230</td>
<td>6.5</td>
<td>2</td>
<td>0.43</td>
<td>Imperial Valley 1979/10/15 23:16; 5158 El Centro Array (CDMG#6)</td>
</tr>
<tr>
<td>B-OOE360</td>
<td>6.7</td>
<td>12.4</td>
<td>0.3</td>
<td>Superstition Hills 1987/11/24 13:16; Poe Road (temp) (USGS)</td>
</tr>
<tr>
<td>H-HVP225</td>
<td>6.5</td>
<td>7.5</td>
<td>0.253</td>
<td>Imperial Valley 1979/10/15 23:16; 5055 Holtville Post Office (USGS)</td>
</tr>
<tr>
<td>A-LAD270</td>
<td>6.2</td>
<td>9.2</td>
<td>0.175</td>
<td>Chalfant Valley 1986/07/21 14:42; 54171 Bishop - LADWP South St. (CDMG)</td>
</tr>
<tr>
<td>H-E04230</td>
<td>6.5</td>
<td>4.2</td>
<td>0.36</td>
<td>Imperial Valley 1979/10/15 23:16; 955 El Centro Array (USGS#4)</td>
</tr>
</tbody>
</table>

Table 4.2  Seed ground motions and their properties, used for Garlock scenario

<table>
<thead>
<tr>
<th>Name</th>
<th>Magnitude</th>
<th>Distance (km)</th>
<th>PGA (g)</th>
<th>Event and Recording Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAS180</td>
<td>7.4</td>
<td>127</td>
<td>0.045</td>
<td>Kern County 1952/07/21 11:53; 80053 Pasadena - CIT Athenaeum (CDMG)</td>
</tr>
<tr>
<td>PAS270</td>
<td>7.4</td>
<td>127</td>
<td>0.053</td>
<td>Kern County 1952/07/21 11:53; 80053 Pasadena - CIT Athenaeum (CDMG)</td>
</tr>
<tr>
<td>FEA000</td>
<td>7.4</td>
<td>122</td>
<td>0.051</td>
<td>Landers 1992/06/28 11:58; 13122 Featherly Park (CDMG)</td>
</tr>
<tr>
<td>FEA090</td>
<td>7.4</td>
<td>122</td>
<td>0.052</td>
<td>Landers 1992/06/28 11:58; 13122 Featherly Park (CDMG)</td>
</tr>
<tr>
<td>PMN090</td>
<td>7.4</td>
<td>117</td>
<td>0.044</td>
<td>Landers 1992/06/28 11:58; 23525 Pomona - 4th &amp; Locust (CDMG)</td>
</tr>
<tr>
<td>BAD270</td>
<td>7.4</td>
<td>128</td>
<td>0.046</td>
<td>Landers 1992/06/28 11:58; 90070 Covina - W Badillo (USC)</td>
</tr>
</tbody>
</table>
Table 4.3 Site characteristics for TSRGP 18. The table specifies the depth and confining pressure at the middle of each layer, which are used in selecting depth-dependent and confining pressure-dependent dynamic properties for sand and clay.

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>Thickness (m)</th>
<th>VS (m/s)</th>
<th>Sediment type</th>
<th>Density (gm/cc)</th>
<th>Depth at middle of layer (m)</th>
<th>Confining pressure at middle of the layer (atm.)</th>
<th>Dynamic properties assigned to the layer sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>560</td>
<td>Sand</td>
<td>2.043</td>
<td>2.5</td>
<td>0.49</td>
<td>EPRI (1993) Depth 0-6 m</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>620</td>
<td>Sand</td>
<td>2.065</td>
<td>10</td>
<td>1.8</td>
<td>EPRI (1993) Depth 6-15 m</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>550</td>
<td>Sand</td>
<td>2.039</td>
<td>20</td>
<td>3.65</td>
<td>EPRI (1993) Depth 15-36 m</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>625</td>
<td>Sand</td>
<td>2.067</td>
<td>32.5</td>
<td>6.20</td>
<td>EPRI (1993) Depth 15-36 m</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>930</td>
<td>Sand</td>
<td>2.160</td>
<td>45</td>
<td>9.10</td>
<td>EPRI (1993) Depth 36-75 m</td>
</tr>
<tr>
<td>6</td>
<td>45</td>
<td>730</td>
<td>Sand</td>
<td>2.102</td>
<td>72.5</td>
<td>14.45</td>
<td>EPRI (1993) Depth 36-75 m</td>
</tr>
<tr>
<td>7</td>
<td>85</td>
<td>890</td>
<td>Sand</td>
<td>2.149</td>
<td>137.5</td>
<td>28.31</td>
<td>EPRI (1993) Depth 75-150 m</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>940</td>
<td>Sand</td>
<td>2.163</td>
<td>190</td>
<td>39.48</td>
<td>EPRI (1993) Depth 75-150 m</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>1020</td>
<td>Sand</td>
<td>2.184</td>
<td>230</td>
<td>48.32</td>
<td>EPRI (1993) Depth 75-150 m</td>
</tr>
<tr>
<td>10</td>
<td>33</td>
<td>1080</td>
<td>Sand</td>
<td>2.199</td>
<td>276.5</td>
<td>58.55</td>
<td>EPRI (1993) Depth 75-150 m</td>
</tr>
<tr>
<td>11</td>
<td>54</td>
<td>1080</td>
<td>Sand</td>
<td>2.199</td>
<td>320</td>
<td>67.82</td>
<td>EPRI (1993) Depth 75-150 m</td>
</tr>
<tr>
<td>12</td>
<td>16</td>
<td>1080</td>
<td>Clay</td>
<td>2.199</td>
<td>355</td>
<td>75.27</td>
<td>Darendeli (2001) PI=15%, 16.0 atm</td>
</tr>
<tr>
<td>13</td>
<td>1100</td>
<td></td>
<td>Rock; Halfspace</td>
<td>2.204</td>
<td></td>
<td></td>
<td>Schnabel (1973)</td>
</tr>
</tbody>
</table>
Figure 4.1 Bedrock surface (Paleozoic or Mesozoic, 145 million years or older) for the Las Vegas Basin plotted in terms of elevation with respect to mean sea level (in m).

Based on work by Langenheim et al. (2001).
Figure 4.2 Lower basin surface (top of Miocene-Oligocene) of the Las Vegas Basin plotted in terms of elevation with respect to mean sea level (in m). This model space is a subset of the one shown in the previous figure (note coordinates). Based on data from 3-D VS model (Murvosh et al., 2013).
Figure 4.3 Partial cross-section illustrating the sub-basins used to develop the 3-D VS model in accordance with the 3-D sediment-lithology model (Taylor et al., 2008). Figure from Luke et al. (2011). Figure not to scale.
Figure 4.4 Image captured from the 3-D shear wave velocity (3-D VS) model developed by the Applied Geophysics Center at University of Nevada Las Vegas (Murvosh et al., 2013), showing strong lateral variability in VS at the ground surface.
Figure 4.5 Sediment-column thickness (depth to halfspace) used for the site response calculations. Maximum thickness is 370 m. The target site response grid points (TSRGP) are as defined in the text. TSRGP identified as black solid squares (■) are not analyzed for site response due to high VS30 (shallow bedrock). The black line represents the boundary of the Las Vegas Valley.
Figure 4.6 Map showing target site response grid points (TSRGPs; coarse mesh, numbered) and grid points for the 3-D VS model (fine mesh). Buffer zones of 300 m radius around TSRGPs are shown. VS profiles within these buffer zones are used to produce the VS profiles for the target sites. The red line represents the boundary of the Las Vegas Valley.
Figure 4.7 (a) Locations of measured VS (red dots) with respect to target site response grid points (black dots with ID numbers); (b) Locations of lithology logs (yellow circles) with respect to the target site response grid points.
Figure 4.8 Optim VS measurement locations with respect to the target site response grid points. The red line represents the boundary of the Las Vegas Valley.
Figure 4.9 (a) Shear wave velocity profiles from the 3-D VS model within 300 m of target site response grid point (TSRGP) 25 (1-7, and nearest), average, interpreted stepped profile, and two Optim VS30 values for TSRGP 25. Note that the depth to model halfspace is not equal to the depth for the nearest profile, rather it is based on lithology model. (b) Same information but to depth of 50 m.
Figure 4.10 Vicinity of target site response grid point (TSRGP) 25. Circle represents 300 m radius around the TSRGP. There are no measured VS or lithology log locations within 300 m, but there are eight grid points from the 3-D VS model (red dots) and two Optim data points (blue diamonds). The numbers in blue are VS30 (m/s) for the Optim data. The numbers in grey and red are VS30 from the 3-D VS model; red signifies proximity to the TSRGP (within 300 m).
Figure 4.11 Revision of VS profile for TSRGP 46 where 3-D VS model has implausible velocity inversion at depth.
Figure 4.12 Colored contour map of percentage differences between VS30s of 3-D VS model with respect to Optim data. (Positive value means VS30 from 3-D VS model is higher than from Optim.) Also shown are lithology wells and measured VS locations used in 3-D VS model, identified in terms of measurement method – crosshole, downhole, REMI or SASW. Also shown are the target site response grid points (TSRGPs; “Grids”), numbered.
Figure 4.13 Vicinity of target site response grid point (TSRGP) 7, where VS30 from 3-D VS model showed largest difference with respect to Optim data. Circle represents 300 m radius around TSRGP. Values in red or gray and blue are VS30 from 3-D VS model and Optim data respectively, in m/s.
Figure 4.14 (a) Shear wave velocity profiles to a depth of 200 m in the vicinity of target site response grid point (TSRGP) 7. This site has the largest discrepancy with respect to the Optim data. “Final VS” is the scaled VS profile as described in the text. “LMNSS1 VS profile (SASW)” is a nearby measurement used in creating the 3-D VS model (Location shown in Figure 4.13). Other legend elements are as defined in Figure 4.8. (b) Expanded view to a depth of 100 m.
Figure 4.15 Dynamic properties of clay with plasticity index of 15% (Darendeli, 2001) used in the site response analysis.
Figure 4.16 Plasticity indexes of clay around the Las Vegas Valley. Based on a limited sampling of data from Clark County, Nevada’s Electronic Submission of Geotechnical Report database.
Figure 4.17 (a) Dynamic curves for sand (EPRI, 1993) used in site response analysis.
Figure 4.17 (b) Dynamic curves for gravel (Rollins et al., 1998 and Seed et al., 1996) used in site response analysis. Mean dynamic curves by Rollins et al. (1998) were used in the site response analysis.
Figure 4.17 (c) Dynamic curves for rock (Schnabel, 1973) used in site response analysis.
Figure 4.18 Uniform hazard spectra (5% damped) for the reference location, from PSHA for 2%, 5% and 10% probability of exceedance in 50 years.
Figure 4.19 Deaggregation of seismic hazard at the reference location (approximate geographical center of LVV) at (a) 0.01 s (nominal PGA) and (b) 4 s period for 2% probability of exceedance in 50 years, from probabilistic seismic hazard analysis.
Figure 4.20 Target site response grid points with respect to the two faults considered for the scenario events (Lamichhane et al., 2014).
Figure 4.21 Site response analysis procedure flowchart. PSA - Peak Spectral Acceleration, GMPE - Ground motion prediction equations, GM - ground motion, PGA - Peak ground acceleration.
Figure 4.22 Target spectrum at TSRGP 18 (reference location) for (a) Eglington fault earthquake scenario ($M = 6.5$, $R = 11$ km, normal fault – hanging wall); (b) Garlock fault earthquake scenario ($M = 7.9$, $R = 121$ km, strike slip fault).
Figure 4.23 Acceleration, velocity and displacement time histories of the seed (red) and spectrum-matched (blue) ground motions for (a) Eglington fault scenario and (b) Garlock fault scenario, for TSRGP 18 (reference location). The spectrum-matched acceleration time history is used as input motion in site response analysis.
Figure 4.24 Response spectra (5% damped) of the seed and spectrum-matched ground motion for (a) the Eglington fault scenario and (b) the Garlock fault scenario for TSRGP 18 (reference location). Target spectra are as shown in Figure 4.22.
Figure 4.25 Site response model for TSRGP 18 (reference location). Top of model halfspace is at 370 m (1210 ft).
Figure 4.26 Response spectra (5% damped) of the input and output motions for the earthquake scenarios on (a) Eglington and (b) Garlock faults using equivalent-linear (SHAKE) and non-linear (DMOD) approaches for TSRGP 18 (reference location).
Figure 4.27 Input motion (PGA at a hypothetical rock outcrop) across the LVV for the Eglington earthquake scenario. Appendix C (Table C.1) and Figure 4.5 identifies those TSRGPs that were not analyzed for site response.
Figure 4.28 Input motion (PGA at hypothetical rock outcrop) across the LVV for the Garlock earthquake scenario. Appendix C (Table C.1) and Figure 4.5 identifies those TSRGPs that were not analyzed for site response.
Figure 4.29 Predicted -PGA (0.01-s SA) from non-linear analysis across the LVV for scenario earthquake event on (a) the Eglington fault, and (b) the Garlock fault.
Figure 4.30 Predicted 0.2-s SA ground motion from non-linear analysis across the LVV for scenario earthquake events on (a) the Eglington fault, and (b) the Garlock fault.
Figure 4.31 Predicted 0.5-s SA ground motion from non-linear analysis across the LVV for scenario earthquake events on (a) the Eglington fault, and (b) the Garlock fault.
Figure 4.32 Predicted 1.0-s SA ground motion from non-linear analysis across the LVV for scenario earthquake events on (a) the Eglington fault, and (b) the Garlock fault.
Figure 4.33 Amplification factors from non-linear analysis across the LVV for ~PGA (0.01-s SA) for scenario earthquake events on
(a) the Eglington fault, and (b) the Garlock fault.
Figure 4.34 Amplification factors from non-linear analysis across the LVV for 0.2-s SA for scenario earthquake events on (a) the Eglington fault, and (b) the Garlock fault.
Figure 4.35 Amplification factors from non-linear analysis across the LVV for 0.5 s S A for scenario earthquake events on (a) the Eglington fault, and (b) the Garlock fault.
Figure 4.36 Amplification factors from non-linear analysis across the LVV for 1.0-s SA for scenario earthquake events on (a) the Eglington fault, and (b) the Garlock fault.
Figure 4.37 Differential site response observed in the LVV during the M5.4 Chino Hills earthquake (July 2008, ~300 km to the southwest; Luke et al. 2009). Seismic traces plotted to same scale.
Figure 4.38 Illustration of predicted accelerations across the LVV for the earthquake scenario on the Garlock fault (M7.9 ~120 km). Seismic traces are not to same scale but peak acceleration are noted on each trace.
Figure 4.39 (a) Shear wave velocity profile for TSRGP 26 (predominantly clay) (b) Response spectra (5% damped) of the input and output motions for the two scenarios. ES – Eglington Scenario, GS – Garlock Scenario, IM – Input Motion, TS – Target Spectrum
Figure 4.40 (a) Shear wave velocity profile for TSRGP 40 (predominantly gravel) (b) Response spectra (5% damped) of the input and output motions for the two scenarios. ES – Eglington Scenario, GS – Garlock Scenario, IM – Input Motion, TS – Target Spectrum
Figure 4.41 (a) Shear wave velocity profile for TSRGP 42 (predominantly sand) (b) Response spectra (5% damped) of the input and output motions for the two scenarios. ES – Eglington Scenario, GS – Garlock Scenario, IM – Input Motion, TS – Target Spectrum
4.11 References


CHAPTER 5

LIMITATIONS, RECOMMENDATIONS AND OUTCOMES

5.1 Limitations and recommendations

A probabilistic seismic hazard analysis for the LVV was presented in this research. The research highlighted some aspect of uncertainties to seismic hazard for the LVV and elsewhere, especially relating to fault characteristics. Uncertainties are assessed for different characteristics of faults especially the Eglington fault and the rest of the Las Vegas Valley fault system (LVVFS), and several regional faults. This research indicates the importance of monitoring and faults characterization, which will help researchers to understand the faults and identify which pose a seismic hazard. Followup study could consider the uncertainty in the “b” value of the recurrence models on the probabilistic seismic hazard calculations in the logic tree formulation. Uncertainty in the "b" value was not included in this study.

Computed response spectra specific to a bridge site in the LVV demonstrated that a wavelet-adjusted, spectrum-matched ground motion predicted comparable results with respect to suites of unscaled and scaled ground motions. Two hypothetical sediment columns were tested to validate the result, but only a single spectrum-matched ground motion was tested. Follow-up studies could test other ground motions.

While this dissertation evaluated the seismic response of the LVV for two scenario cases (earthquakes on Eglington and Garlock faults) making use of our best estimate 3-D
VS and sediment lithology models, the VS model can be improved by incorporating the extensive VS dataset acquired by Optim. (Only VS30 from the Optim dataset was available at the time this research was started; the VS profiles were obtained only after most of the analyses were completed.) It was found from the analysis that 1-D analyses can not sufficiently capture site response of the LVV. Future studies should also incorporate 2-D and 3-D analysis for a better understanding of the response of the LVV to earthquake shaking.

5.2 Outcomes to date

This study has contributed to the Nevada Bureau of Mines and Geology’s (NMBG) recognition of elevated hazards and risks associated with the LVVFS, especially Eglington fault, compared to previous understanding. The NMBG has recommended that the USGS increase the slip rate of Eglington fault in the next update to the national seismic hazard model. A slip rate of 0.6 mm/yr was recommended, which is a significant increase over the rate used in the 2008 NSHM which was 0.1 mm/yr. (This study used a slip rate of 0.66 mm/yr.) As a result, the current draft of the new national seismic hazard calculations show an increased hazard for the LVV by a factor of ~1.3 for PGA for 2% PE in 50 years (draft report for 2014 NSHM: http://earthquake.usgs.gov/hazards/2014prelim/).

This outcome demonstrates how the results of this research will improve earthquake safety by providing a better understanding of the earthquake hazard and risks in the LVV, and thereby encouraging updates and further research on the characteristics of the seismic
sources in and near the LVV and adjacent areas of Southern Nevada, California, Utah and Arizona.
APPENDIX A: DEAGGREGATION OF HAZARD

This appendix includes the deaggregation of seismic hazard for different spectral accelerations (SA) at 2% probabilistic of exceedance (PE) in 50 years (~2500-year return period).

Deaggregation of hazard was carried out for the reference location at nominal PGA (peak ground acceleration; 0.01 s SA; Figure A.1), 0.2-s SA (Figure A.2), 1.0-s SA (Figure A.3) and 4.0-s SA (Figure A.4). For all cases, contributions from distant sources including the added regional faults are dwarfed by the near sources. For all cases, the faults of the LVVFS were found to make a substantial contribution to the hazard. The Eglington fault dominates the hazard and far exceeds the contribution from other sources including the gridded and background source. At both PGA and 0.2-s SA, the deaggregation shows significant contributions from nearby earthquakes and the background source, with no notable contribution from distant earthquakes. Contribution from distant sources increases as spectral period increases, while the contribution from gridded and background sources diminishes (Figure A.4).

Most of the contributions to PGA are from events of magnitude 6.25 to 6.95 at a distance of ~1 to ~20 km from the reference location, producing a mean magnitude of 6.4 and mean distance of 9 km. For deaggregation at 0.2-s SA, the mean magnitude and distance are 6.44 and ~9 km, respectively. The Garlock and Death Valley faults contribute more than any other distant sources for long-period (1.0 s and 4.0 s) SA. For deaggregation at 1.0-s SA, a mean magnitude of 6.61 and a mean distance of 15 km were calculated. Most of the contributions at 4.0-s SA are observed from events of magnitude 6.15 to 7.05 at a distance of 1-20 km, producing a mean magnitude of ~6.8 and mean
distance of ~34 km from the reference location. Due to considerable contribution from strong distant sources (>100 km), the mean magnitude and distance has increased with respect to the earlier cases.
Figure A.1 Deaggregation of hazard at 0.01 s (~PGA) for 2% PE in 50 years

Figure A.2 Deaggregation of hazard at 0.2-s SA for 2% PE in 50 years
Figure A.3 Deaggregation of hazard at 1.0-s SA for 2% PE in 50 years

Figure A.4 Deaggregation of hazard at 4.0-s SA for 2% PE in 50 years
APPENDIX B: TIME HISTORIES OF GROUND MOTIONS

This appendix shows time histories – acceleration, velocity and displacement – of the ground motions used in this study to match to a target spectrum. First are shown time histories of the unscaled ground motions (Figures B.1 to B.7). Then are shown the time histories of the scaled ground motions (Figure B.8 to B.14). These time histories are shown in raw form. Only acceleration time histories are recorded; the other two are derived by integration (using SHAKE2000).
Figure B.1 Acceleration, velocity and displacement time histories for A-GRV330
Figure B.2 Acceleration, velocity and displacement time histories for A-ZAK360
Figure B.3 Acceleration, velocity and displacement time histories for B-PTS225
Figure B.4 Acceleration, velocity and displacement time histories for D-OLC360
Figure B.5 Acceleration, velocity and displacement time histories for H-E06230
Figure B.6 Acceleration, velocity and displacement time histories for I-CVK180
Figure B.7 Acceleration, velocity and displacement time histories for STG000
Figure B.8 Acceleration, velocity and displacement time histories for A-GRV060
Figure B.9 Acceleration, velocity and displacement time histories for G04360
Figure B.10 Acceleration, velocity and displacement time histories for H-E05140
Figure B.11 Acceleration, velocity and displacement time histories for H-E06140
Figure B.12 Acceleration, velocity and displacement time histories for I-CVK090
Figure B.13 Acceleration, velocity and displacement time histories for LOB000
Figure B.14 Acceleration, velocity and displacement time histories for STG000
APPENDIX C: COORDINATES OF TARGET SITE RESPONSE GRID POINTS AND DISTANCE OF THE GRID POINTS TO THE SCENARIO EARTHQUAKE FAULT SOURCE

Table C.1 provides coordinates (Universal Transverse Mercator coordinate system) for all the target site response grid points (TSRGPs) considered in this dissertation. The TSRGPs are numbered from 1 to 80. Table C.1 and Figure 4.4 show which of these were subject to site response analysis. The others were considered to be on or close to bedrock, so that sediment-column effects were considered negligible. Table C.2 shows the distance of the grid points to the scenario earthquake fault source.

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§Closest distance of the target site response grid point to the surface rupture of the scenario earthquake fault source.

*Target site response grid point where site response analysis was not performed (same as given in Table C.1).
APPENDIX D: SHEAR WAVE VELOCITY PROFILES OF ALL TARGET SITE RESPONSE GRID POINTS

This appendix contains shear wave velocity (VS) profiles developed for all target site response grid points (TSRGPs). The VS profiles are shown in three groups - primary (Figure D.1), secondary (Figure D.2) and tertiary (Figure D.3). To distinguish the primary TSRGPs profiles from each other, Figure D.1 is subdivided into Figure D.1a (TSRGP 1-10), Figure D.1b (TSRGP 11-20) and Figure D.1c (TSRGP 21-30). Finally, this appendix presents the VS profiles for those TSRGPs where site response analyses were not performed (Figure D.4).
Figure D.1a Shear wave velocity profiles for primary TSRGPs (1-10).
Figure D.1b Shear wave velocity profiles for primary TSRGPs (11-20).
Figure D.1c Shear wave velocity profiles for primary TSRGPs (21-30).
Figure D.2 Shear wave velocity profiles for secondary TSRGPs.
Figure D.3 Shear wave velocity profiles for tertiary TSRGPs.
Figure D.4 Shear wave velocity profiles for TSRGPs where site response analyses were not performed.
A sensitivity study was carried out to study the effect of different dynamic curves for gravel and rock on the site response. For each study, two different profiles were looked into – a simple profile and a complex profile. The simple profile has a gradually increasing shear wave velocity with depth. For this, we used the profile we generated for bridge G953, which was presented in Chapter 3 (Figure E.1). For the complex profile, we used an example profile for the Las Vegas Valley (LVV), Nevada given in the appendix of Liu (2006) (36 layers, about 400 m deep). This profile has a caliche layer at a shallow depth and shows some velocity inversion (Figure E.2). The example profile in Liu (2006) does not have a gravel layer, therefore, sand and gravel material in that profile was changed to gravel. The effect of two different dynamic curves for gravel were analyzed (Figure E.3) – one by Rollins et al. (1998) and the other by Seed et al. (1986). For the former, we considered the mean dynamic curves. All other properties remained the same. Similarly for rock, we tested two dynamic curves (Figure E.4) – one by Schnabel (1973) and the other a set of depth-dependent dynamic curves for rock by EPRI (1993). Site responses were compared in terms of acceleration response spectra after analyses using SHAKE2000, an equivalent linear site response analysis computer program.
Figure E.1 Simple profile (bridge G953) used for sensitivity study

Figure E.2 Complex profile (Liu, 2006) used for sensitivity study
Figure E.3 Dynamic curves for gravel. SD represents standard deviation. For Rollins et al. (1998), only “mean” is considered.
Figure E.4 Dynamic curves for rock.
After the analyses, the following results were observed:

1. For gravel: Figure E.5 results indicated that using Rollins et al. (1998) predicted higher spectral acceleration than that by using Seed et al. (1986). Rollins et al. (1998) is a more conservative choice to represent gravel.

Figure E.5 Acceleration response spectra after analysis for the two profiles and using two different dynamic curves for gravel
2. For rock: Figure E.6 shows the results after the site response analyses were carried out. The spectral responses are not sensitive to the choice of curves for either profile. This result indicates no preference between the dynamic curves for rock for the profiles studied, where rock appears only in the halfspace and the caliche layer.

Figure E.6 Acceleration response spectra after analysis for the two profiles and using two different dynamic curves for rock. The two results are virtually indistinguishable.
APPENDIX F: ACCELERATION RESPONSE SPECTRA FOR ALL TARGET SITE RESPONSE GRID POINTS

The TSRGs (Target Site Response Grid Point) that are not given in here are those either at engineering rock (VS30 ≥ 760 m/s) or at bedrock and therefore no site response analyses were performed.

ES DMOD – Eglington fault earthquake Scenario with DMOD nonlinear analysis

ES SHAKE – Eglington fault earthquake Scenario with SHAKE equivalent-linear analysis

GS DMOD – Garlock fault earthquake Scenario with DMOD nonlinear analysis

GS SHAKE – Garlock fault earthquake Scenario with SHAKE equivalent-linear analysis

SA – Spectral Acceleration (5% damping)

IM – Input Motion

TS – Target Spectrum
VITA

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Organizing committee (student representative), 43rd Symposium on Engineering Geology and Geotechnical Engineering, University of Nevada Las Vegas, Las Vegas, Nevada (2011)

Publications:


Dissertation Title: Evaluation of earthquake hazard for Las Vegas Valley, Nevada Incorporating Probabilistic Hazard Assessment and Non-linear Site Response