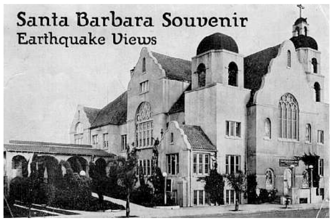

4th IASPEI / IAEE International Symposium:

Effects of Surface Geology on Seismic Motion

August 23–26, 2011 · University of California Santa Barbara

PRELIMINARY SITE RESPONSE STUDY IN THE BÍO BÍO REGION, CHILE USING THE κ METHOD

Corrie Neighbors
University of California
Riverside, CA 92521 USA

Eric Liao
University of California
Riverside, CA 92521 USA

Elizabeth S. Cochran
US Geological Survey
Pasadena, CA 91106 USA

Angela Chung
Stanford University
Stanford, CA 94305 USA

Jesse F. Lawrence
Stanford University
Stanford, CA 94305 USA

Arturo Belmonte
Universidad de Concepcíon
Concepcíon, Chile

Matt Miller
Universidad de Concepcíon
Concepcíon, Chile

Hector H. Sepulveda
Universidad de Concepcíon
Concepcíon, Chile

ABSTRACT

The Bío Bío region of Chile experienced a vigorous aftershock sequence following the 27 February 2010 M 8.8 earthquake. It was noted that metropolitan areas suffered a highly variable pattern of structural damage (*Geo-Engineering Extreme Events Reconnaissance, 2010)* similar to variability observed in ground motion after other large events (*Singh et al., 1988; Hanks and Brady, 1991*). The immediate aftershock sequence was captured by over 70 Quake-Catcher Network (QCN) low-resolution seismometers (*Cochran et al., 2009; Chung et al., 2011*). Initial analysis of the data show that aftershocks of magnitude greater than M 4.8 within a 40 km hypocentral distance are well recorded on QCN sensors. Due to the spatial relationship between source and receiver locations, this investigation adopts a method that estimates site amplification by calculation of kappa, κ (*Anderson and Hough, 1984; Douglas et al., 2010*). Kappa is a parameter used in the characterization of strong ground motion at high frequencies (> 1 Hz) that models the linear decay of the acceleration spectrum. This study follows the routine outlined in *Douglas et al.* (2010) (*adapted from Anderson and Hough, 1984*), whereby a 5-sec S-wave time window is used to calculate the Fourier spectra and κ for each station. Investigation of κ values between stations can illuminate the influence of local geology on seismic wave behavior at individual sites. We identify areas of the Bío Bío region that may be more susceptible to higher amplitude ground shaking; information that can be used to mitigate loss following future large earthquakes.

BACKGROUND INFORMATION

Tectonic setting

The goal of this study is to understand the seismic risk to the built environment in a region that has high seismic hazard potential but has not been well-studied due to insufficient instrumentation. Like many regions of the world with limited permanent seismic monitoring capabilities, Chile suffers from a shortage of observational ground motion datasets. Thus, prediction of ground motions from future earthquakes and the assessment of seismic hazard suffer as a result of large uncertainties. However, based on damage suffered from the recent M_w8.8 event and the aftershock sequence, it is acknowledged that the central Bío Bío region is an at-risk area. The Bío Bío region of Chile has a high seismic hazard potential due to the proximity of the offshore Peru-Chile subduction zone whereby the Nazca oceanic plate is thrusting underneath the South American continental plate at a rate of 7-9 cm/yr (*DeMets et al.,1990*) (Fig. 1). Stresses that build up along this plate boundary interface as well as in the subducting and overriding plates are released in the form of earthquakes that can be very large and cause extreme damage. One such event is the largest recorded earthquake in the world to date, a magnitude of 9.5 in 1960 that caused an estimated $550 million in damage (*USGS NEIC online database*). Recently, Chile suffered another large event in this subduction zone, a magnitude 8.8 on February 27, 2010 which caused extensive building damage in the capital city of Santiago to the town of Curanilahue (700 km distance), 80 km south of the city of Concepción.

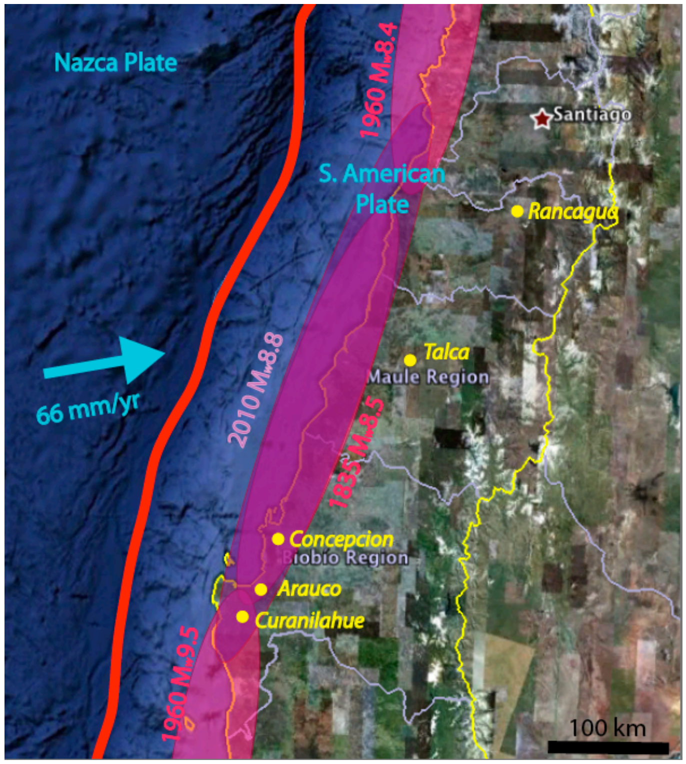

Fig. 1: *Tectonic setting of Bío Bío region with Chile outlined in yellow and region boundaries in grey lines. Major cities (yellow circles) and the capital, Santiago (red star), shown in relation to estimated rupture areas of recent earthquakes of M > 8 (Beck and Ruff, 1989; Comte and Pardo, 1991; Lomnitz, 1970; Melnick et al., 2009).*

In addition to the seismic hazard associated with proximity to a major plate boundary, the densely populated urban centers of the Bío Bío region are also predominantly located on coastal and riverine sediments as well as on thick sediment infills known as basins. It is well documented that seismic waves become modified as they travel through soft geologic material of significant thickness, such as a sedimentary basin (*Hough et al., 1990; Frankel et al., 1999*). This is due to the impedance contrast between a stiffer, denser geologic material and a softer, less dense overlying sedimentary material. This phenomenon has been observed to cause increased amplitude and duration of shaking of these geologic and man-made structures during an earthquake and is due to resonant frequencies of the waves traveling both within the basin and the building structures. Site response analyses of urban areas that are located on sedimentary basins are important for understanding how buildings respond to ground motion in order to mitigate future seismic risk.

The Peru-Chile subduction zone is characterized by the young oceanic Nazca plate subducting beneath the continental South American plate and is known as one of the most seismically hazardous regions in the world. Convergence occurs at an estimated rate of 7-9 cm/yr in the N78°E direction producing earthquakes along the interface of the plate boundary as well as in the downgoing subducting slab (*DeMets et al., 1990; Arango et al., 2011*). Events in this region have been large and relatively frequent, with 17 events of magnitude greater than 7.5 observed in the last 50 years (*Arango et al., 2011*). Central Chile, where the capital of Santiago as well as the coastal cities Valparaiso and Vina del Mar are situated, has a historical earthquake record beginning in 1582 with a magnitude M7.9, a M8.4 in 1647, a M8.2 in 1730, a M8.4 in 1822 and a M8.3 in 1906 (*Comte et al., 1986; Comte and Pardo, 1991; Arango et al., 2011*). South-central Chile, where Concepción and Chillan are located, experienced a large intraslab event on 25 January 1939 of magnitude 8.1 and is one of the most damaging events to have known to occurred in Chile (*Beck et al., 1998; Arango et al., 2011*). Previously, this segment ruptured in February 1835 producing a M8.5 that severely damaged the city of Concepción (*Arango et al., 2011*). Concepción was most recently hit again on February 27, 2010 by a M_w 8.8 earthquake located less than 100 km offshore that shook parts of the region for over a minute (*Chung et al., 2011)*. Reports estimate that the earthquake claimed over 500 lives and caused extensive damage to the cities of Concepción, Arauco and Coronel (Fig. 2) (*Arango et al., 2011*). Effects of the earthquake were felt as far as 600 km from the central coast of Chile.

Following the M_w 8.8 event, the NSF-funded Geo-Engineering Extreme Event Reconnaissance (GEER) Association amassed a team of scientists, engineers, and geologists to review the geotechnical effects of the earthquake (*GEER, 2010*). GEER researchers found localized damage patterns and evidence for ground failure indicating that seismic site effects played a large role in damage caused by the earthquake (*GEER, 2010*). The influence of site conditions on strong ground motion has been known for almost 200 years and was documented in the 1891 great Japan earthquake (M8.0), the 1906 San Francisco earthquake (M7.9) and quantitatively studied for the first time in Southern California by Gutenberg in 1957 (*Milne, 1898; Wood, 1908; Gutenberg, 1957; Field and the SCEC Phase III Working Group, 2000*). More recent studies have expanded on this knowledge and shown that a relationship exists between older, stiffer soils and rock experiencing lower amplification relative to younger, softer soils (e.g. *Bonilla et al., 1997; Frankel et al., 2002*). And, in addition to soil type, subsurface structures such as sedimentary basins can increase the amount of shaking and duration of shaking at a given site. At longer periods (0.5 to 5 sec), it has been observed that the characteristics and geometry of the basin can generate spatially variable patterns in strong ground motion (*Vidale and Helmberger, 1988; Frankel and Vidale, 1992; Graves, 1993*). Previous studies have determined that this longer period energy is amplified within the basin as a result of surface waves generated within basin margins and can be reflected within the basin producing resonances across the volume of the basin (*Rial, 1989; Graves, 1993*). Researchers have found that sites overlying younger, softer soil and deeper portions of the basin typically experience higher amplification at low to moderate frequencies (<1 - 5 Hz) (*Hartzell et al., 2000; Pratt et al., 2003*).

Fig. 2: *(A) Collapsed 20-story apartment complex located in downtown Concepcíon near the Bío Bío River. (B) Damage to newly built (2008) hospital facilities in Curanilahue (near Arauco) about 80 km southwest of Concepcíon. The hospital sits on an old river channel and evidence of liquefaction was observed following the earthquake. Estimated ground motion for such coastal sites of NEHRP soil class D (stiff soil) equivalent is 0.4g (GEER, 2010) (photos by C. Neighbors)*

To analyze seismic hazards, seismologists and earthquake engineers often estimate ground motion by using a method known as probabilistic seismic hazard analysis (PSHA) that attempts to account for all possible damaging earthquakes that may affect a region. PSHA calculations depend on a source model that includes the magnitude, location, and probability of occurrence for all possible earthquakes in the region, and attenuation relationships that describe the estimated ground motion at a site (*Field and the SCEC Phase III Working Group, 2000*). Given the intrinsic uncertainty associated with the parameters of the earthquake source, this results in many different attenuation functions possible for a region. However, the epistemic uncertainty that arises from a lack of knowledge of the state of the system can be decreased with true values of ground motion analyzed after an event (*Field and the SCEC Phase III Working Group, 2000*). In this manner, many attenuation relationships, also known as ground motion prediction equations (GMPE's), can be determined for a region using local or global earthquake datasets. However, using different relationships for a single site can produce highly variable estimated peak ground acceleration (PGA) based on the geologic material at that site, such as if the site is located on rock or soil. This variability reflects an overriding issue that parameters which strongly influence seismic hazard estimates, such as recorded ground motion observations at a large number of sites, are the least constrained (*Field and the SCEC Phase III Working Group, 2000*).

To address this problem, solutions such as small, portable accelerometers like those developed and utilized by the Quake-Catcher Network can augment or provide low-cost alternatives to traditional strong motion stations (*Cochran et al., 2009*). These strong-motion sensors record moderate to large magnitude local earthquakes and, with dense station spacing, can provide a large amount of near-source ground motion data. Such a seismic network would previously have been impossible to achieve with the cost and resources required to install and monitor a traditional seismic network of the same size. Chile currently has attenuation functions that are developed on a network of stations in central Chile using peak ground acceleration (PGA) data from the March 3, 1985 M_s 7.8 (M_w 8.0 equivalent) (*Ruiz and Saragoni, 2005; Saragoni et al., 2008*). The Chilean seismic network has 42 stations covering northern and central Chile, though not all stations are currently in operation (*Arango et al., 2011*). Based on the recent reconnaissance work of *Arango et al.* (2011), a strong-motion database has been created and metadata such as a description of the surface geology, shear-wave velocity profile, and NEHRP site classification based on the shear-wave velocity of the top 30 m are included for each station. Despite these improvements to the network, there are less than 10 stations located in the south-central region, which suffered the most damage from the recent M_w 8.8 earthquake. Thus using data collected by the QCN RAMP, Chile project, this study is expected to analyze recorded ground motion data to improve the understanding of the localized site effects and as well as the seismic hazards associated with the Bío Bío region of Chile.

INSTRUMENTATION AND DATA COLLECTION

The Quake Catcher Network (QCN)

This project uses low-cost MEMS (**m**icro-**e**lectro-**m**echanical **s**ystem) accelerometers that are internal to modern laptops or external sensors that are attached to a computer. These sensors, exploited by the Quake-Catcher Network, operate by volunteer distributed computing based on the BOINC (Berkley Open Infrastructure for Network Computing) open source platform to detect local strong ground motion in the frequency range of 0-25 Hz (Fig. 3) (*Cochran et al., 2009; Anderson, 2004*). Unlike traditional seismic monitoring equipment, these sensors lack a GPS and therefore utilize Network Time Protocol (NTP) to synchronize recording time on individual network machines (*Chung et al., 2011, Frasetto et al., 2003*). The Quake-Catcher Network was initially conceived for internal accelerometers built into Lenovo Thinkpads and Apple MacBooks, but has since expanded to support external sensors that attach to an open USB (Universal Serial Bus) port on a computer. The Quake-Catcher Network uses a suite of 3-axis sensors including the JoyWarrior-10, JoyWarrior-14, MotionNode Accel-12 and O-Navi-16-bit. Sensors are set to a sampling rate of 50 samples per second (sps) and a dynamic range of +/- 2*g* with a resolution of roughly 1-4 m*g* (*Cochran et al., 2009; Chung et al., 2011*). Sensor location is manually entered by the user with either known coordinates or the aid of internet mapping software. During installation, the USB sensors are attached to the floor and oriented with respect to the compass direction of north. Additional location details, such as estimated elevation, building construction type, and sensor type, are input by the user.

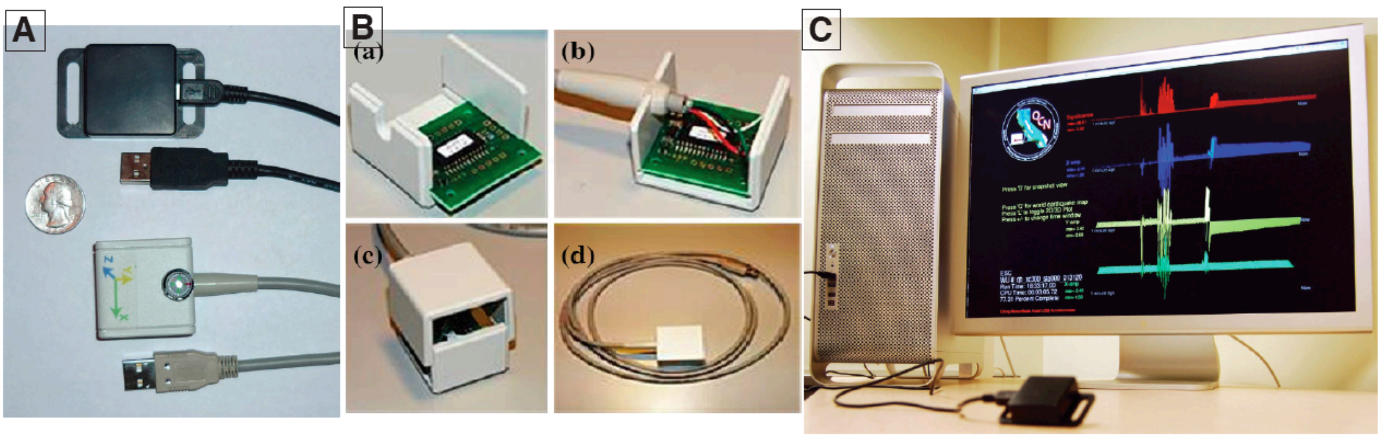

Fig. 3: *(A) QCN sensors MotionNode Accel-12 (top) and JoyWarrior-10 (bottom) with quarter for scale (photo by E. Cochran) (B) Assemblage of the JoyWarrior-10 sensor (from Haritos, 2009) (C) MotionNode Accel-12 sensor attached via USB to computer running QCN BOINC software (photo by E. Cochran).*

The Quake-Catcher Network is quickly revolutionizing traditional methods of studying strong motion seismology and moving toward redefining our abilities in the fields of earthquake rapid-detection, source-characterization, and early-warning. By utilizing the idle time of a growing number of computers, QCN has effectively created a dense network of seismic monitoring stations at 1% of the cost of a traditional array (*Chung et al., 2011*). The size of the network is made possible by the use of distributed computing, i.e. using individual computers to minimize the constraints of overall processing needs. While the QCN servers are continually monitoring the health of all sensors in the network, almost all of the data collection and processing is done at an individual user computer. Through the BOINC software, QCN utilizes a small percentage (< 2%) of a computer's CPU to monitor the motion of the sensor. QCN uses an algorithm that calculates the current acceleration in comparison to the average acceleration over a 60-sec interval (*Cochran et al., 2009*). A 'trigger' occurs if the magnitude of the current vector sum of the three-component acceleration is more than three times the standard deviation of the average over the last minute. This signifies (with 99% confidence) that the current signal is above the ambient background noise level and the computer then issues a 'trigger' alert to the QCN server. For rapid detection to be effective, the duration of this process must be minimized; thus, a trigger includes only a minimal amount of data, such as the time of the trigger, the signal amplitude, and the sensor location, to be transferred between the computer and the server. This process has been estimated to take < 4 sec for computers in the continental U.S. and < 5 sec for computers on the global network (*Cochran et al., 2009; Chung et al., 2011*). An individual computer sends an average of 35 triggers to the server daily; however, triggers are only determined to be potential earthquakes if the server detects that in a limited geographic area the number of triggers received is more than six standard deviations above the average rate of triggers received in the past 10 minutes (*Cochran et al., 2009*). Additionally, the server fits the incoming trigger times to determine if the signals can be fitted to a radiating seismic wave pattern propagating from a point source. Once the triggered event is deemed an actual earthquake, the waveform data is uploaded to the server and removed from the individual computer. Based on aftershock data collected following the 27 February 2010 M_w 8.8 Maule, Chile and the 3 September 2010 M_w 7.2 Christchurch, New Zealand earthquakes, these methods have been refined to include epicenter location and magnitude estimates. Preliminary tests and results of the updated method are described in *Chung et al., 2011*.

In addition to collecting data by triggering algorithms that are used for rapid detection, QCN also utilizes a 'continual' data collection method. Data is recorded at 50 sps on an individual computer for ten-minute intervals and transferred to the server. Once the server receives the waveform file, the record is deleted from the individual computer and the disk space is rewritten with the subsequent 10-minute record. This method of recording was primarily used during the Chile project (see next section).

<u>QCN Rapid-Aftershock Mobilization Project (RAMP), Chile</u>

Following the 27 February 2010 M_w 8.8 Maule Chile earthquake, QCN was granted a NSF RAPID grant to travel to the region as part of what is known as a Rapid Aftershock Mobilization Project (RAMP). Graduate students A. Chung of Stanford University and C. Neighbors of the University of California, Riverside flew 100 USB sensors into Concepción, the urban center closest to the epicenter. In addition to choosing a location that would likely experience a large number of aftershocks with which to test QCN's rapid detection algorithms, the main purpose of choosing an area of high population was to meet the need for the sensors to be attached to computers that are connected to the Internet. Over the course of a week, Chung and Neighbors were assisted by seismological researchers and students at the University of Concepcíon in installing sensors at medical and emergency response facilities as well as individual homes and businesses. The goal was to create high density networks in Concepcíon and Santiago as well as more widely spaced sensors over the Bío Bío and central Chile region. However, due to the need for computers and Internet connectivity, individual sensor locations were largely driven by the availability of volunteer computers. Volunteers were acquired through personal contacts as well as an online registration at the official QCN website. The project received widespread media coverage in local and regional radio, television, and newspaper formats and generated over 700 volunteer participants in roughly a week (*Chung et al., 2011*).

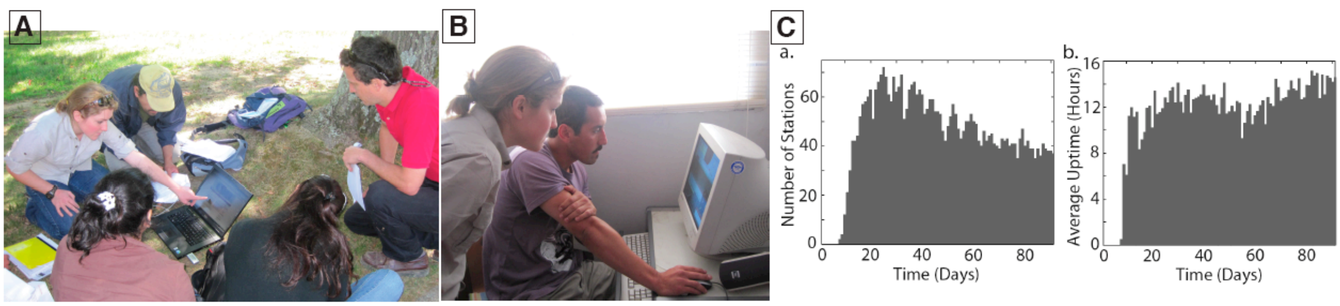

Fig. 4: *(A) A. Chung instructing research scientists and undergraduate students at the University of Concepcíon on how to install a QCN sensor. QCN Installation Manuals available on the QCN website were translated into Spanish and distributed to the students. (B) A. Chung assisting an undergraduate student in the installation of a QCN sensor on his home personal computer. (photos by C. Neighbors) (C) Number of active QCN stations and average length of daily operation of each station from March 1 - June 1, 2010 (from Chung et al., 2011).*

Roughly four weeks following the mainshock event, the RAMP network was monitoring over 70 USB sensors and over 15 laptop sensors (Fig. 4) (*Chung et al., 2011*). External sensors primarily consisted of JoyWarrior-10-bit (4 m*g* resolution) models followed by the MotionNode Accel-12-bit (1 m*g*) models. Two prototype models of the newly developed JoyWarrior-14 (0.24 m*g*) and O-Navi-16-bit (0.060 m*g*) sensors were also deployed. Expecting a large number of aftershocks, computers were programmed to collect data continuously to insure maximum waveform recovery of data sent to the QCN server.

During sensor deployment in Concepción, Chung and Neighbors observed a spatially variable pattern of damage to buildings in the city that has since been mapped by researchers (Fig. 5) (*GEER Report, 2010*). Such damage has been reported in other urban centers following large events, most notably in Mexico City after the September 19th, 1985 M_w 8.1 Mexico City, Mexico earthquake that occurred off the coast of Mexico (*Singh et al., 1988*). Such a variable pattern of damage is thought to be caused by the amplification of seismic waves as they travel through soft, unconsolidated geologic material. Understanding the dynamic behavior of seismic waves traveling within different types of geologic material is currently being investigated in the geophysical literature and is the focus of the proposed study. Identifying and quantifying with greater spatial resolution areas that may experience amplified ground motions has broad implications in the fields of seismic hazard, seismic engineering, mitigation and preparedness.

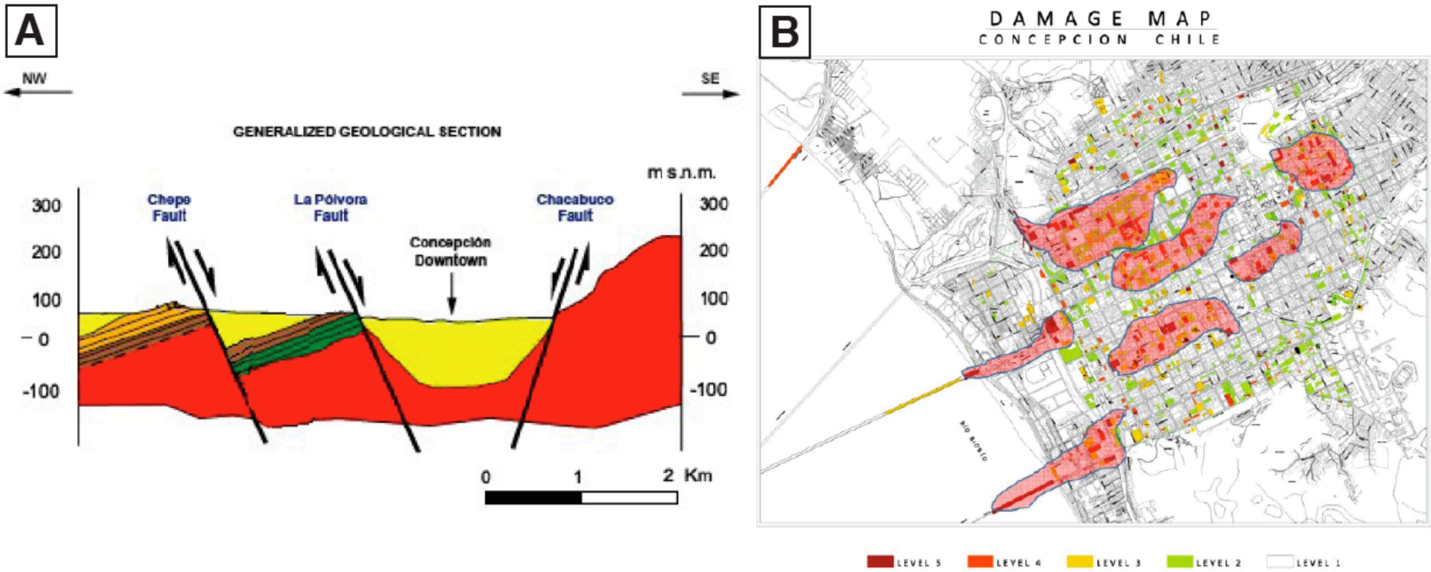

Fig. 5: *(A) Schematic cross-section of Concepción with yellow areas representing Tertiary sediments and other colors representing older metamorphic and plutonic formations. The sedimentary basin underlying Concepcíon is bounded by two main faults, La Polvora and the Chacabuco faults. Vertical axis in 'metros sobre el nivel del mar (m.s.n.m)' or 'meters above sea level' (B) Seven zones (red) in Concepcíon that suffered major building and/or bridge damage as mapped by GEER scientists. (from GEER, 2010)*

METHODS

Site amplification is the local response of seismic energy to subsurface structure and geologic material, which can result in spatially varying patterns of surface damage following an earthquake. It is important to clarify that this effect represents the average response of a site to moderate to large earthquake events; thus uncertainties produced by variability in seismic ray incidence angles, azimuthal directions, and waves types are reduced. The most common method used to determine site amplification is known as the spectral ratio method, initially developed by *Borcherdt* (1970), which estimates the site-response by dividing the spectrum at a given location by the spectrum at a reference site. A reference site is a location that is expected to experience little to no amplification such as bedrock, soft rock or very dense soil. This method is constructed on the principle that seismograms of recorded earthquake events can be understood as the convolution of source, path, and site effects and instrument response. The relative amplification at different sites can be simplified to a function of only the site effect if the seismic source is assumed to be the same for each station, and for closely spaced stations in which the station spacing is small relative to the source-receiver distance, the path is assumed to be the same. An additional correction is made for geometrical spreading and when using multiple types of sensors, instrument response is removed as part of processing.

Implicit in the assumptions of the spectral ratio method is that the site response represents the average amplification of the site. For this to be valid, we would need to have sampled the site response from sources occurring at multiple azimuthal directions to rule out bias from geometrical decay path effects due to a limited azimuthal window. However, most aftershocks of the M_w 8.8 event occur offshore to the west of the QCN stations (Fig. 6). Thus, due to the orientation of our source-receiver pairs and also a lack of an adequate reference site, we propose to use another method known as the kappa (κ) method as originally developed by *Anderson and Hough* (1984).

Kappa is a parameter used in the characterization of strong ground motion at high frequencies (> 1 Hz) and is a critical parameter for estimations of peak ground acceleration and ground motion prediction equations (GMPE's) as κ varies with region and surface geology (*Douglas et al., 2009; Douglas et al., 2010*). Reliable estimates of the near-surface (< 2 km) attenuation (κ) range between 0.005 and 0.15 and are important for calculating more precise amplification estimates at high frequencies (*Douglas et al., 2009; Douglas et al., 2010*). The kappa (κ) method is built upon work explored in *Douglas et al.* (2009) for France, which is similar to Chile in that the seismic monitoring network is sparse and the seismic hazard associated with future earthquakes has large uncertainties due to the scarcity of local ground motion records. In attempting to develop Franco-centric GMPE's, *Douglas et al.* (2009) estimated the shear wave velocity profile (describing how S-wave velocity varies with depth) using local site data, such as soil type and depth to bedrock. Despite considering these parameters when estimating the shear-wave velocity profile at each site, *Douglas et al.* (2009) found that the high-frequency site amplification is characterized by large remaining uncertainties due to a lack of constraint on κ, the near surface attenuation.

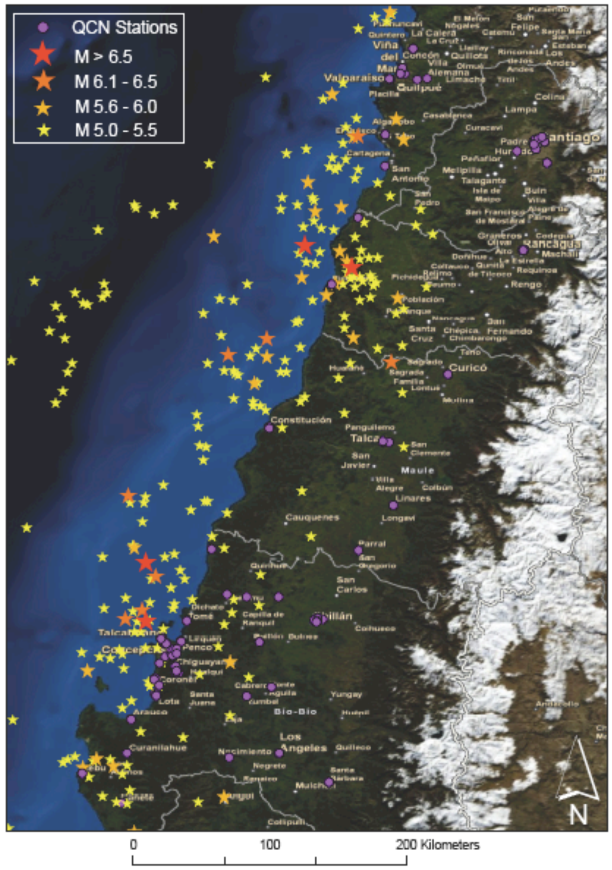

Fig. 6: *QCN sensor locations in Chile highlighting the spatial relationship between stations (purple dots) and aftershock locations (stars).*

Following the method outlined in *Douglas et al.* (2010) (adapted from *Anderson and Hough, 1984 and Hough et al., 1988*), we use seismograms of earthquakes of magnitude 4.5 or greater that were recorded on both vertical and horizontal components of the QCN sensors during the period of 1 March to 1 June 2010. For each record, the acceleration time history is visually inspected for clarity of P- and S-wave arrivals—noisy or other poor quality records are discarded from further analysis. The P-wave and S-wave arrivals are picked manually—5-sec time windows of pre-event noise and direct S-wave are cut from the length of the record and tapered at the cut ends using a 5% Hanning taper. The Fourier spectra of the pre-event and S-wave time windows are computed and by visually inspecting the S-wave spectrum, two frequencies are manually picked: the f_E, the initiation of the linear downward trend in acceleration, and the f_X, the end of the linear downward trend or when the S-wave spectrum approaches the noise spectrum (*Douglas et al., 2010*).

A standard least-squares regression line is fitted between the points f_E and f_X with kappa being estimated from the slope of the line by the relationship

$$\kappa = - \lambda/\pi \qquad (1)$$

where λ is the slope of the line. *Douglas et al*. (2010) note that the point of the initial linear downward trend in acceleration, f_E, must be greater than the corner frequency, f_C of the source, otherwise the estimates of κ may be biased underestimating the values. We can check for such bias by examining the Fourier amplitude spectra, which should be flat above the corner frequency. By performing this check, we can determine that all f_E picks are above f_C and the κ not subject to bias. To decrease dependence on the azimuthal direction of the wave path, *Douglas et al.* (2010) averaged the κ calculated on the horizontal components at a station. Investigation of the averaged horizontal κ values and the geologic material at the stations will highlight the influence of local geology on seismic wave behavior at individual sites.

Once κ is estimated for a site, the dependence of source distance, region, and site conditions can be developed using the model

$$\kappa = \kappa_0 + m_k \text{ x } r_{epi} \qquad (2)$$

where r_{epi} is the epicentral distance and κ_0 and m_k are constants related to the near-surface attenuation in the upper couple of kilometers at the site and the regional-dependent attenuation, respectively. These values can be estimated using a weighted regression analysis from the standard deviations of each κ value as described in *Douglas et al.* (2010).

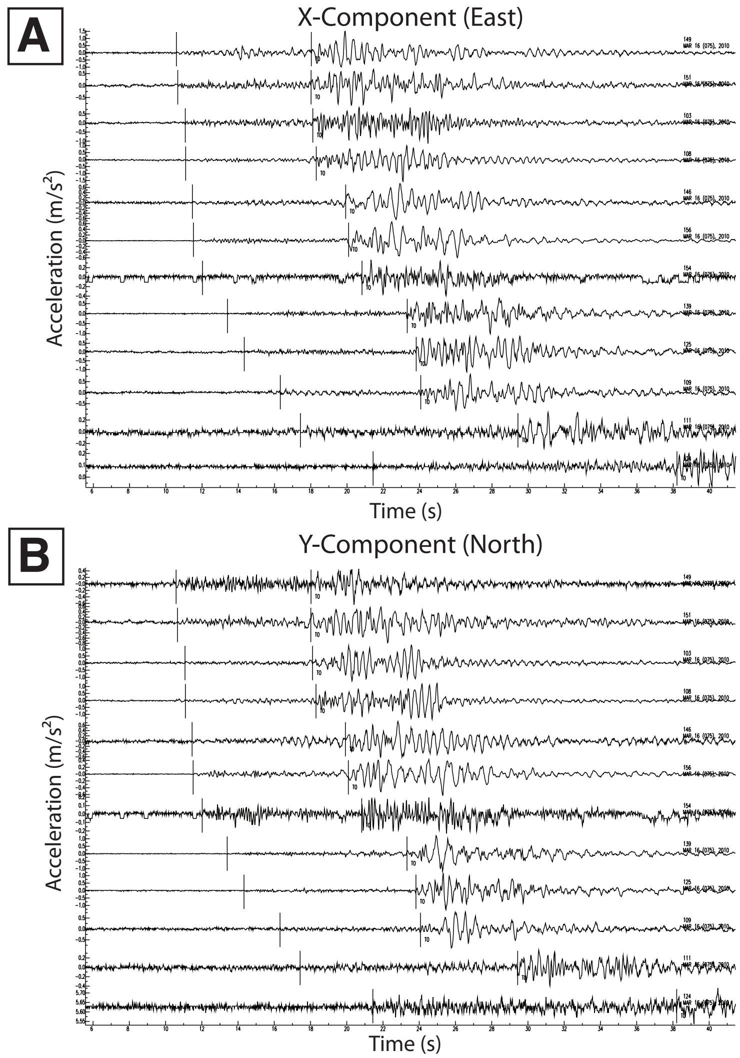

Fig. 7: *Time-series records from 12 QCN stations for the 16 April 2010 M_w6.7 aftershock. P-wave and S-wave arrivals are picked (vertical bars) on horizontal components X (East) (A) and Y (North) (B).*

SAMPLE DATA AND PRELIMINARY RESULTS

The data were collected by QCN sensors from March 1 to June 1, 2010. During the deployment, the QCN network recorded over 229 earthquakes of magnitude 4.5 and greater. Of the 229 earthquakes, 64 earthquakes (28%) had sufficient signal-to-noise for use in site response analysis, as determined by visual inspection. Following the method outlined above, the S-wave arrivals were manually picked (Fig. 7) and 5-second S-wave and noise windows were cut from the time-series. S-wave windows were cut beginning at the pick and noise windows were cut at 30 seconds before the S-wave arrival. Cut windows were transformed into spectra and the points f_E and f_X were visually picked from the S-wave data on a plot containing both noise and S-wave windows to ensure that picks occur where the signal is greater than the noise (Fig. 8). Preliminary kappa results focus on the April 16, 2010 M_w6.7 earthquake that was recorded on 12 QCN stations at source-receiver distances ranging from 50.7 to 112.0 km (Fig. 9). The average kappa value on the X-component is 0.0437 s and on the Y-component is 0.0388 s with an average overall kappa of 0.0407 for the stations (Fig. 9).

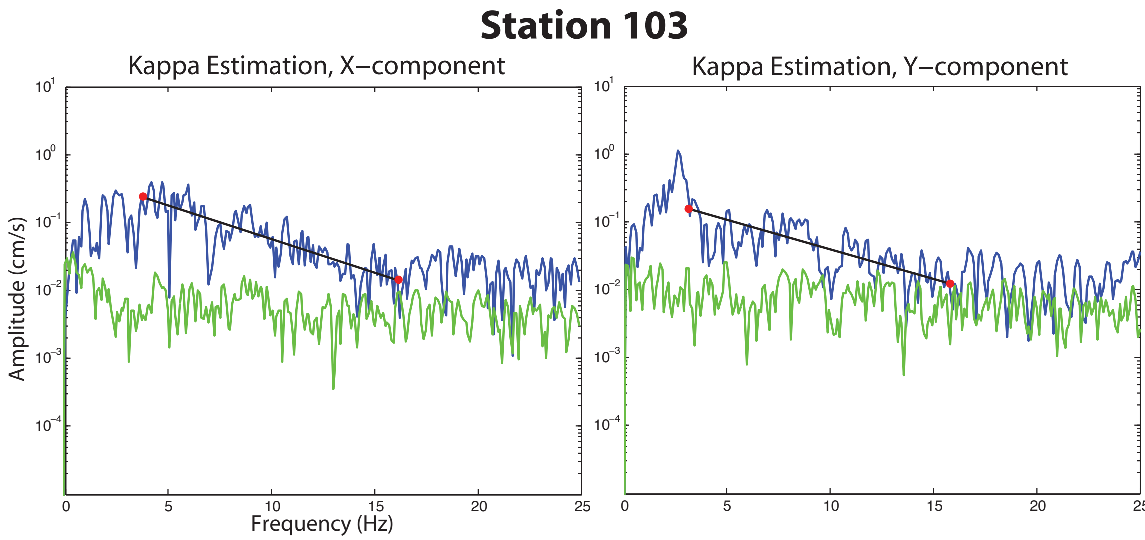

Fig. 8: *Spectra of noise (green) and S-wave (blue) windows with the points f_E and f_X (red) plotted for Station 103 from the April 16, 2010 M_w6.7 earthquake. The slope of the line drawn between the points (black) is used to calculate kappa (κ), the high frequency decay parameter.*

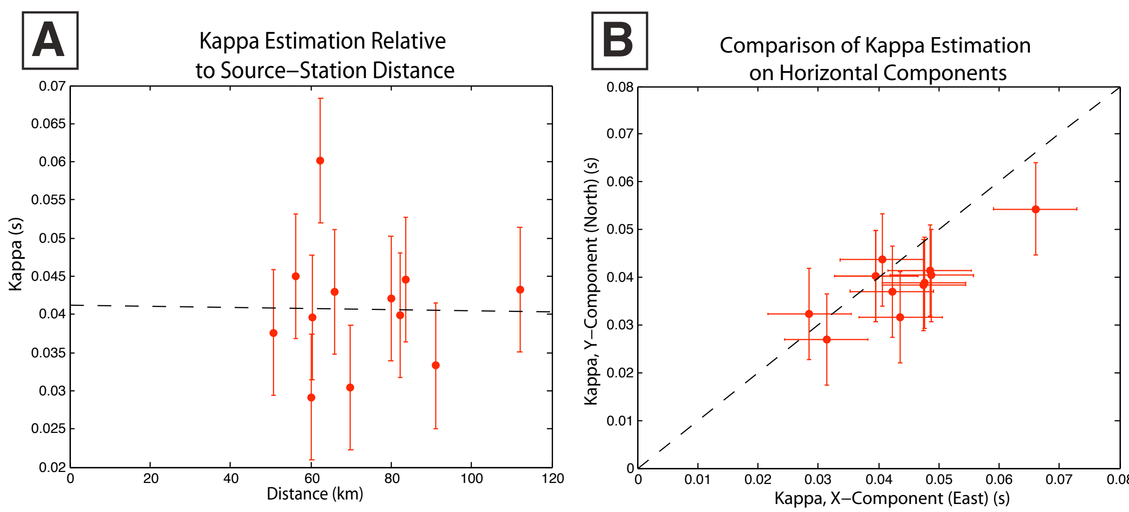

Fig. 9: *Kappa (κ) estimations for the 12 QCN stations that recorded the April 16, 2010 M_w6.7 earthquake. (A) The horizontally averaged κ value with 1 standard deviation error bars for each station relative to source-station distance. Black dashed line is a standard least squares regression fit to the data. (B) Comparison of the κ estimated on both horizontal components with 1 standard deviation error bars. Black dashed line represents a one-to-one correlation.*

DISCUSSION

The kappa (κ) values obtained in this study can be compared to global κ estimates to constrain seismic hazard assessment; for example, Western North America has a κ around 0.04 s and Eastern North America has a much lower κ around 0.006 s for rock sites. Larger kappa values correspond to higher attenuation and less competent rock with lower shear-wave velocities (*Douglas et al., 2010*). Our preliminary kappa estimates of 0.0407 s for one earthquake are in line with global studies from Europe and Western North America. Based on one earthquake, κ does not appear to have a direct correlation with source-station distance; however, this relationship will be more thoroughly explored as additional earthquake records are analyzed. The preliminary estimates of κ are based on the work of one analyst and future work will include kappa estimations from multiple researchers, similar to the method of Douglas et al. (2010). This will provide an important aspect to error analysis given that *Douglas et al*. (2010) found different selections of the pre-event and S-wave arrivals and windows can affect the determination of the f_E and f_x points, ultimately affecting the estimated κ. Specifically, when picking f_E and f_x points, if the record has a clear linear amplitude dependence on frequency, κ for individual analysts are within 10-20% of one another; however, when there is not a clear relationship, κ can vary up to 50% (*Douglas et al., 2010*). Other studies have also explored the variation in κ across soil and rock sites; however, at this time there has been no differentiation in geologic material across the QCN station locations and the assignment of soil and rock classification at station sites remains as future work. Additionally, compared to traditional seismometers which cover a wider frequency band (24 bit) and are buried underground, the QCN sensors are located within structures. Despite the lower resolution (10 to 12-bit) and non-free-field placements of the QCN sensors, we find that we are able to estimate κ within the lower limit of the frequency band width (10-34 Hz) as prescribed in other studies (*Drouet et al., 2008; Parolai and Bindi, 2004; Douglas et al., 2010*). Using traditional broadband seismometers, *Douglas et al*. (2010) found that f_E ranges from 2-12 Hz and f_X varies between 20-50 Hz, which is within the upper bound of the frequency resolution of the QCN sensors. Cochran et al. (*2011*) compared the 14-bit Joy Warrior QCN sensors to broadband stations in the New Zealand GeoNet network and found favorable comparison between station responses.

CONCLUSION

The Bío Bío region of Chile experienced a vigorous aftershock sequence following the 27 February 2010 M_w 8.8 earthquake and the immediate aftershock sequence was captured by the Quake-Catcher Network (QCN) low-resolution seismometers (*Cochran et al., 2009; Chung et al., 2011*). In the month following the mainshock, more than 100 sensors were deployed in central Chile with over 70 of those located in the Bío Bío region. For a region with limited resources available for installing and maintaining an expensive traditional seismic network, the use of the Quake-Catcher Network sensors allows both local and global seismologists access to data that previously would not exist. With a dense network of sensors covering the region, we investigate the site response that caused the observed variable pattern of damage following the mainshock and subsequent large magnitude aftershocks. The near-surface attenuation parameter, κ, is calculated using S-wave spectra to assess site response in the Bío Bío region of Chile. In this preliminary analysis, we estimate κ using data from a M 6.7 aftershock recorded on 12 QCN stations. We find κ values between 0.03 and 0.06, with an average value of 0.0407. This estimate suggests the Bío Bío region of Chile has high attenuation suggestive of less competent rock, as expected.

Previous studies have shown that sedimentary basins may amplify ground motion during an earthquake (*Hough et al., 1990; Frankel et al., 1999*). The coastal Bío Bío region is predominantly located on a shallow Neogene-aged sedimentary basin. It was noted that the metropolitan areas suffered a highly variable pattern of structural damage (*GEER Report, 2010)*; similar ground motion variability has been observed after other large events (*Singh et al., 1988; Hanks and Brady, 1991*). Shallow basins and short-storied buildings, both of which are characteristic of the coastal Bío Bío region, are more affected by moderate to high frequency seismic energy (1-10 Hz). The results of our investigation will provide the basis for microzonation and urban hazard mapping in the region.

REFERENCES

Aki, K., and P. G. Richards [1980]. "*Quantitative Seismology",* Vol. 1, W. H. Freeman, San Francisco.

Aki, K. [1993], "Local Site Effects on Weak and Strong Ground Motion", Tectonophysics, Vol. 218, pp. 93-111.

Anderson, J.G., and S.E. Hough [1984],"A Model for the Shape of the Fourier Amplitude Spectrum of Acceleration at High Frequencies", Bull. Seism. Soc. Am., Vol. 74, No. 5, pp. 1969-1993.

Anderson, D. P. [2004] "BOINC: A System for Public-Resource Computing and Storage*", 5th IEEE/ACM International Workshop on Grid Computing*, Pittsburgh, USA.

Arango, M. C., F.O. Strasser, J. J. Bommer, R. Boroschek, D. Comte, and H. Tavera [2011], "A strong-motion database from the Peru–Chile subduction zone", J. Seism., Vol. 15, pp. 19–41.

Beck, S. L., and L. J. Ruff [1989], "Great earthquakes and subduction along the Peru trench", Phys. Earth Planet. Inter., Vol. 57, pp. 199– 224.

Beck, S., S. Barrientos, E. Kausel, and M. Reyes [1998], "Source characteristics of historic earthquakes along the central Chile subduction zone", J. South Am. Earth Sciences, Vol. 11, No. 2, pp. 115–129.

Bonilla, L. F., J H. Steidl, G. T. Lindley, A. G. Tumarkin, and R. J. Archuleta [1997], "Site Amplification in the San Fernando Valley, California: Variability on Site Effect Estimation Using the S-wave, Coda, and H/V Methods", Bull. Seism. Soc. Am., Vol. 87, No. 3, pp. 710-730.

Borcherdt, R. D. [1970], "Effects of Local Geology on Ground Motion Near San Francisco Bay", Bull. Seism. Soc. Am., Vol. 60, No. 1, pp. 29-61.

Bullen, K. E. [1965]. "*An Introduction to the Theory of Seismology",* Cambridge University Press, Cambridge.

Chung, A. I., C. J. Neighbors, A. Belmonte, M. Miller, H. H. Sepulveda, C. Christensen, R. S. Jakka, E. S. Cochran, and J. F. Lawrence [2011], "The Quake-Catcher Network Rapid Aftershock Mobilization Project Following the 2010 M8.8 Maule, Chile Earthquake", Seism. Res. Lett., Vol. 82, No. 4, pp 526-532.

Cochran, E. S., J. F. Lawrence, C. Christensen, and R. Jakka, [2009], "The Quake-Catcher Network: Citizen science expanding seismic horizons", Seism. Res. Lett., Vol. 80, pp. 26-30.

Cochran, E. S., J. F. Lawrence, A. Kaiser, B. Fry, A. Chung, and C. Christensen [2011], Comparison between low-cost MEMS and traditional accelerometers: a case study from the M7.1 Darfield earthquake aftershock deployment, Annals Geophys., submitted.

Comte D., A. Eisenberg, E. Lorca, M. Pardo, I. Ponce, R. Saragoni, S. K. Singh, and G. Suárez [1986], "The 1985 Central Chile earthquake: a repeat of previous great earthquakes in the region?", Science, Vol. 233, No. 4762, pp. 449–453.

Comte, D., and M. Pardo [1991], "Reappraisal of great historical earthquakes in the northern Chile and southern Peru seismic gaps", Nat. Hazards, Vol. 4, pp. 23– 44.

DeMets C., R. G. Gordon, D. F. Argus and S. Stein [1990], "Current plate motions", Geophy. J. Int., Vol. 101, No. 2, pp. 425–478.

Douglas, J., P. Gehl, L. B. Bonilla, O. Scotti, J. Regnier, A. M. Duval, E. Bertrand [2009],"Making the most of available site information for empirical ground-motion prediction", Bull. Seism. Soc. Am., Vol. 99, No. 3, pp. 1502–1520.

Douglas, J., P. Gehl, L. F. Bonilla, and C. Gelis [2010], "A κ Model for Mainland France", Pure Appl. Geophys., Vol 167, No. 11, pp. 1303-1315.

Drouet, S., S. Chevrot, F. Cotton, and A. Souriau [2008], "Simultaneous inversion of source spectra, attenuation parameters,and site responses: Application to the data of the French Accelerometric Network", Bull. Seism. Soc. Am., Vol. 98, No. 1, pp. 198–219.

Field and the SCEC Phase III Working Group [2000], "Accounting for Site Effects in Probabilistic Seismic Hazard Analyses of Southern California," Bull. Seism. Soc. Am., Vol. 90**,** No. 6B, pp. S1-S31.

Frankel, A. and J E. Vidale [1992], "A three-dimensional simulation of seismic waves in the Santa Clara Valley, California, from a Loma Prieta aftershock", Bull. Seism. Soc. Am., Vol. 82, pp. 2045-2074.

Frankel, A., D. Carver, F. Cranswick, M. Meremonte, T. Bice, and D. Overturf [1999], "Site response for Seattle and source parameters of earthquakes in the Puget Sound region", Bull. Seism. Soc. Am., Vol. 89, pp. 468–483.

Frankel, A., D. L. Carver, and R. A. Williams [2002], "Nonlinear and Linear Site Response and Basin Effects in Seattle for the M6.8 Nisqually, Washington Earthquake", Bull. Seism. Soc. Am., Vol. 92, No. 6, pp. 2090-2109.

Frassetto, A., T. J. Owens, and P. Crotwell [2003], "Evaluating the Network Time Protocol (NTP) for Timing in the South Carolina Earth Physics Project (SCEPP)", Seism. Res. Lett., Vol. 74, No. 5, pp. 649-652.

Geo-Engineering Extreme Events Reconnaissance (GEER) Association [2010]. "*Geo-engineering Reconnaissance of the 2010 Maule, Chile Earthquake*", Report GEER-022.

Graves, R.W. [1993], "Modeling Three-Dimensional Site Response Effects in the Marina District Basin, San Francisco, California", Bull. Seism. Soc. Am., Vol. 83, No. 4, pp. 1042-1063.

Gutenberg, B. [1957], "Effects of ground on earthquake motion", Bull. Seism. Soc. Am., Vol. 47, pp. 221–250.

Hanks, T. C., and A. G. Brady [1991], "The Loma Prieta Earthquake, Ground Motion and Damage in Oakland, Treasure Island and San Francisco", Bull. Seism. Soc. Am., Vol. 81, pp. 2019-2047.

Hartzell, S .H. [1992], "Site Response Estimate from Earthquake Data", Bull. Seism. Soc. Am., Vol. 82, No. 6, pp. 2308-2327.

Hartzell, S., D. Carver, F. Cranswick, and A. Frankel [2000], "Variability of site response in Seattle, Washington", Bull. Seism. Soc. Am., Vol. 90, pp. 1237–1250.

Haritos, N. [2009], "Low Cost Accelerometer Sensors - Applications and Challenges", *Australian Earthquake Engineering Society Conference*.

Hough, S. E. and J. G. Anderson [1988], "High-frequency spectra observed at Anza, California: Implications for Q structure", Bull. Seism. Soc. Am., Vol. 78, No. 2, pp. 692-707.

Hough, S. E., P. A. Friberg, R. Busby, E. F. Field, K. H. Jacob, and R. D. Borcherdt [1990], "Sediment-induced amplification and the collapse of the Nimitz Freeway", Nature, Vol. 344, pp. 853-855.

King, J. L. and B. E. Tucker [1984] "Observed Variation of Earthquake Motion Across a Sediment Filled Valley", Bull. Seism. Soc. Am., Vol. 74, No. 1, pp. 137-151.

Lomnitz, C. [1970] "Major earthquakes and tsunamis in Chile during the period 1535 to 1955", Geol. Rundsch., Vol. 59, pp. 938–960.

Melnick, D., B. Bookhagen, M. R. Strecker, and H. P. Echtler [2009], "Segmentation of megathrust rupture zones from fore-arc deformation patterns over hundreds to millions of years, Arauco peninsula, Chile", J. Geophys. Res., Vol. 114, No. B01407.

Milne, J. [1898], "*Seismology",* first Ed., Kegan Paul, Trench, Trube, London.

Parolai, S. and D. Bindi [2004], "Influence of soil-layer properties on κ evaluation", Bull. Seism. Soc. Am., Vol. 94, No. 1, pp. 349–356.

Pratt, T.L., T. M. Brocher, C. S. Weaver, K. C. Creager, C. M. Snelson, R. S. Crosson, K. C. Miller, and A. M. Trehu [2003], "Amplification of Seismic Waves by the Seattle Basin, Washington State", Bull. Seism. Soc. Am., Vol. 93, No. 2, pp. 533–545.

Rial, J. A. [1989], "Seismic wave resonances in 3D sedimentary basins", Geophys. J. Int., Vol. 99, pp. 81-90.

Ruiz, S. and G. R. Saragoni [2005], "Attenuation relationships for the Chile subduction of interplate thrust earthquakes considering the effect of the soils and the asperities," *IX Chilean Congress on Seismology and Earthquake Engineering*, Santiago, Chile. (In Spanish)

Saragoni, G. R., M. Astroza, and S. Ruiz [2008], "Study of the accelerogram destructiveness of Nazca plate subduction earthquakes", *The 14th World Conference on Earthquake Engineering*, Beijing, China.

Servicio Nacional de Geologia y Mineria [1982]. "*Mapa geológico de Chile 1 : 1,000,000",* Electronic Format.

Singh, S. K., J. Lermo, T. Dominguez, M. Ordaz, J. M. Espinosa, E. Mena, and R. Quass [1988], "The Mexico earthquake of September 19,1985--a study of amplification of seismic waves in the valley of Mexico with respect to a hill zone site", Earthquake Spectra, Vol. 4, pp. 653-673.

Vidale, J. E. and D. V. Helmberger [1988], "Elastic finite-difference modeling of the 1971 San Fernando, California earthquake", Bull. Seism. Soc. Am., Vol. 78, pp. 122-141.

Wood, H. D. [1908]. "*Distribution of apparent intensity in San Francisco, in the California earthquake of April 18, 1906*", Report of the State Earthquake Investigation Commission, Carnegie Institute, Washington, D.C., Publ. 87, pp. 220–245.