PACIFIC EARTHQUAKE ENGINEERING
RESEARCH CENTER

Seismic Velocity Site Characterization of Thirty-One Chilean Seismometer Stations by Spectral Analysis of Surface Wave Dispersion

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PEER Report 2014/05
Pacific Earthquake Engineering Research Center
Headquarters at the University of California, Berkeley

April 2014

ABSTRACT

We present one-dimensional shear-wave velocity (V_S) profiles at 31 strong-motion sites in Chile, from Valdivia in southern Chile to Copiapo in the northern Atacama Desert. We estimate the V_S profiles with the spectral analysis of surface waves (SASW) method. The SASW method is a non-invasive method that is useful for indirect estimate of the V_S at depth from variations in the Rayleigh wave phase velocity at the surface. The purpose of the study is to determine the detailed site velocity profile, the average velocity in the upper 30 m of the profile V_{S30}, the average velocity for the entire profile, $V_{S,z}$, and the NEHRP site classification.

ACKNOWLEDGMENTS

This work was supported by the USGS Award Number G12AP20008, and the Pacific Earthquake Engineering Research Center (PEER) as part of NGA-Subduction Research Project. This support is gratefully acknowledged. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the sponsoring agencies.

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1.1 INTRODUCTION

This project focuses on the measurement of shear-wave velocity (V_S) of the near-surface materials at strong-motion recording stations in Chile. During four data collection campaigns, data were collected in the states of Atacama, Coquimbo, Valpariso, Metro Region, Libertador, Maule, Bio Bio, Araucania, and Los Rios. These states are regionally instrumented with permanent seismometer recording stations. In addition, these stations have been supplemented with more closely-spaced temporary aftershock recorders in response to local seismic activity. The V_S profiles presented in this report are collected for calibration of strong-motion site amplification models based on direct measurement of velocity, by topography, or by surface geologic unit. Data presented here were gathered using the continuous harmonic sine wave approach for the spectral analysis of surface waves presented by Kayen et al. [2004, 2013], which is a stepped-sine wave method that utilizes a notch-filter methodology that improves on the approach developed by Satoh et al. [1991). The continuous swept-sine wave spectral analysis of surface waves (CSS–SASW) test is an inexpensive and efficient means of non-invasively estimating the near-surface V_S of the ground. Though it is possible to measure V_S in cased boreholes or by penetration tests, these approaches tend not to be useful for evaluation of Chilean strong-motion sites as they cannot reach the meaningful depths required for seismic site response analysis without expensive drilling and casing. Because many of the Chilean sites are stiff profiles with weathered bedrock, near the surface penetration methods are not useful.

1.2 MAULE EARTHQUAKE

The 27 February 2010 Maule, Chile, earthquake (Mw = 8.8) is the fifth largest earthquake to occur since 1900. Its effects were felt over 600 km of the central Chile coast. The Mw = 8.8 earthquake occurred in a subduction zone where the Nazca plate passes eastward and downward beneath the South American plate. The rate of convergence of the two plates is 70 mm/year. The mainshock occurred at 3:34 AM local time on 27 February 2010; its epicenter was located at -36.027° and -72.834° with a hypocentral depth of 30 km. Field observations suggest that tectonic displacement of the hanging wall produced both uplift of over 2 m and subsidence of up to 1 m in coastal regions. Strong shaking lasted for over a minute in some areas, and widespread damage occurred in some cities. A large number of significant aftershocks resulted in additional damage to an already fragile infrastructure.

1.3 STUDY SITES

Between 25 September 2012 and 25 June 2013, testing was performed at 31 sites across a broad region of Chile, from Latitude 40°S in Valdivia, Region de Los Rios to Latitude 27°S in Copiapo, Atacama Region; see Figure 1. Listed in Table 1 are the V_S profiles for local site conditions in nine administrative regions in Chile.

Figure 1 **Surface wave test locations for 31 sites in Chile affected by the 2010 Maule Mw8.8 earthquake.**

Table 1 **Chilean seismometer, SASW test number, inversion V_{s30}'s, NEHRP code, PGA from Maule event, latitude, longitude, and site name.**

ID	Station	SASW Test #	Vs30 Man.	Vs30 Auto.	NEHRP Man.	NEHRI Auto.	PGA (g) 2/27/10	Latitude	Longitude	Site
1	COPI	993COPI	349	339	D	D	0.022	-27.374	-70.322	COPIAP-HOSPITAL
2	VALLE	992VALLE	561	549	C	C	0.019	-28.576	-70.755	VALLENAR-HOSPITAL
3	PAP	991PAPU	687	714	C	C	0.352	-32.507	-71.448	PAPUDO
4	ROBL	990ROBLE	1951	1999	A	A	0.188	-32.976	-71.016	CERRO EL ROBLE
5	OLMU	981-OLMU	372	376	C	C	0.354	-32.994	-71.173	OLMU-Casa
6	VINA	979VIN	289	290	D	D	0.27	-33.0253	-71.553	VINA DEL MAR
7	VALU	967VALU	925.6	1026	B	B	0.204	-33.035	-71.596	VALPARASO-UTFSM
8	MAR	980MAR	280	261	D	D	0.345	-33.048	-71.51	VDM-MARGA MARGA
9	VAL	968VALP	454	429	C	C	0.244	-33.048	-71.604	VALPARASO-Almendral
10	CASB	983CASB	303	312	D	D	0.328	-33.321	-71.411	CASABLANCA-Teatro
11	LCON	963LCON	619	615	C	C	0.224	-33.396	-70.537	LASCONDES
12	SLUC	965SLUC	1411	1400	B	B	0.338	-33.441	-70.643	SANTIAGO-CerroSTA. LUCIA
13	LRNA	964LRN	574	615	C	C	0.308	-33.452	-70.531	LA REINA
14	SANT	966SANT	420	483	C	C	0.26	-33.467	-70.652	SANTIAGO-Conjunto
15	HTIS	962HTIS	312	307	D	D	0.294	-33.501	-70.579	PENALOLEN-Hospital
16	CRMA	985CRMA	428	466	C	C	0.518	-33.509	-70.772	MAIP-Centro
17	MET	988MET	598	638	C	C	0.197	-33.514	-70.606	LA FLORIDA METRO
18	ANTU	970ANTU	621	621	C	C	0.272	-33.569	-70.634	LA PINTANA
19	HSOR	989HSOR	496	524	C	C	0.264	-33.577	-70.581	PUENTEALTO HOSP
20	LLO	984LLO	360	377	C	C	0.424	-33.616	-71.611	LLOLLEO
21	SNJM	969SJM	495	491	C	C	0.48	-33.641	-70.354	SAN JOSE DE MAIPO
22	MELP	986MELP	636	620	C	C	0.777	-33.687	-71.214	MELIPILLA-Compaa
23	MAT	987MAT	370	372	C	C	0.325	-33.96	-71.873	MATANZAS-Escuela
24	HUAL	973HUA	528	541	C	C	0.423	-34.977	-71.805	HUALA-Hospital
25	CURI	971CUR	537	510	C	C	0.439	-34.99	-71.236	CURIC-Hospital
26	CONT	974CONST	294	NO SOL	D		0.594	-35.34	-72.406	CONSTITUCIN-Hospital

ID	Station	SASW Test #	Vs30 Man.	Vs30 Auto.	NEHRP Man.	NEHRI Auto.	PGA (g) 2/27/10	Latitude	Longitude	Site
27	TAL	972TAL	548	551	C	C	0.45	-35.43	-71.665	TALCA-Colegio Integrado SAN PO X
28	CONC	977CONC	423	361	C	C	0.338	-36.828	-73.048	CONCEPCIN-Colegio Inmaculada Concepcin
29	CCSP	978CCSP	332	340	D	D	0.649	-36.844	-73.109	CONCEPCIN-Colegio San Pedro De La Paz
30	ANGO	975ANG	417	419	C	C	0.796	-37.795	-72.706	ANGOL-Hospital
31	VALD	976VLD	454	429	C	C	0.113	-39.831	-73.239	QDR

1.3.1 Region A: Santiago Area

Stations near the city of Santiago experienced an average peak ground acceleration (PGA) of about 0.32*g*. Figure 2 shows that 9 stations are located within a 15-km-radius circle. The station San Jose De Maipo (SNJM) is located on a thick fluvial gravel deposit in a river valley above and south of the city of Santiago. All stations are located on the gravel soils; shear-wave velocities were available for three stations using two different survey methods.

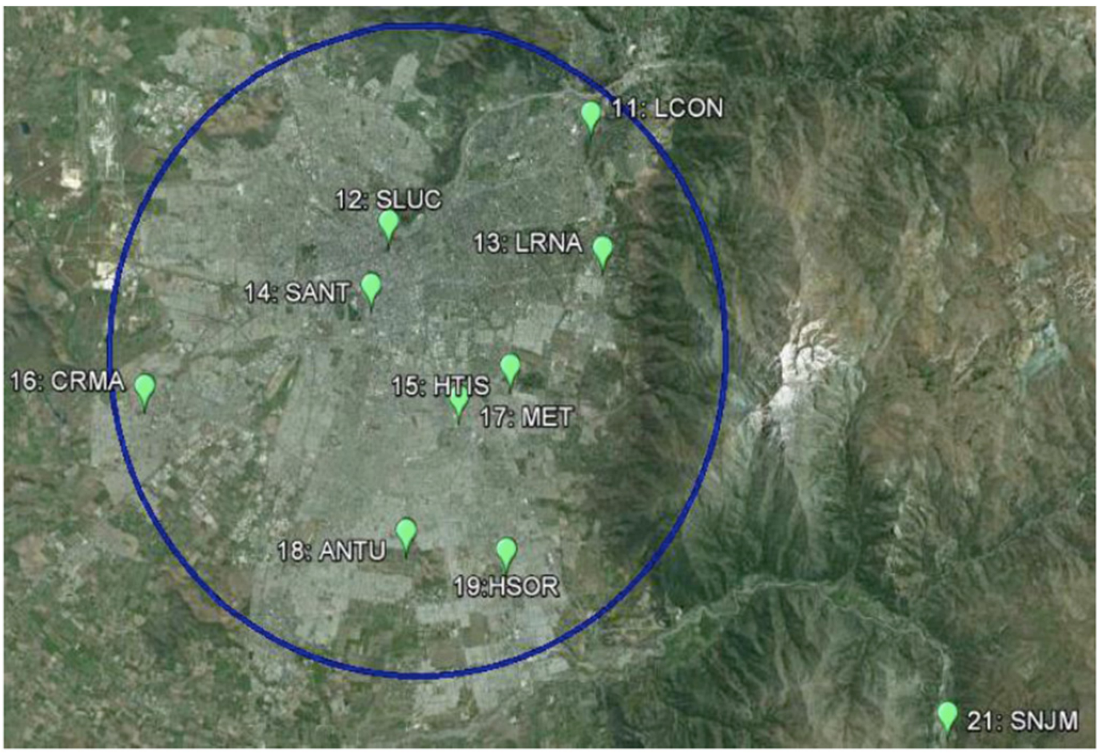

Figure 2 Station locations in the Santiago, Metropolitan, and Libertador regions.

1.3.2 Region B: Valparaiso Area

As shown in Figure 3, four stations are located in Valparaiso and Vin del Mar within a 10-km-radius circle area, which felt an average PGA of 0.32*g*. Midorikawa [1992] studied this region by comparing the acceleration recordings at rock site (VALU) and soil sites (VINA and VAL). That report describes a V_S profile estimated at VINA from a boring and measured at Station VAL (the V_S profile is available in Sargoni [2005]). Midorikawa noted that the VINA measurement may include soil-structure interaction effects due to the adjacent building. The paper describes granite rock exposed at Station VALU for which V_{S30} was estimated as 1300 m/sec; see Arenda and Saragoni [1994]. The V_{S30} at Station MAR was estimated at 280 m/sec; see Daza [2003].

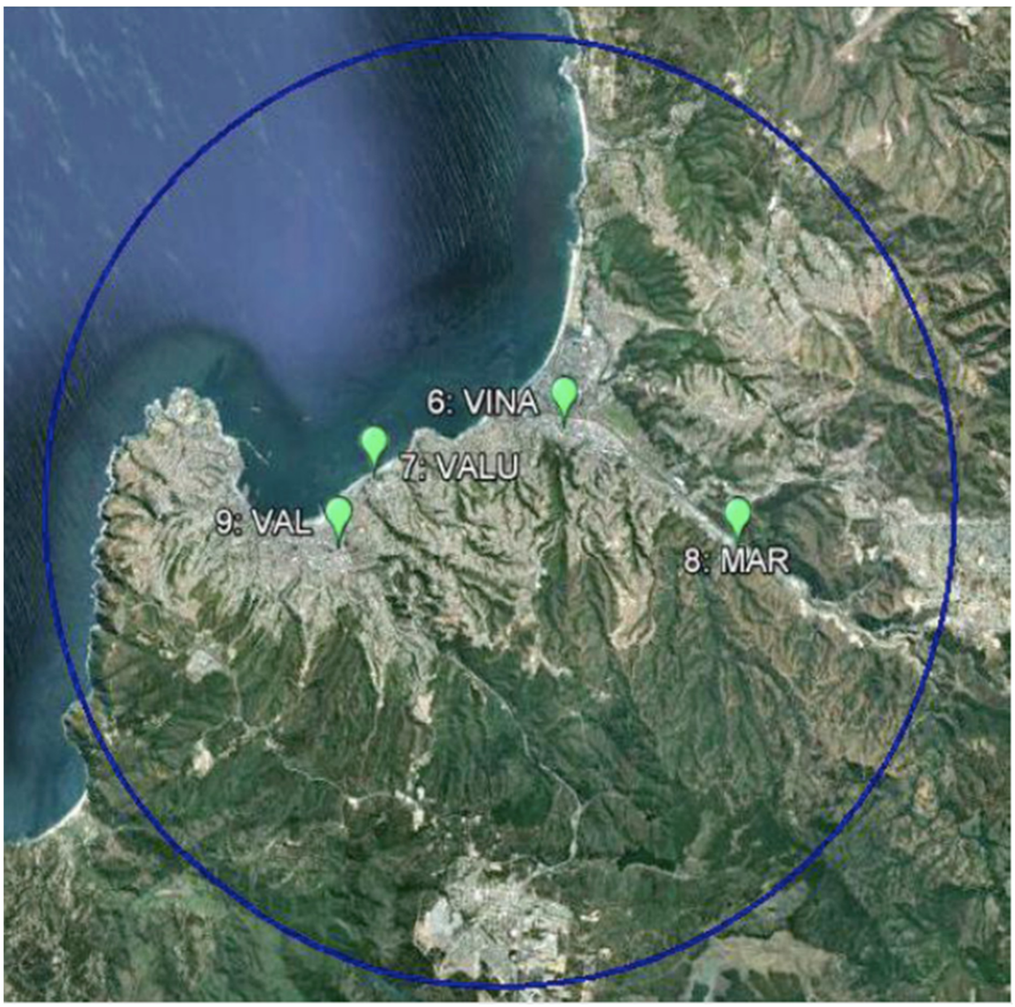

Figure 3 Station locations at Valparaiso and Vin Del Mar in the Valpariso region.

1.3.3 Region C: San Antonio Area

Four stations near the city of San Antonio felt an average PGA of 0.46*g*. Figure 4 shows four stations within a 40-km-radius circle; thus CASB is about 80 km away from MAT. Of the four stations, down-hole measurements are available at CASB, MELP, and MAT; see Boroschek et al. [2012]. The other station (LLO) also has a V_{S30} profile up to 19 m; see Arenda and Saragoni [1994].

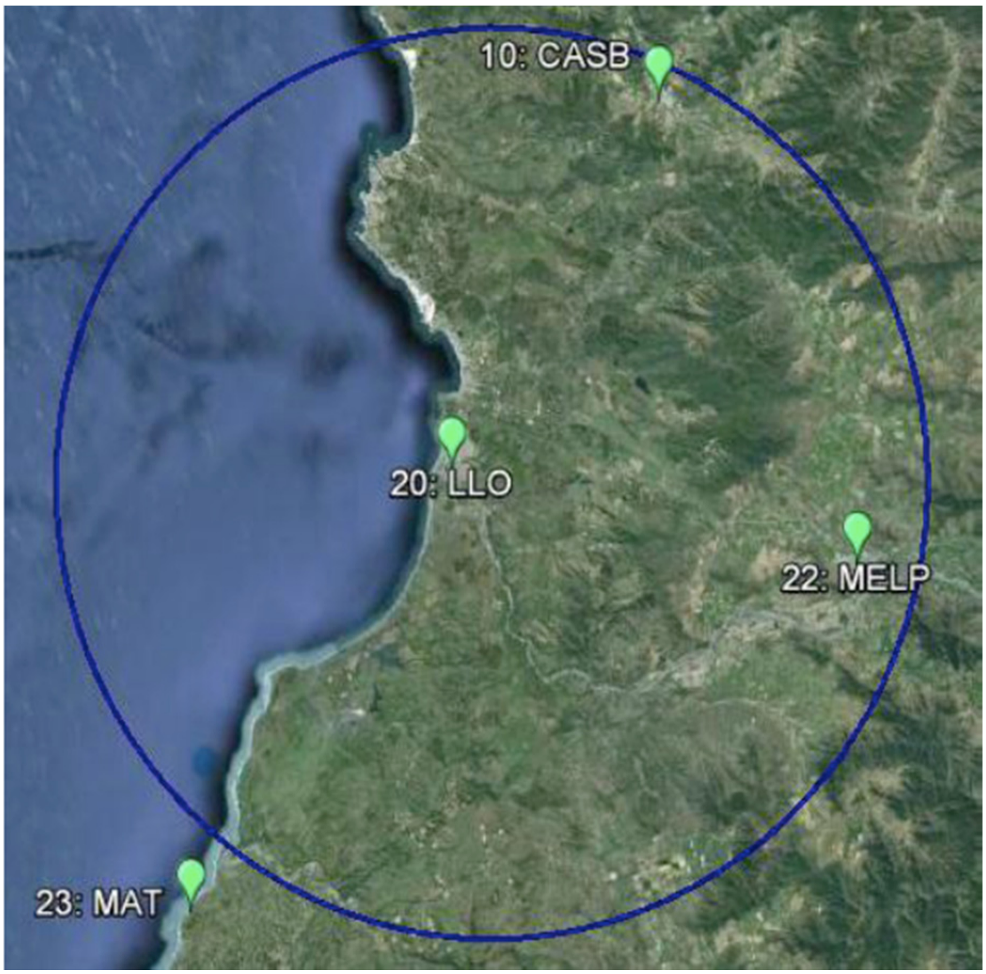

Figure 4 Station locations in the San Antonio region.

1.3.4 Region D: Talca Area

Four stations near city of Talca felt an average PGA of 0.48*g*. Figure 4 shows these stations within a 40-km-radius circle; thus, CURI is about 110 km away from CONT. The shear-wave velocity measurements were obtained for all these stations by the down-hole method and by micro-tremor measurements; see Boroschek et al. [2012] and Kataoka [2011], respectively.

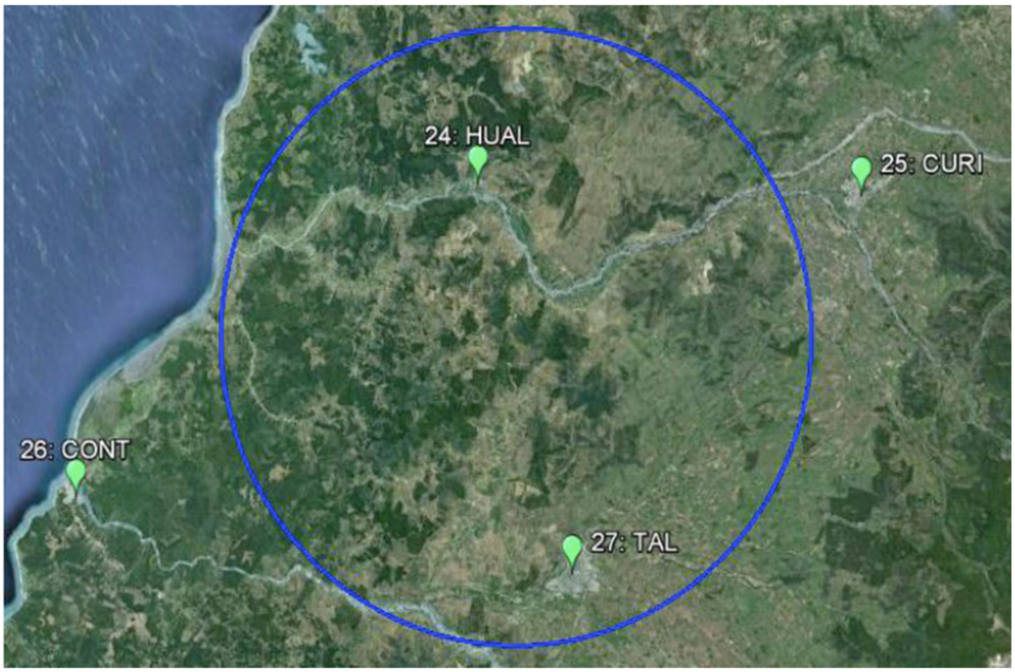

Figure 5 **Station locations in the Maule region near Talca, Constitucion, Curico, and Hualane.**

1.3.5 Regions E and F: Olmue Area and Papudo

Three stations located near the cities of Olmue and Papudo felt an average PGA of 0.27*g* in the Olmue area and 0.45*g* in Papudo. As shown in Figure 6, two stations are within a 10-km-radius circle of Olmue and one station in Papudo; these stations are separated by 60 km. There are no available shear-wave velocity measurements for the two stations (ROBL, OLMU) located in Olmue. In Papudo, the shear-wave velocity profile is available up to depth of 16 m; see Arenda and Saragoni [1994].

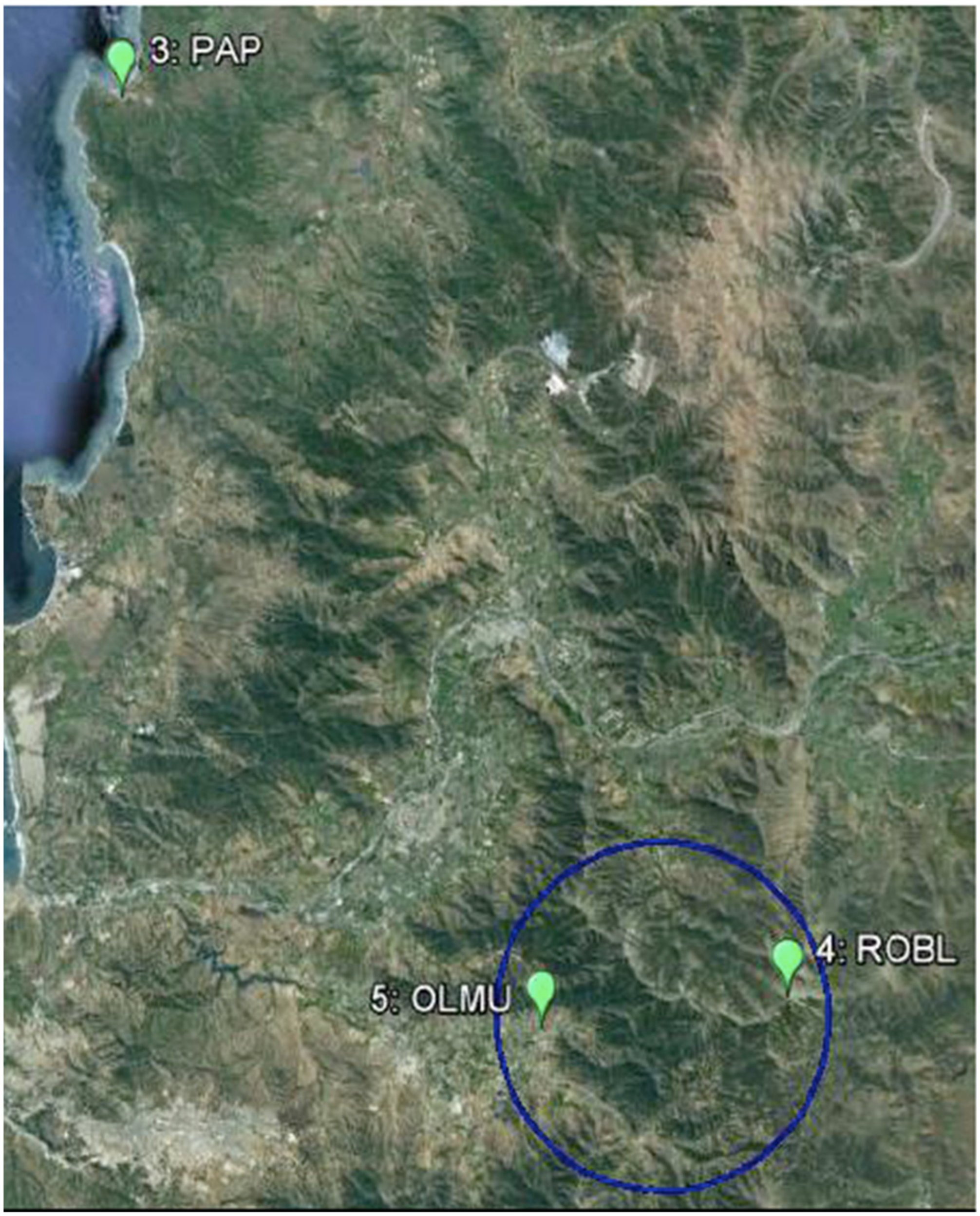

Figure 6 Station locations near Olmue and Papudo northwest of Santiago.

1.3.6 Region G: Concepcion Area

Two stations are located near the city of Concepcion, which felt an average PGA of 0.49*g*. Figure 7 shows the two stations within a 5-km-radius circle. Boroschek et al. [2012] obtained shear-wave velocity measurements for both stations.

Figure 7 Station locations near the city of Concepcion in the Bio Bio region.

1.3.7 Regions H and I: Angol and Valdivia Areas

The cities of Angol and Valdivia have one station each. During the Maule earthquake, PGAs of 0.80*g* and 0.11*g* were felt in in Angol and Valdivia, respectively. Figure 8 shows that the two stations are separated by 240 km. The shear-wave velocity is available at ANGO in Angol [Boroschek et al. 2012], but not available at VALD in Valdivia.

Figure 8 Station locations near Angol and Valdiva areas, in de Los Rios region.

1.3.8 Region J: Copiapo Area

Table 1 and Figure 8 show the station information and their locations near the city of Copiapo. Peak ground accelerations were 0.022*g* at COPI and 0.019*g* at VALL. Figure 8 shows that the two stations are separated by 140 km; VALL is about 500 km north of the city of Santiago. Because the shaking level was small and far away from the other stations, these sites were considered a low priority in obtaining shear-wave velocity profiles.

Figure 9 Station locations near Vallenar, Coquimbo, and Copiapo, Atacama.

1.4 RAYLEIGH WAVE DISPERSION

Active-source surface wave analysis testing typically profiles the upper tens of meters of the ground using drop weights or harmonic sources. The upper 30 m is needed to compute the widely used site parameter V_{S30}, defined as 30 m divided by the shear-wave travel time to 30 m depth. The SASW method employed in this study by the U.S. Geological Survey is a technique that uses a parallel array of mass shakers. This method allows for profiling to depths up to 100 m without the use of massive drop weights or heavy track-mounted machinery. For this method, we substituted using a low-frequency array, in the 100 Hz-1 Hz range, with electro-mechanical shakers. Surface waves were generated with an array of up to several APS Dynamics Model 400 shakers and amplifier units, powered by a generator and controlled by a spectral analyzer.

The shakers have a long-stroke capable of cycling to as low as 1 Hz. The output signal from the spectral analyzer is split into a parallel circuit and sent to the separate amplifiers. The amplifiers power the shakers to produce a continuously vibrating, coherent, in-phase harmonic-wave that vertically loads the ground. Most of this energy produces Rayleigh retrograde elliptical surface waves that propagate away from the source in a vertical cylindrical wavefront perpendicular to the ground surface. The amplitude of the surface waves decay exponentially with depth, such that the energy of the wavefront is centered at a depth of approximately one-third to one-half the wavelength.

Frequency domain analyses are made on two or more signals received by sensors placed in the field in the linear array some distance from the source. First, all channels of time domain data are transformed into their equivalent linear spectrum in the frequency domain using a Fourier transform. One of the sensor's signals (typically the sensor closest to the source) is used for a reference input signal, and the other sensor signals are used to compute the linear spectrums of the output. The separation of the reference seismometer and output seismometer ($d_s - d_{ref}$) radially from the source is later used to compute the wave velocity. The cross-power spectrum, $G_{xy}(\omega)$, is determined by multiplying the complex conjugate of the linear spectrum of the input signal, $S_x^*(\omega)$, and the real portion of the linear spectrum of the output signal, $S_y(\omega)$. The cross-power spectrum is defined as

$$G_{xy}(\omega) = S_x^*(\omega) \cdot S_y(\omega) \tag{1}$$

The autopower spectrum, a measure of the energy at each frequency of the sweep, can be used to determine the strength of individual frequencies and is equal to the linear spectrum of a given sensor times its complex conjugate pair:

$$G_{xx}(\omega) = S_x(\omega) \cdot S_x^*(\omega) \tag{2}$$

and

$$G_{yy}(\omega) = S_y(\omega) \cdot S_y^*(\omega) \tag{3}$$

A cross-power spectrum can be represented by its real and imaginary components, and by its phase θ and magnitude m. The phase θ is the relative lag between the signals at each frequency; the magnitude is a measure of the power between the two signals at each frequency. Because the phases are relative, they can be stacked to enhance signal-to-noise ratio of the phase lag at each frequency.

The phase of the cross-power spectrum is computed as the inverse tangent of the ratio of the imaginary and real portions of the cross-power spectrum:

$$\theta_{xy}(\omega) = \tan^{-1} \frac{\mathrm{Im}\left[G_{xy}(\omega)\right]}{\mathrm{Re}\left[G_{xy}(\omega)\right]} \tag{4}$$

The travel time $t(f)$ of one cycle of a wave of frequency (f) is computed as,

$$t(f) = \theta(\omega)/\omega \tag{5}$$

and the wavelength, λ, at each frequency is

$$\lambda(\theta) = \left(d_s - d_{ref}\right)/\theta(f) \tag{6}$$

The Rayleigh wave velocity, V_r, is computed as

$$\begin{aligned} V_r(f) &= \left(d_s - d_{ref}\right)/t(f) \\ &= f \cdot \left(d_s - d_{ref}\right)360°/\theta \quad \text{(degrees)} \\ &= f \cdot \left(d_s - d_{ref}\right)2\pi/\theta(\phi) \quad \text{(radians)} \\ &= f \cdot \lambda(f) \end{aligned} \tag{7}$$

The SASW procedure maps the change in θ across the frequency spectrum and merges these phase lags with the sensor array geometry to measure velocity. Typically with the shaker source, the discrete frequencies are cycled in a swept (stepped)-sine fashion across a range of low frequencies (1–200 Hz). Rayleigh-wave phase velocity is then mapped in frequency or wavelength space. This velocity map or profile—called a dispersion curve—characterizes changes in the frequency-dependent Rayleigh wave velocity. The evaluation of velocities is constrained to the wavelength zone, where $\lambda(f)/3 < \left(d_s - d_{ref}\right) < 2\lambda(f)$ for typical data and $\lambda(f)/3 < \left(d_s - d_{ref}\right) < 3\lambda(f)$ for excellent data, corresponding to phase lags of 180°–1080° (typical data) and 120°–1080° (excellent data). At longer and shorter wavelengths, the data become unreliable for computing velocities.

As the useable wavelengths are constrained by the seismometer separation, the array is expanded to capture Rayleigh wave dispersion representative of a specific range of wavelengths. The near surface is characterized by short wavelengths and high frequencies, whereas the deeper portion of the profile is characterized by long wavelengths and low frequencies. Each wavelength range requires a separate independent test that is merged together with other wavelength ranges to determine an average dispersion curve for the site.

At the largest seismometer separations, the increasing area of the wave front causes the wave amplitude to diminish due to geometric damping, and the overall quality of the data diminishes. Two measures of data quality are used to evaluate the field measurements in the frequency domain. Coherence, $\gamma^2(\omega)$, is a normalized real function with values between 0 and 1, corresponding to the ratio of the power of the cross-power spectrum, $G_{yx}(\omega)\cdot G_{yx}^*(\omega)$, to the autopower spectrum of the outboard seismometer, $G_{xx}(\omega)\cdot G_{yy}(\omega)$. Values close to 1 indicate high correlation between the reference and outboard seismometers across narrow frequency bands. This is a useful data quality parameter for hammer impact data.

$$\gamma_{xy}^2(\omega)=\frac{G_{yx}(\omega)\cdot G_{yx}^*(\omega)}{G_{xx}(\omega)\cdot G_{yy}(\omega)} \tag{8}$$

For swept sine data where discrete frequencies are used to compute phase rather than narrow frequency bands, the frequency response function (FRF) is a complex measure of the data quality of the output (outboard) seismometer, and is sometimes called the "transfer function":

$$FRF(\omega)=\frac{G_{yx}(\omega)}{G_{xx}(\omega)} \tag{9}$$

where x is the input (reference) signal and y is the response (output) signal.

The FRF is a two-sided complex parameter. To evaluate the amplitude of the output response to the input stimulus, a rectangular-to-polar coordinate conversion is used to convert to the frequency response gain (magnitude).

1.4.1 Adjustments for Missing First-Wrapped Phase

At some sensor separations, the field data have a poorly formed first phase such that the first clear wrapped phase crossing occurs not at 180°, but at 540°. For these dispersion data files, a simple reprocessing was done to add one phase jump (360°, 2π) to the dispersion curves preceding the 540° jump, which then adjusts the file to the correct wrapped phase number. This adjustment corrects the wavelength calculation as follows:

$$\lambda(corrected)=2\pi d/(\theta+2\pi) \tag{10}$$

With the wavelength adjusted, the velocity, V_R, decreases by

$$V_R=f\cdot 2\pi d/(\theta+2\pi) \tag{11}$$

The effect of correcting the phase wrap and reducing the calculated wavelength is to reduce the depth of influence of the adjusted dispersion curve.

1.5 INVERSION OF THE V_S PROFILE

The relation between Rayleigh-wave (V_R), shear-wave (V_S), and compression-wave (V_P) velocities can be formulated through Navier's equations for dynamic equilibrium. On the surface of the ground and in the case of plane strain, the following characteristic equation may be used:

$$\frac{V_R^6}{V_S}-8\frac{V_R^4}{V_S}+\left\{24-16\left[\frac{1-2\nu}{2(1-\nu)}\right]\right\}\frac{V_R^2}{V_S}+16\left\{\left[\frac{1-2\nu}{2(1-\nu)}\right]-1\right\}=0 \qquad (12)$$

where ν is the Poisson ratio and

$$\frac{V_S}{V_P}=\gamma=\sqrt{\left[\frac{1-2\nu}{2(1-\nu)}\right]} \qquad (13)$$

For reasonable values of Poisson ratio for earth materials between 0.20 and 0.49, Viktorov [1967] demonstrated that the shear-wave velocity ranges between 105%–115% of the measured Rayleigh wave velocity.

$$\frac{V_R}{V_S}=K=\frac{0.87+1.12\nu}{1+\nu} \qquad (14)$$

such that across the range $0.2<\nu<0.49$, the range of K is $0.87<K<0.96$.

The inversion method seeks to infer an acceptable best-fit *model* of seismic shear-wave velocity, V_S, of the ground given the *measured* dispersive characteristics of Rayleigh waves observed in the frequency domain, and the estimated profile of Poisson ratio and material density. The inversion attempts to build a model from observations, as opposed to the normal prediction of behavior based upon a model. If the inversion model is simple and linear, it will result in a unique and stable solution. The French mathematician Hadamard defined mathematical problems that have solutions that exist as being unique; those that are stable are "well-posed" [Zhdanov 2002]. However, surface wave inversion is an "ill-posed" inverse problem, as solutions are not unique; therefore, the solutions may become unstable, and multiple shear way velocity profiles can result in approximately the same dispersion curve [Zhdanov 2002].

The dispersive characteristic of Rayleigh wave propagation allows us to infer the V_S at depth based on measurements at the free surface. The inversion problem computes the Rayleigh wave phase velocity (V_R) from laterally constant layers of an infinite half space. For each of these layers, the shear modulus, Poisson ratio, density, and thickness are unknown. In the far field, displacements for a vertically acting harmonic point load can be computed as follows if we neglect body wave components:

$$u_\beta(r,z,\omega)=F_z\cdot G_\beta\cdot(r,z,\omega)\cdot e^{i\left[\omega t-\psi_\beta(r,z,\omega)\right]} \qquad (15)$$

where β stands for the generic component either vertical or radial, $G_{\beta} \cdot \left(\rho, \zeta, \omega\right)$ is the Rayleigh geometrical spreading function, and $\psi_{\beta} \cdot \left(\rho, \zeta, \omega\right)$ is the composite phase function [Lai and Rix 1998].

Regularization methods have been developed for solving the ill-posed inversion problem e.g., the velocity profiles computed herein). The Levenberg-Marquardt method, also called damped least squares, is one example of a regularization method. These and other techniques, such as artificial neural networks and genetic algorithms, are discussed by Santamarina and Fratta [1998]. One drawback of these stochastic methods is that they often require many more iterations; therefore, they are much more computationally intensive.

The parameters of the inversion problem can be chosen such that the difference between the observational dispersion data and the output of the inversion problem are minimized. Such a constraint is insufficient for ill-posed problems because many solutions can fit the data equally well, and some of these solutions will be physically unrealistic. The most common approach is to constrain the inversion solution space by selecting the smoothest solution from a suite of solutions that all exhibit a sufficient goodness-of-fit to the observed data, as indicated by a root mean square (RMS) error minimum.

An empirical approach serves as a counterpoint to the inversion methods used in this report. Pelekis and Athanosopoulos [2011] advanced the work of Satoh et al. [1991] in a technique termed the Simplified Inversion Method (SIM), which computes the shear-wave velocity profile as a function of the incremental slope of the Rayleigh wave dispersion curve where:

$$V_{Sn,normal\,dispersion} = 1.1 \cdot \frac{\bar{V}_{Rn} D_n - \bar{V}_{Rn-1} D_{n-1}}{D_n - D_{n-1}} \tag{16}$$

$$V_{Sn,inverted\,dispersion} = 1.1 \cdot \frac{D_n - D_{n-1}}{D_n / \bar{V}_{Rn} - D_{n-1} / \bar{V}_{Rn-1}} \tag{17}$$

The dispersion curve V_R plotted against λ_R is converted into an apparent velocity $\left(\bar{V}_R\right)$ and depth (z) by converting λ_R to an estimated depth of $z_{eq} = a_R \cdot \lambda_R \approx 0.635\lambda_R$.The parameter a_R is a penetration depth coefficient optimized to achieve a minimum weighted average difference between the simplified velocity profile and that computed through the more advanced inversion of Pelekis and Athansopoulos [2011]. The apparent phase velocity, $\bar{V}_R$, is approximated as the velocity at each segment node (layer interface) of a multi-linear curve fit to the dispersion curve. A positive slope of a segment indicates normal dispersion; a negative slope indicates inverted dispersion. The value of V_S for each individual layer is calculated using the equations above for the cases of normal dispersion or inverted dispersion, respectively. The approach of Pelekis and Athansopoulos [2011] improves on the Satoh et al. [1991] method notably by optimizing the penetration depth coefficient a_R.

1.6 RESULTS

We provide two profile solutions at each site (Inversion and SIM model). We varied the assumptions about the layer thicknesses and the threshold RMS error that determines if the inversion has converged to best characterize the site. The decision as to whether or not the more complex model is warranted by the fit of the theoretical dispersion curve (TDC) to the empirical dispersion curve (EDC) is subjective. Table 1 summarizes results and provides the SASW site ID, the site description, the date of data collection, the latitude and longitude of the SASW test site, and the V_{S30}.

Appendix A includes plots of the model profiles and the EDC and TDC's for each site. Appendix A also includes the site photos and a vicinity map for each site. Where possible, we have indicated the location of the strong-motion station in the site photographs and vicinity maps to assess the distance between the SASW survey and the strong-motion station. A NEHRP classification was used to average the site conditions in the upper 30 m of ground (V_{s30} from the IBC, [2002]). Equation (18) was used to compute this average velocity based on the unit layer thickness (d_i) and the corresponding interval-velocity (V_{Si}).

$$V_{S-depth\ averaged} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{Si}}} \tag{18}$$

These site categories were used to assign design spectra in the evaluation of performance for new and built structures

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ISSN 1547-0587X