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Large-Scale Earthquake-Hazard Class Mapping by Parcel in Las Vegas Valley, Nevada

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Abstract Clark County and the city of Henderson, Nevada, completed the United States' first effort to map earthquake site classifications with systematic, direct measurements through an entire urban area. Urban development, disaster response planning, and especially building code implementation and enforcement motivated map development. The municipalities contracted the Nevada System of Higher Education to classify ~1500 km^2 including urban Las Vegas Valley and exurban areas of future development. The resulting Parcel Map includes over 10,000 surface-wave array measurements accomplished within three years using Optim's SeisOpt ReMi refraction microtremor measurement and processing technology adapted for large-scale data collection. The noisy urban setting necessitated use of microtremor as the seismic source. With a nominal measurement spacing of 300 m or less, the Parcel Map classifies every parcel on the National Earthquake Hazards Reduction Program V_{S30} site-class scale. The most important revelation of the Parcel Map was that 84% of the mapped region was found to be stiffer than the default site class D category previously imposed on the whole of the Las Vegas Valley. Details of the mapping also revealed the high variability of V_{S30} over short distances (<200 m) in many areas. We describe a class C+ for sites with class B V_{S30} velocities but soft surface soil more than 3 m thick. Correlation between the occurrence of class C+ sites and topographic slope varied spatially from north to south along the western margin of Las Vegas Valley. Of particular significance was the delineation of an alluvial fan surface that was not topographically expressed in the southwest part of the valley. Given the density of velocity measurements required for code enforcement, ReMi proved to cost-effectively produce the desired Parcel Map within the three-year contract period.

Electronic Supplement: Table listing the "Priorities for Action" outlined for disaster risk reduction under the Sendai Framework for Disaster Risk Reduction accomplished through the Parcel Mapping Project.

Introduction

A challenge for engineers and urban planners is to promote community resilience to earthquakes, while not making the cost of compliance impossibly high. Current earthquake-hazard maps may miss details of localized, potentially safer stiffer soils and potentially dangerous unknown softer soils. Sparse geological and geotechnical data may predict such variations, but detailed direct measurements can map them with certainty. Neither property owners nor local authorities can bear the cost of individualized engineering studies of every block and every building. Likewise, no economy can bear the cost of building and retrofitting to reduce earthquake risks when guided solely by overconservative, interpolated, extrapolated, and overgeneralized regional earthquake-hazard maps. Regional hazard maps are often developed from predictions based on geologic map units and sparse seismic shear-wave velocity (V_S) measurements (e.g., Wills *et al.*, 2000; Ashland, 2001). However, results from studies employing detailed measurements show that generalized maps may not predict the intrinsic variability of near-surface shallow velocities. Dependence of V_S on dominant grain size that resulted in

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overlap of velocity range between different lithologies had already been established by prior studies (e.g., Wills and Silva, 1998; Ashland and Rollins, 1999). Detailed surveys along three separate transects in Reno, Las Vegas, and Los Angeles emphasize the high spatial variability of near-surface V_S (Scott *et al.*, 2004, 2006; Thelen *et al.*, 2006). Extensive analyses of the transect data revealed that correlations of V_S with geology and soil classifications are weak at best in these urban areas. Good correlation was observed in Salt Lake City by Ashland and Rollins (1999), though their hazard mapping based on geologic correlation has not been confirmed by dense, direct measurements.

We present the results of a systematic campaign of more than 10,000 direct microzonation measurements across the Las Vegas, Nevada, metropolitan region. These measurements were an integral component of what the municipalities in Las Vegas Valley term a Parcel Mapping program. Parcel Mapping characterized near-surface V_S and mapped localized areas of soft or deep soil structure, determining each parcel's National Earthquake Hazards Reduction Program (NEHRP) earthquake-hazard site classification as defined in the International Building Code (IBC; Building Seismic Safety Council [BSSC], 1997, 2004).

Although Hunter *et al.* (2010) developed a V_{S30} map for the city of Ottawa utilizing over 21,700 borehole logs, only 700 direct geophysical measurements were acquired. Clark County and the city of Henderson (CoH) desired a more comprehensive mapping strategy, demanding dense measurements and increased sampling where variations necessitated. Such data will help identify existing buildings prone to severe shaking in the event of an earthquake, whereas new buildings and infrastructure can have the necessary construction to confidently meet building code standards. City officials can then plan retrofit campaigns and ensure buildings meet requisite safety standards on the basis of knowledge rather than guesswork.

Seismic provisions in the building code involve the inclusion of the Seismic Site Class factor that modifies the intensity of ground motion that a building or structure is required to resist (Dobry *et al.*, 2000). Current building codes, including the 2006 and 2009 IBC (2006, 2009), are based upon the design recommendations specified by American Society of Civil Engineers 7-05 (ASCE, 2010) and the 2004 NEHRP Provisions (BSSC, 1997, 2004). The time-averaged shear-wave velocity value for the top 100 ft or 30 m (V_{S100}-foot or V_{S30}-meter) as per table 1613.5.5 from the IBC (2006) is the principal determinant of the site classification. Site class directly determines the seismic design category used by structural engineers and is integral to the seismic design of structures per the IBC and International Residential Code (IBC, 2009, and the International Code Council [ICC], 2009, respectively) in the United States.

The building codes for southern Nevada all require determination of the seismic site class. The site class factors are determined from the results of on-site testing and assessment; otherwise the default low-velocity hazardous site class

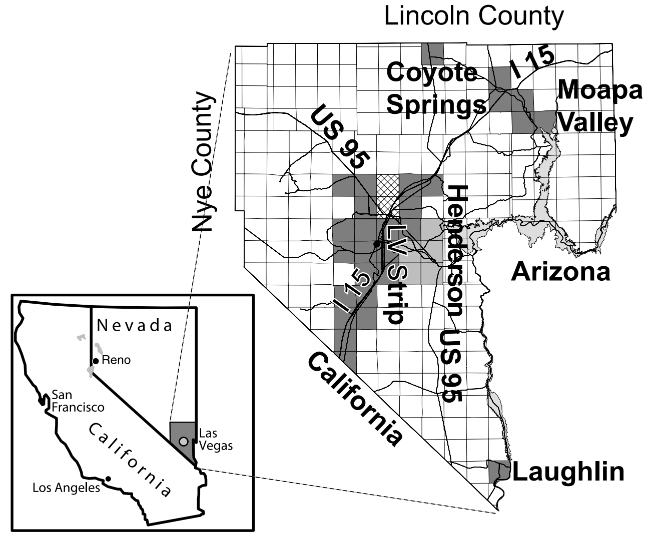

Figure 1. Area within Clark County (dark gray) and the city of Henderson (CoH; light gray) mapped for earthquake parcel classification. The municipalities defined and prioritized specific areas for mapping. The unmapped region encompassing the city of North Las Vegas is displayed in a cross-hatched pattern. Inset shows the location of the Parcel Mapping area within the state of Nevada.

value of D must be adopted (Southern Nevada Building Officials, 2012). Often this means adhering to a more stringent site class than the actual physical ground conditions would dictate and indirectly increases the costs of building design and construction. The Parcel Map is designed to supply measured, actual V_{S30} values across the urban and urbanizing areas of Clark County, providing essential data for seismic-hazard mitigation, with potential cost savings for new construction and in the retrofitting of existing buildings.

Prior to this study, designing to the imposed generalized NEHRP default site class D had costly results. Engineering investigations found that in the majority of cases, site conditions were much stiffer than the default site class D classification (per Clark County, Nevada, Department of Building estimates). A transect of 49 measurements along the Las Vegas Strip by Scott *et al.* (2006) revealed that 80% of the measurements (i.e., 39 of the 49 transect arrays) had V_{S30} values above the 360 m/s maximum for NEHRP D classification.

Prior experience in the area that the stipulated default regularly proved to be overly conservative constituted a dilemma. Neither property owners nor local authorities could bear the cost of engineering studies for every building permit. Likewise, Nevada's economy could not bear the cost of all building construction meeting the default site class D. Builders and developers convinced two local authorities within Las Vegas Valley (Fig. 1), Clark County and the CoH, Nevada, that large-scale mapping was essential for effective building code enforcement. The two municipalities have a combined population over 2 million. This initiative had broad support from builders, developers, engineers, and the public. In conjunction with the Nevada System of Higher Education (NSHE), the municipalities addressed this large-scale mapping challenge through a comprehensive Earthquake Parcel Mapping program. Completed in 2010, the Clark County Parcel Map was the United States' first effort to map earthquake V_{S30} site class through an entire urban area with systematic, direct measurements at such density. Rather than research driven, the project and the desired outputs were driven by end-user needs. Unfortunately, due to budget restrictions, the city of North Las Vegas was unable to join in the Parcel Mapping campaign, leaving a small part of the valley unmapped (cross-hatched area of Fig. 1).

The municipalities are using the resultant Parcel Map in planning for development and disaster response, in addition to its direct use for building code implementation and enforcement. Further, the V_{S30} measurements have been incorporated into 3D numerical earthquake simulations toward a more comprehensive seismic-hazard assessment of the city (Flinchum *et al.*, 2014). In this article, we present the methodology used to accomplish the Parcel Mapping within a three-year project period, details of the resultant site-class Parcel Map, and the benefits of the V_S mapping.

Project Description and Methodology

The Clark County Department of Development Services (CCDDS) and the CoH contracted NSHE and Optim to create a classification map based on measured site-specific V_S values (a microzonation map) of Clark County (Fig. 1). Optim, a seismic services provider, executed all necessary tasks for completion of the work, including field data acquisition, data processing, and reporting, in collaboration with NSHE/Nevada Seismological Laboratory personnel. Characterized areas of the Parcel Map, specified by the CCDDS and CoH, included urbanized and urbanizing areas of unincorporated Clark County, the urbanized area of the CoH, portions of the city of Las Vegas within Las Vegas Valley, plus certain outlying urban areas and planned future developments. The mapped area totaled ~1500 km^2 (Fig. 1).

Shear-wave velocities measured as a function of depth were estimated at each of the measurement locations using the refraction microtremor (ReMi) technique of Louie (2001). As with all surface-wave measurements, refraction microtremor is a volume-averaging measurement, summing interval travel times for which geology is laterally variable (as concluded by Raptakis, 2012). ReMi measurements thus differ from the single-point measurements obtained by downhole logs. In this method, Rayleigh waves in the ground are recorded by a linear array of vertical refraction geophones. These Rayleigh waves are excited by microtremor noise generated by background sources (e.g., vehicles, trains, airplanes, machinery, tree movements, and ocean-wave action). Louie (2001) developed the refraction microtremor technology as a rapid and cost-effective method of measuring V_{S30} to meet IBC requirements (BSSC, 1997, 2004; IBC, 2006, 2009) and to determine the 1D velocity–depth structure for seismic-hazard assessment. The technology is owned by the State of Nevada, exclusively licensed to Optim, and only available commercially as SeisOpt ReMi (Optim 2001–2016).

The refraction microtremor method underwent peer review and has extensively been blind-tested against results from borehole measurements, multichannel analysis of surface waves (MASW), and spectral analysis of surface waves (e.g., Louie, 2001; Liu *et al.*, 2005; Stephenson *et al.*, 2005; Thelen *et al.*, 2006). The noisy environment of urban streets in the Parcel Map area led Clark County to the realization that the setting was ideal for the use of microtremor as the seismic source, recorded on linear arrays, allowing the project to be conducted cost-effectively and within the allocated time frame.

The contracts with Clark County and the CoH required V_S measurements to maintain a density of one array for each 36 acres of mapped area (1 array per 0.146 km^2, or 7 arrays per km^2) with no more than 1000 ft (0.30 km) between array locations. This density of measurement allowed site class to be characterized on the Parcel scale as defined by BSSC (1997) and was essential to achieve the objectives of the Parcel Mapping program and meet the desired needs of the intended Parcel Map end users. Nominally, a linear ReMi array with 24 channels of vertical geophones spaced 8 m apart, for a typical array length of 184 m, was deployed to measure each site (e.g., array photos in Fig. 2). Standard vertical 4.5-Hz seismic refraction geophones, placed on pavements, recorded ambient-noise microtremor at a time-sample interval of 2 ms for multiple records of 30 s each. Each seismic array collected 12–20, 30-s-long ambient-noise recordings. Hammer hits using an 8- or 10-pound (3.5–4.5 kg) sledge and strike plate placed ~5 and 10 m off both ends of each seismic array augmented the normal passively recorded data, to increase the high-frequency energy (above 7 Hz) and improve velocity resolution in the upper 0.5–5 m of the resultant velocity–depth profiles.

Once collected, the ambient-noise data were processed using SeisOpt ReMi software (Optim, Inc., 2001–2016). A 2D slowness–frequency ($p-f$) transformation of the data creates a velocity spectrum imaging the Rayleigh-wave dispersion curve (Louie, 2001; examples in Fig. 2, inset). The fundamental-mode Rayleigh dispersion was then picked along the minimum-phase-velocity envelope for which the gradient of the power spectral ratio is greatest (Louie, 2001; Pancha *et al.*, 2008). Using the dispersion-curve picks (Fig. 2, top), a matching calculated dispersion curve and the associated 1D V_S model were then determined (Louie, 2001; Fig. 2, bottom).

Use of linear arrays is often not favored for microtremor sources due to potential dominance of energy arriving obliquely to the array. However, energy propagating along the linear array is always associated with power spectral energy along the minimum velocity envelope of the Rayleigh-wave dispersion curve. The off-end hammer shots were performed during data collection to ensure that the minimum phase velocity of the Rayleigh wave along the array is correctly identified. In comparison, oblique energy occurs at higher apparent velocities, causing the peak spectral ratio value to appear at a higher apparent velocity than the funda-

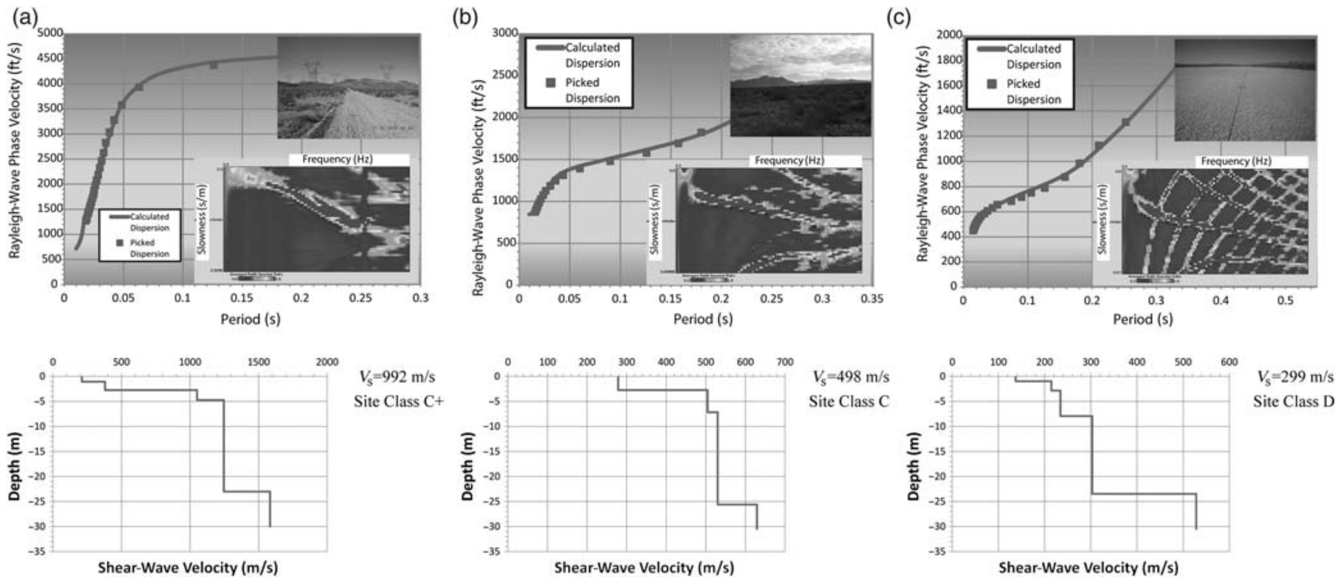

Figure 2. Parcel map refraction microtremor (Louie, 2001) analysis examples for typical sites having velocities in the National Earthquake Hazards Reduction Program (NEHRP) class range (a) B; (b) C; and (c) D. Upper plots show a site photo and the picked and modeled dispersion (top) from the slowness–frequency ($p-f$) image (inset). Lower plots (bottom) show the corresponding $V_{S(z)}$ profiles. Recorded ambient (microtremor) array recordings are first transformed into the frequency–slowness domain (Louie, 2001). The Rayleigh-wave dispersion curve is then picked (inset) and forward modeled to obtain a 1D shear-wave velocity profile (bottom). Note that the ReMi method allows the Rayleigh-wave dispersion curve to be picked along the low-velocity envelope of the $p-f$ image to obtain the fundamental-mode Rayleigh dispersion curve.

mental mode at a particular frequency (Louie, 2001). Obliquely arriving energy cannot produce an apparent velocity lower than the true phase velocity. Consequently, the refraction microtremor methodology necessitates picking the minimum velocity of the envelope of the energy in the spectral image to obtain the phase-velocity dispersion curve at the site as verified by Pancha *et al.* (2008). This differs from other surface-wave methods such as the passive MASW technique, which requires picking of peaks in frequency–slowness image.

Interactive forward modeling of the measured dispersion curve was preferred to automatic inversion methods. Garofalo, Foti, Hollender, Bard, Cornou, Cox, Ohmberger, *et al.* (2016) reported that intercomparison of dispersion curves between different surface-wave array methods at blind test sites was usually successful but that experienced modelers often produced differing velocity–depth profile results from similar dispersion data. The interactive modeling allowed velocities of prominent layers to be held constant for adjoining models in a neighborhood of the map, if needed. This ensured consistency between adjacent models within a region and minimized variations due to the velocity–depth trade-off (Louie, 2001). Single V_{S30} values used to assess NEHRP-Uniform Building Code requirements were then computed by vertically averaging the resultant depth–velocity profiles using the formula and tables provided in IBC (2009). Figure 2 presents examples of the data, ReMi analysis, and resultant 1D velocity–depth profiles for typical Parcel Map sites in the IBC/NEHRP B, C, and D classification ranges.

The goal of the project was not the absolute accuracy of the velocity–depth profile, but rather characterization of the average shear-wave velocities over a volume beneath each 184-m-wide sensor array. Variability in the estimation of V_{S30} is minimal, due to it being an average parameter and therefore less influenced by the nonuniqueness of the solution for the estimates of individual layer thickness and V_S values. Nevertheless, great care was exercised to produce the most accurate representation of the velocity–depth profile as possible, given the contract requirements, by maintaining consistency between adjacent measurements, incorporation of known constraints, and avoiding overfitting of the dispersion curves with unnecessary layers or inversions, unless required by the data.

Blind tests were periodically conducted to test the repeatability of the data and analysis results. Data from the blind tests were independently analyzed to test for interpreter bias. These analysts differed from those who had analyzed and modeled the original Parcel Map data. Of the 93 randomly selected sites, only 6 of the 93 test sites showed a difference in V_{S30} greater than 10%, with a maximum difference of only 13.55%. The root mean square (rms) difference between the blind analyses and that of the Parcel Map is 4.92% (30 m/s rms difference). The consistency of the V_{S30} results of the blind tests is in agreement with the study of Garofalo, Foti, Hollender, Bard, Cornou, Cox, Dechamp, *et al.* (2016), in which the V_{S30} values were within 4% when a variety of invasive and noninvasive methods were compared at a single site. As V_{S30} is derived from arithmetic slowness averaging of the velocity–depth profile, issues arising due to solution nonuniqueness are mitigated (Comina, 2010). Results of our blind tests as well as those of Garofalo, Foti, Hollender, Bard, Cornou, Cox, Dechamp, *et al.* (2016)

and Comina (2010) highlight the reproducibility and repeatability of surface-wave methods in determination of V_{S30}, and thus the consistency of the Parcel Map measurements.

Results

Parcel Mapping of Clark County and the CoH were produced through the acquisition and processing of more than 10,000 ReMi array measurements, yielding V_{S30} determinations at 10,722 locations in total. Submitted to CCDDS and the CoH, a Geographic Information Systems (GIS) database developed by NSHE and Optim archived the V_S data. For each measurement site, the database provides the array location, a site description, a summary of the ReMi analysis showing the experimentally imaged and calculated dispersion curves, the full velocity–depth profile, and the site classification as per IBC 2006 Section 1613.5.5. This database allowed the generation of the microzonation map in ArcGIS via the method of kriging, using the V_{S30} values determined from the 10,722 seismic arrays distributed throughout the mapping area.

Figure 3 presents the complete microzonation parcel class map measured for Las Vegas Valley. Property owners, builders, city planners, building officials, design professionals, and researchers alike can now consult the Parcel Map to determine the actual, measured NEHRP site class value of any particular parcel, before performing site-specific investigations. The Parcel Map is available to the public through Clark County's website (see Data and Resources). Figure 3a shows classification results from Las Vegas Valley and the Interstate 15 corridor, with the NEHRP site class C+ range in red, C in green, and D in blue (the proposed site class C+ is explained below). Figure 3c displays a portion of the complete V_{S30} map showing enhanced details of the V_{S30} measurement values within Las Vegas Valley, with warmer colors for higher velocities. Thiessen polygons were used to interpolate the point values, defined mathematically by the perpendicular bisectors of the lines between points. Presenting the data in this way, we can see the details of localized stiffer soils (orange and red in Fig. 3c) and softer soils (light purple) that were otherwise unknown prior to Parcel Mapping.

Based purely on the V_{S30} values, the microzonation map in Figure 3a should show site class B values on the west side of Las Vegas Valley. However, IBC (2006, p. 305) Section 1613.5.5 states "The rock categories, Site Classes A and B, shall not be used if there is more than 3048 mm (10 feet) of soil between the rock surface and the bottom of the spread footing or mat foundation." Even though V_{S30} values may give an average velocity representing site class A or B, additional criteria defined in the same section of the IBC (2006, 2009) must be applied by a geotechnical engineer to assess the final site class category. When the V_{S30} value suggests class B, a site-specific assessment can be made (depth of foundation, competency of rock, etc.) to determine whether the site qualifies as a class B. At a majority of the high-V_{S30} sites, our velocity–depth profiles show more than 3.0 m (10 ft) of low-velocity soil at the surface. Accordingly, Clark County and the CoH designate such areas as site class C. An engineer would be best qualified to make a site class determination for such locations based on specific site conditions. We follow this convention adopted by the municipalities and introduce a class C+ here for sites with V_{S30} velocities in the site class B range, with a soft surface soil, denoted with red in Figure 3a.

As is clearly seen from Figure 3a, the municipalities found 84% of the 1500 km^2 Parcel Map area (red and green) to be classified as being stiffer, and potentially safer, than the previously inferred, default NEHRP site class D (blue). The high V_{S30} values observed throughout the Parcel Map region are frequently due to calcite cementation (caliche) of shallow alluvial deposits in isolated layers, as observed by Liu *et al.* (2005). Scott *et al.* (2006) detected large variations in V_{S30} along the Las Vegas Strip, with high values attributed to caliche layers, with velocity inversions to softer material underneath. Thus, a surface-wave technique was essential for the success of the Parcel Map, compared to the *P*-wave refraction mapping employed by Hunter *et al.* (2010) that relied on the assumption that velocity increases with depth, with no velocity inversions occurring.

Out of the 10,722 V_{S30} values used in the Parcel Map, the minimum V_{S30} of 184 m/s was found at two sites, atop the East Vegas Valley Drive landfill and along the Muddy River in Moapa Valley. The maximum V_{S30} of 1353 m/s is located near the base of a small rock outcrop along South Las Vegas Boulevard between Jean and Sloan. All three sites would otherwise be rated NEHRP D, with V_{S30} between 180 and 360 m/s, by the topographic criteria of Wald and Allen (2007), or the geologic classifications of Wills *et al.* (2000) or Wills and Clahan (2006). Only 1680 of the 10,722 Parcel Map measurements, 15.7%, produced V_{S30} values of 360 m/s or lower. The number of sites measured in the NEHRP C class, with V_{S30} between 361 and 760 m/s, was 5723 or 53.4%, leaving 3320 or 31.0% of sites measuring with NEHRP C+ (or B) V_{S30} values above 760 m/s.

The measured Parcel Map shows a clearly definable C+ to C (red to green in Fig. 3a) boundary on the west side of Las Vegas Valley. Mapping of class C+ velocities along the western margin of the valley appear to depict the outlines of three alluvial fan systems and the bajadas in between. Previously existing spot measurements could not define this region of high velocities along the west side of the valley, particularly in the southwest part of the valley (e.g., Luke and Liu, 2008; Luke *et al.*, 2008, 2009; Murvosh *et al.*, 2013). Parcel Mapping greatly increased data density in this region and was necessary to better define both the extent and boundaries of the alluvial fans and to characterize the variation in V_{S30} values observed within them. As seen in Figure 3c within the dashed circle, even within this site class C+ area, V_{S30} measurements vary by as much as 1000 m/s over a 205-m distance.

Figure 3b displays the terrain slope of the Las Vegas Valley, based on the categories defined by Wald and Allen (2007) for tectonic regions. As seen from the topographic

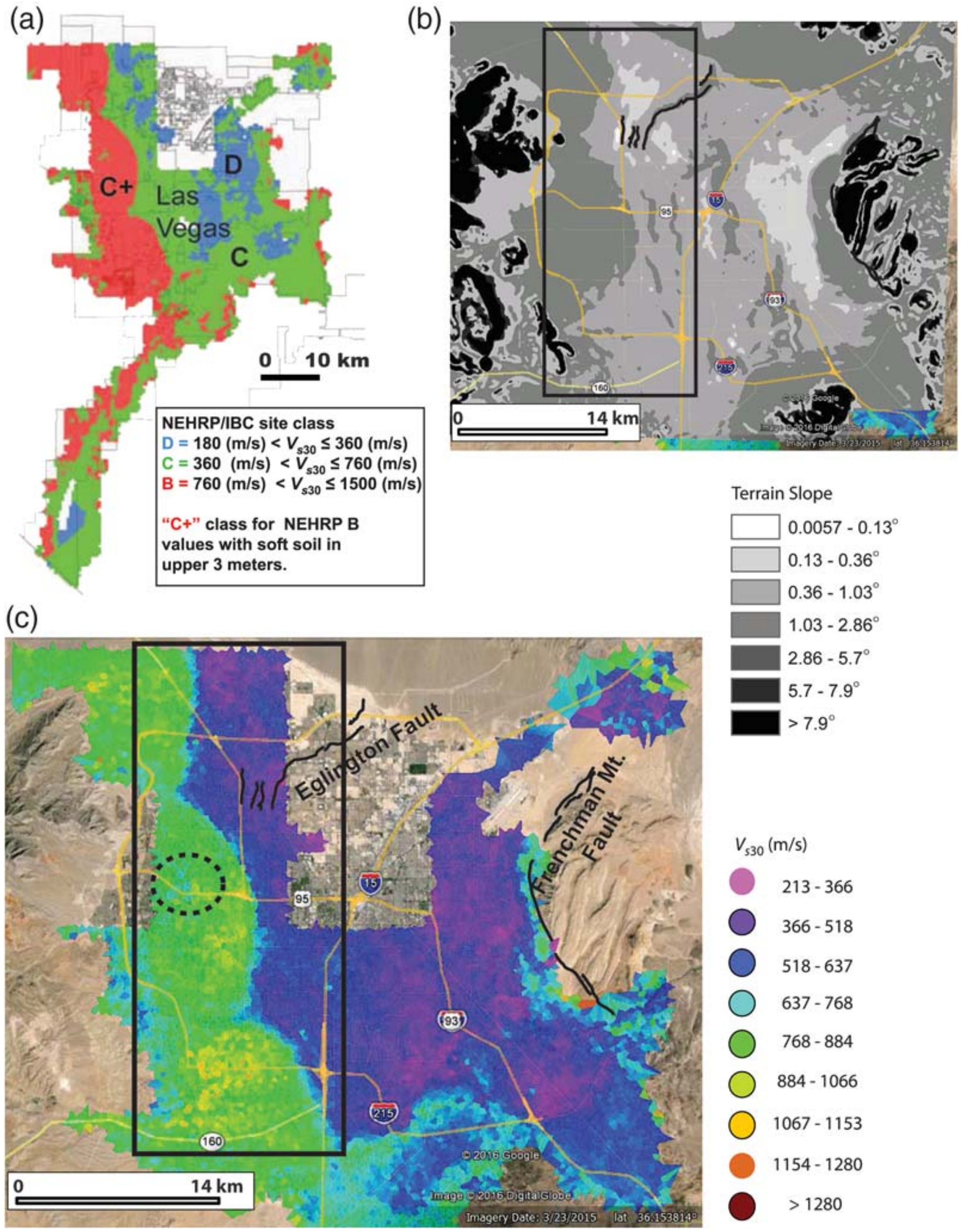

Figure 3. (a) Map showing the NEHRP/International Building Code (IBC) site classification results of the Earthquake Parcel Mapping projects undertaken by Clark County and the CoH. Gray lines are municipal and state boundaries. The NEHRP D zone is blue; the NEHRP C zone is green; and the proposed C+ zone is red. (b) Topographic slope map of Las Vegas Valley, with darker shading for larger slope angle. The slope map was created using 30-m digital elevation models (DEMs). The DEMs were smoothed using the neighborhood mean over a 10-cell circle radius (radius = 10). The eight topographic slope categories are representative of slope ranges for tectonic regions as defined by Wald and Allen (2007). (c) Map of the Las Vegas Valley area of the Parcel Map. Individual V_{S30} values for each array measurement site are displayed using Thiessen polygons with a velocity-color scale, with warmer colors for higher values of V_{S30}. The Thiessen polygon map is mathematically generated from the site locations and defined by the perpendicular bisectors of the lines between the V_{S30}-measurement array center points. The boundaries of each polygon define the area that is closest to each measured point relative to all other points.

slope map (focusing on the black rectangle in Fig. 3b), the class C+ boundary along the western side of the valley, shown in Figure 3a,c (black rectangle), corresponds approximately to the area of higher topographic slope, except in the south. The C+ to C boundary occurs at a different but relatively constant elevation along each of the three alluvial fans. The southernmost fan, as depicted by the high velocities, has no surface expression of slope along its toe.

The well-defined class C+ to C boundary bears little resemblance to the less well-defined and geometrically complex boundary between site classes C and D in the central valley region (green to blue in Fig. 3a). Regions classified as class D show a general association with soils requiring greater geotechnical consideration, as identified by geotechnical soils maps created previously by Clark County (a link to the Expansive Soils Map and the Soils Guidelines Map is provided in Data and Resources). Geological data show a concentration of fine-grained and dune sand deposits within the central valley region (Page *et al.*, 2005; Schmidt and McMackin, 2006; Beard *et al.*, 2007). However, these surface soil hazard and geological maps do not predict the random patches of class C that are scattered within the general region classified as class D area nor the isolated patches of class D within the wider area classified as class C, as directly measured by Parcel Mapping. In several areas, measurement density was increased to better define the observed variation of V_{S30}, aiding in characterization of site class boundaries and identification of localized areas of lower or higher velocities. Where the strands of the Eglington fault intersect the mapped area, a notable decrease in V_{S30} is observed in Figure 3c. It is unfortunate that funding was unavailable to extend the V_{S30} mapping into the city of North Las Vegas to investigate whether this correlation between the Eglington faults and low V_{S30} continued over the remainder of the urbanized area.

Discussion

Data from the Parcel Map contributes valuable information toward earthquake-hazard assessment by identifying soil properties to >30 m depth. The 1D velocity–depth profiles obtained for the Parcel Mapping presented in this study frequently obtained velocity structure as deep as 100 m and provide information regarding near-surface shear-wave velocity values, soil thicknesses and interface depths, maximum depth limits for soils, depths to bedrock, and soil resonant frequencies. The Rayleigh-wave velocity–depth profiles thus provide many of the assessment parameters required for more sophisticated classifications than required by the IBC (IBC, 2009; ICC, 2009), NERHP Provisions (BSSC, 1997), and Eurocode 8 (2004), for determination of loading standards for building code compliance. An example of a more comprehensive hazard classification system, using more of the Parcel Map results, would be the NZS 1170.5:2004 site subsoil classes from Standards New Zealand (2004). Moreover, the unprecedented wealth of velocity–depth information provided through the Parcel Mapping provides the unique opportunity to comprehensively develop and rigorously test more stringent soil and site classifications schemes, for both implementation of building codes and seismic site-response evaluation.

Despite the limitations of the single-value V_{S30} parameter in defining the effects of soil structure on ground motion, applications utilizing V_{S30} still clearly demonstrate its significance for describing the overall site effect on ground-motion estimation (e.g., Sandikkaya *et al.*, 2013). Flinchum *et al.* (2014) validated deterministic computations of ground motions and amplifications against earthquake recordings of the 1992 M_L 5.6–5.8 Little Skull Mountain event (Smith *et al.*, 2001) across Las Vegas Valley, matching amplitudes and time histories of shaking at 0.2 Hz and below. This work included the CCDDS and CoH Parcel Map results from this study in building the 3D geological and geotechnical model for wave propagation. The Parcel Map V_{S30} velocity values replaced default NEHRP site class geotechnical velocities to test the sensitivity of the ground motions. Parcel Map V_{S30} geotechnical details were essential for correctly simulating the data, even for low-frequency computations, as demonstrated by the comparisons made by Flinchum *et al.* (2014). Results from Flinchum *et al.* (2014) confirm the findings of Anderson *et al.* (1996), demonstrating the upper 30 m have a large influence on observed ground motions. Further, the tests clearly demonstrated how individual areas of high or low geotechnical velocities in the very near-surface influence wave propagation, channeling amplifications.

Conclusions

The NSHE and Optim completed the Parcel Mapping project successfully for Clark County and the CoH, Nevada. The Parcel Map was a world-first effort to map earthquake-hazard class systematically through an entire urban area using direct measurements, in detail, at the parcel scale. This density of data was at the explicit request of CCDDS and the CoH. Results of the Parcel Map emphasize the inherent aleatory variability of shallow shear-wave velocities and the variation observed in geologically complex regions.

Parcel Map results demonstrate that 84% of the mapped area is stiffer than the default NEHRP site class D category. Improvement in site class from D to C can result in savings of about 2% of construction costs, depending on the type of structure and location (Ebelhar, 2010). Moreover, the detailed mapping allowed the delineation of a previously undetected high-velocity alluvial fan surface that exhibits no topographic surface expression, as seen from Figure 3b,c. This discovery highlights the fact the topographic slope is not always an appropriate proxy for V_{S30} (as proposed by Wald and Allen, 2007) in Las Vegas Valley. Because of the presence of caliche, the quality of correlations with other geological parameters is also doubtful throughout the mapped area. The lack of reliable correlations and proxies justifies the requirement by the municipalities that measurements be performed at the parcel scale in this project. The Parcel Map also contributes valuable information toward more thorough earthquake-hazard assessment through characterization of site response and 3D velocity models of the near surface for rigorous earthquake simulations.

Through the Parcel Mapping Project, Clark County and the CoH accomplished many of the priorities for action outlined for disaster risk reduction under the Sendai Framework, as detailed in Ⓔ Table S1, available in the electronic supplement to this article. These actions have the goal of preventing and reducing hazard exposure and vulnerability, increasing preparedness for response and recovery, and strengthening resilience. The effort, including the planning, financing, scientific engagement, and resulting shear-wave velocity dataset, represents the extensive commitment that Clark County and the CoH made toward innovative protection of their communities from earthquake disasters.

Data and Resources

The Parcel Map presented in Figure 3a is available to anyone through Clark County's website at http://gisgate.co.clark.nv.us/openweb/ (last accessed July 2016) via the earthquake information page at http://www.clarkcountynv.gov/Depts/development_services/engineering/Pages/EarthquakeInformation.aspx (last accessed August 2015). Clark County has archived all raw data, Geographic Information Systems (GIS) info, processed data, dispersion picks, and V_S–depth profiles. In addition, archive of all V_{S30} values and their locations has been deposited with the University of Nevada, Reno (UNR) and University of Nevada, Las Vegas (UNLV) campus libraries (call number: QE539.2.S34 O685 2010 v1-v3). The Expansive Soils Map and the Soils Guidelines Map created by Clark County and discussed in the article are at http://www.clarkcountynv.gov/Depts/development_services/engineering/Pages/SoilsGeotechnicalMaps.aspx (last accessed August 2015). The digital elevation model shown in Figure 3b was obtained from http://srtm.csi.cgiar.org/ (last accessed August 2016). Authority: The European Union per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC. SeisOpt and ReMi are registered Trademarks of Optim, Inc.

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