Cost-Effective Community Resilience: Detailed Earthquake Hazard Class Mapping

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ABSTRACT: Clark County and the City of Henderson, Nevada completed the USA's first effort to map earthquake hazard class with systematic, direct measurements throughout an entire urban area. Urban development, disaster response planning, and especially building code implementation and enforcement motivated the map development. The local authorities contracted the Nevada Seismological Laboratory to classify ~1500 square kilometres 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 ambient noise as the seismic source. With a typical measurement spacing of 300 m or less, ReMi™ was the only method able to cost-effectively produce the desired, accurate Parcel Map within three years that could be used for building code enforcement.

1 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 miss details of localized safer hard spots and dangerous unknown soft spots that sparse geological and geotechnical data cannot predict, and which only detailed direct measurements can identify. Neither property owners nor local authorities can bear the cost of individualised engineering studies of every block and every building. Likewise, no economy can bear the cost of building and retrofitting to mitigate earthquake risks when guided solely by the currently over-conservative, interpolated, extrapolated, and overgeneralized hazard maps.

Two local authorities, with a population of 2 million within Las Vegas, in southern Nevada (USA) (Figure 1), addressed this challenge with a comprehensive Earthquake Parcel Mapping program. Clark County and the City of Henderson completed the USA's first effort to map earthquake hazard class with systematic measurements through an entire urban area. Carried out by Optim and the Seismological Laboratory at the University of Nevada, Reno, the project classified an area of ~1500 square kilometres. The resulting "Parcel Map" includes over 10,000 surface-wave array measurements completed within three years. Optim's SeisOpt® ReMi™ refraction microtremor measurement and processing technology, adapted for large-scale data collection, obtained shear-wave velocity-depth profiles at the 10,000 sites. The noisy urban setting necessitated use of ambient noise as the seismic source, making ReMi™ the only cost-effective method available for such detailed mapping. ReMi™

velocity-depth profiles provide all the details required to determine NZS 1170.5:2004 site subsoil classes: near surface shear-wave velocity data; depths to soil interfaces; natural period from velocities and interface depths; maximum depth limits for "Class C" soils; and depths to bedrock.

Figure 1. Map showing the location of Las Vegas, Nevada, USA.

The Parcel Map benefits the entire community, including engineering companies, builders, owners, planners, emergency responders, and the public in addition to local authorities. Information from the Parcel Map will be integrated with geological data and other hazard assessments to help formulate policy towards mitigating the risks from earthquakes. In the wake of the Christchurch earthquakes and the degree of liquefaction that occurred, the need to systematically measure shallow (<30 m) and deep shear-wave velocities for detailed site condition characterisation in our metropolitan regions is evident.

1.1 Why the need to map site class?

The propagation velocities of seismic waves are modified by differences in near surface material. These differences in material composition can amplify seismic waves and increase shaking during an earthquake. Amplification refers to the amplitude of the seismic waves and the intensity of their shaking. The less rigid, less coherent, less consolidated, and thus lower-velocity the material, the higher the amplification and greater the potential for damage to structures. Amplification is sensitive mainly to shear-wave velocities. Site Class Parcel Mapping will map the near-surface shear-wave velocities and identify localised soft spots. This will help identify existing buildings that could be subjected to severe shaking in the event of an earthquake, while new construction can confidently be built to code with the Parcel Map in hand. City officials can plan retrofitting and ensure buildings meet requisite safety standards.

1.2 Information provided by Parcel Mapping

The shear-velocity mapping yields velocity versus depth information that will provide:

- Near surface shear-wave velocity data, indicating material strength.
- Velocities also indicating material characteristics.
- Depths to soil interfaces.
- Natural period, from velocities and interface depths.
- Maximum depth limits for soils.
- Depths to soil-bedrock interface.

1.3 How does velocity-depth mapping help identify liquefaction potential?

Seismic velocity of soils is a mechanical property, directly related to the stiffness and shear strength of the soil material. These in turn are indicators of liquefaction potential.

2 THE REFRACTION MICROTREMOR (REMI™) METHOD

2.1 Methodology

The essence of the ReMi™ technique is that ambient noise caused mainly by human activities (e.g. trucks, trains, airplanes, machinery, tree movements, and wave action) contains usable signal that can be used to predict velocity structure underneath the measurement array. Microtremor noise from these sources excite Rayleigh waves in the ground, which are recorded by a linear array of vertical geophones similar to those used for a conventional seismic refraction survey. The advantages of ReMi™ from a seismic surveying point of view are several, including: it requires only standard, commonly used seismic refraction equipment; it requires no triggered source of wave energy; and it will work best in a seismically noisy urban setting. Traffic and other vehicles, and possibly the wind responses of trees, buildings, and utility standards provide the surface waves this method analyses.

The data acquisition procedure consists of recording several 30-second records on linear, 24-channel geophone arrays. Figure 2 illustrates a typical array deployment. The Rayleigh waves contained in the recorded microtremors (ambient noise) are separated from other wave arrivals using a two dimensional slowness–frequency (p–f) transform of the noise records. The fundamental-mode phase-velocity Rayleigh wave dispersion curve is picked along the minimum velocity of the energy envelope within the slowness–frequency spectral image (Figure 3A). The spectrum is normalized as the ratio of the power spectrum at a particular frequency and slowness (inverse velocity) over the average value for all slowness values at that frequency (Louie 2001). Modelling of the dispersion curve (Figure 3B) produces a depth–velocity model (Figure 3C). The velocity model determines the surface-to-30-m depth average Vs30 value for the site as well as soil depths, used for determining building code site class using the International Building Code (IBC, 2006 and 2009) or the New Zealand Standard ™ (NZS 1170.5:2004; Table 1 and Table 2). The preferred profile will always be the profile interpretation that results in the minimum number of layers to accommodate the observed Rayleigh-wave dispersion and produces a best estimate, reliable, and repeatable velocity structure.

Figure 2. Ambient noise is recorded and analysed to determine one-dimensional (1-D) shear wave velocity profile (Figure 3) beneath each seismic profile.

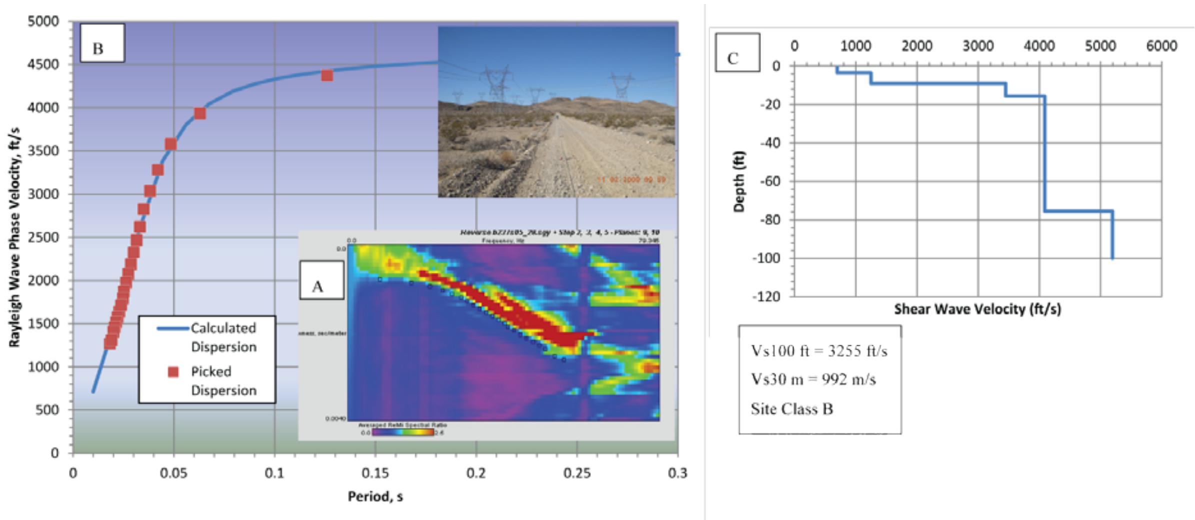

Figure 3. Recorded ambient (microtremor) data are first transformed into the frequency-slowness domain (Louie, 2001) (A). These dispersion picks are modelled (B) to obtain a 1D shear-wave velocity profile (C) that matches these picks.

2.2 The New Zealand building Code

Past earthquakes throughout the world have demonstrated that the local geologic (site) conditions influence the intensity of ground shaking and earthquake damage. Structural design in New Zealand takes into consideration site conditions largely through the loading standard (NZS 1170.5:2004) specified by the New Zealand Standard ™ Structural Design Actions. The loading standard prescribes structural design actions on the basis of site subsoil class to accommodate likely increased earthquake loadings due to shaking modification. The New Zealand Standard ™ describes five site subsoil class categories, based on geological and geotechnical properties. Site subsoil classes D (soft or deep soil) and E (very soft soil) require increased loadings to be considered, resulting in increased design and construction costs.

The New Zealand site classification also uses the “site period” parameter. Site period is measured directly from ground motions. When not measured directly, it is defined as four times the shear wave travel time from the surface to bedrock. This approach addresses the effects of deeper softer soils, which exhibit longer period site response characteristics. However, the ability to classify sites using shear-wave velocities has been limited by a lack of data. The velocity-depth profiles determined through the Parcel Mapping provide the parameters outlined in Section 1.2 towards determination of site subsoil class at each of the survey locations.

Table 1. NZS1170.5:2004 Site Subsoil Classes.

Class	Description	Definition
A	Strong Rock	UCS > 50 MPa & Vs30 > 1500 m/s and not underlain by < 18 MPa or Vs 600 m/s materials.
B	Rock	1 < UCS <50 MPa & Vs30> 360 m/s and not underlain by < 0.8 MPa or Vs 300 m/s materials, a surface layer no more than 3 m depth (HW-CW rock/soil).
C	Shallow Soil	not class A, B or E, low amplitude natural period ≤ 0.6s, or depths of soils not exceeding those in Table 2.
D	Deep or Soft Soil	not class A, B or E, low amplitude natural period > 0.6s, or depths of soils exceeding those in Table 2, or underlain by < 10 m soils with undrained shear strength < 12.5 KPa, or < 10m soils SPT N < 6.
E	Very Soft Soil	> 10m soils with undrained shear strength < 12.5 KPa, or > 10m soils with SPT N < 6, or > 10m soils with Vs ≤ 150m/s, or > 10m combined depth of previous properties.

Table 2. Maximum depth limits for site subsoil class C.

Soil type and description		Maximum depth of soil (m)
Cohesive Soil	Representative undrained shear strengths (KPa)	
Very soft	< 12.5	0
Soft	12.5-25	20
Firm	25-50	25
Stiff	50-100	40
Very stiff or hard	100-200	60
Cohesionless	Representative SPT N values	
Very loose	< 6	0
Loose dry	6-10	40
Medium dense	10-30	45
Dense	30-50	55
Very Dense	> 50	60
Gravels	>30	100

3 LAS VEGAS PARCEL MAP RESULTS

3.1 Project Description

Measurement of shear-wave velocity (Vs) in the shallow subsurface is essential for seismic hazard assessment. The time-averaged shear-wave velocity value for the top 100 feet or 30 meters (Vs100-foot or Vs30-meter) as per IBC 2006 Section 1613.5.5 representing the site class measurement is integral to the seismic design of structures per the International Building Code and International Residential Code (IBC and IRC, respectively). Clark County and the City of Henderson required velocity measurements to maintain a minimum density of 6 arrays per square kilometre (1 array per 40 acres).

3.2 Resulting Parcel Map

Figure 4 shows representative results from sites yielding velocities in the NEHRP B, C, and D ranges. Based purely on the Vs30-meter (Vs100-foot) values, the Parcel Map (Figure 4) should show Site Class B values on the west side of Las Vegas Valley. However, IBC (2006) Section 1613.5.5 states that: “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.” Accordingly, Clark County and the City of Henderson designate such areas as Site Class “C+”.

The measured Parcel Map shows a clearly definable C+ to C (red to green) boundary on the west side of the Valley. Mapping along the western margin of the Valley clearly depicts outlines of alluvial fan systems. Comparisons with surface elevations indicate that the southernmost fan has no surface expression whatsoever. It is evident that the Parcel Mapping was able to reveal well-defined details that would otherwise be unknown. Previously existing sparse spot measurements could not define hidden alluvial fan boundaries. The C to D (green to blue) boundary is much more complex. The most important revelation of the Parcel Map was that 84% of the approximately 1,500 square kilometre region was found to be stiffer than the default Site Class D default previously assumed for the whole of Las Vegas Valley by the municipalities, based on map generalised over-conservative hazard mapping.

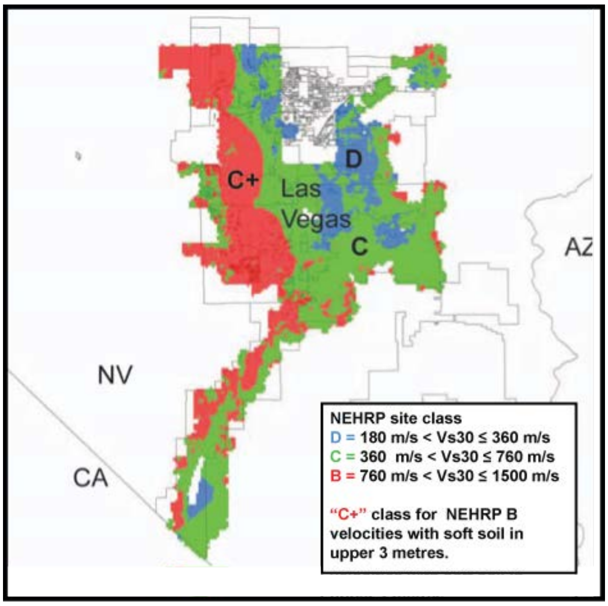

Figure 4. The resultant site classification Parcel Map: 84% of the 1500 square km area was found to be stiffer and safer than previously specified by the generalised hazard maps.

Figure 5 shows the complete Parcel Map for Las Vegas Valley, using the Vs30-meter values determined from the distribution of seismic arrays. This map was generated in ArcGIS via the method of kriging. The velocity measurements uncover the details of the localised safer hard spots. The map also highlights dangerous soft spots within the higher velocity areas that were unknown prior to these densely spaced direct measurements. Only detailed direct measurements can identify such variations.

4 CONCLUSIONS

4.1 Success and Benefits of the Las Vegas Parcel Map

The maps generated result in a more reliable hazard evaluation with all the detail needed at the parcel, block, and building scale. They are being used by Clark County as a resource for the general public, builders, engineers, developers and government officials. The shear-wave velocity measurements provide information towards building code enforcement through the resultant velocity-depth profiles, providing information on velocities, soil thicknesses, interface depths, and resonant frequencies. The Parcel Map contributes valuable information towards earthquake hazard assessment by identifying soil properties to depth, which in turn provide details on the shear modulus and elastic properties of the near-surface materials. The resulting map was used to build a 3D geological and geotechnical model for wave propagation and earthquake scenario modelling. Flinchum et al. (2014) have validated deterministic computations of ground motions and amplifications against earthquake recordings of the 1992 ML 5.6–5.8 Little Skull Mountain event (Smith et al. 2001).

The final Parcel Map benefits the entire community, including engineering companies, builders, owners, planners, emergency responders, and the public, in addition to the territorial authorities. The Parcel Map demonstrated that 84% of the region was stiffer than the default site class category value of "D", saving property owners and Nevada's economy billions of dollars in unneeded, and unjustified, over-strengthening. Nevertheless, large projects still require specific engineering studies. The effort represents the extensive commitment that Clark County and the City of Henderson have made towards innovative protection of their communities from earthquake disasters.

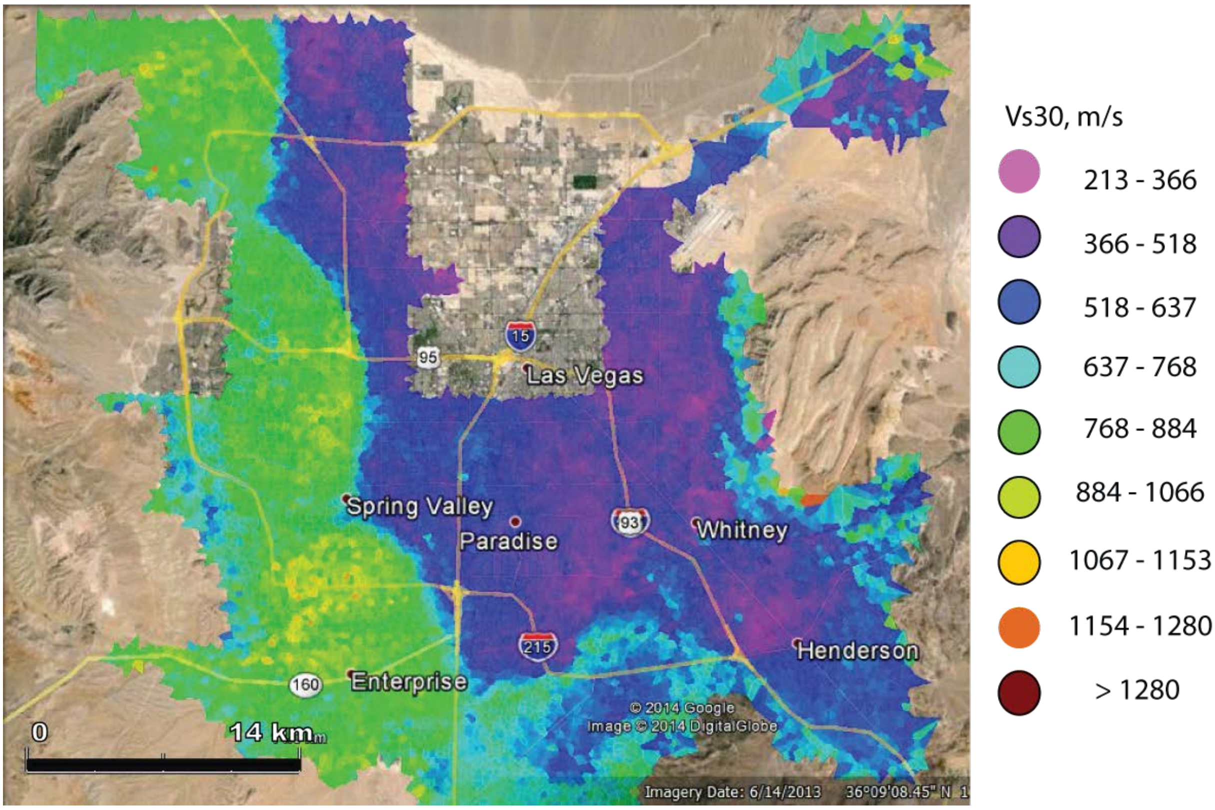

Figure 5. A portion of the Parcel Map generated in ArcGIS via the method of kriging. The detailed mapping uncovers the details of localized safer hard spots (warm colours) and dangerous soft spots (lavender colour) that only detailed direct measurements can identify.

5 REFERENCES

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