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Site characterization at Chilean strong-motion stations: Comparison of downhole and microtremor shear-wave velocity methods

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ABSTRACT

A blind comparison of independent invasive (downhole, standard penetration, bender element) and non-invasive microtremor shear-wave velocity (V_S) profiling is presented for 11 strong-motion stations in central and southern Chile that recorded the 2010 M_W 8.8 Maule earthquake. For the majority of stations, site classification based on average V_S in the upper 30 m (V_{S30}) is consistent irrespective of methodology. For a variety of geological conditions, excellent to good agreement is obtained between invasive and non-invasive V_S structure at five stations over the entire borehole length and in the uppermost layer at three stations. Site classification based on site period is evaluated using earthquake and microtremor recordings. Short site periods are observed at stiff coarse-grained stations whereas longer site periods are observed at soft fine-grained stations. The use of both V_{S30} and site period criteria are recommended in future revisions of the Chilean building code for robust earthquake site response characterization.

1. Introduction

Earthquake ground shaking is amplified by the presence of material with reduced shear-wave velocity (V_S) generally towards surface. Currently, most building codes classify site conditions for seismic site response based on average properties of the upper 30-m such as the travel-time averaged shear-wave velocity (V_{S30}), average standard penetration resistance (N_{60}), and soil undrained shear strength (S_u). The Chilean building code [1 and references therein] adopted the use of V_{S30} as the main parameter for seismic site classification (Table 1) primarily due to observed damage in deep sandy deposits in downtown Concepcion following the 2010 M_W 8.8 Maule, Chile, subduction earthquake.

A variety of invasive and non-invasive field methodologies have been developed to provide a reliable V_S-depth profile at a site, for which the least expensive and time-consuming method is of particular interest. Invasive testing methods provide detailed, but restricted, information of the subsurface within the tested soil column with cost directly related to penetration depth. Non-invasive surface seismic methods provide broad-stroke subsurface imaging without direct retrieval of small-scale structure or geologic material for lower cost and less site disruption. In reality, combinations of invasive and non-invasive V_S profiling methods are generally used together for earthquake site response assessment, due to their inherent advantages and disadvantages.

Non-invasive surface-wave methods may be further categorized by the use of an active source, e.g. hammer impact, or a passive source, e.g. ambient vibrations. Active-source surface-wave seismic techniques, such as spectral analysis, SASW [2], or multichannel analysis, MASW [3], of surface waves, generally offer a restricted investigation depth (a few tens of meters) related to the frequency content of the source. The microtremor array method [4–6], a passive-source method that uses background ambient vibrations with a wide frequency content from a variety of natural and man-made sources, is generally sensitive to greater depth, e.g. ≥ 100 m [6,7]. It is important to note that measured field data of discrete invasive V_S measurements and surface-wave dispersion data are not directly comparable: the discrete V_S measurements must be converted to a continuous V_S-depth function in order to compare with either the inverted continuous V_S-depth function of the surface-wave dispersion data or converted to dispersion estimates for comparison with the measured dispersion data.

Independent evaluations of non-invasive surface wave methods with respect to well-regarded invasive methods, i.e. blind test

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Table 1
Site classification based on V_{S30} in revised Chilean building code [1].

Site class	Description	V_{S30} range (m/s)
A	Rocks, cemented soils	≥ 900
B	Soft or fractured rocks, very dense or very firm soils	≥ 500
C	Dense or firm soils	≥ 350
D	Medium dense or medium firm soils	≥ 180
E	Medium loose soils	< 180
F	Special soils	

comparison, were accomplished in the 1990s during development of the non-invasive methods. For example, at Fraser River delta sites, south of Vancouver, Canada, the average relative difference in V_S to a maximum 30-m depth between the optimal inversion result of active-source (MASW or SASW) acquired dispersion data and invasive (downhole or SCPT) V_S measurements is 25% or better [8–10]. Blind-test comparison of the Bayesian inversion result of microtremor-array acquired dispersion data and invasive downhole and SCPT V_S measurements resulted in an average relative difference in V_S of 5% to 120-m depth [7] and 25% to 60-m depth [11]. Otherwise few case studies of blind-test comparisons are available at sites that have experienced strong earthquake shaking; when discrete invasive-method V_S measurements are available they are generally used to constrain the inversion of non-invasive dispersion data for V_S-depth structure (profiles). A comprehensive examination of 9 blind-test comparisons of invasive and non-invasive V_S profiling methods at sites in California determined that for V_{S30} estimates > 200 m/s, invasive-method estimates are biased higher than non-invasive method estimates [12]; the coefficient-of-variation of V_{S30} estimates was determined to be 1–3% for co-located invasive methods, 5–6% for co-located non-invasive SASW methods, and 20–35% for correlated V_{S30} estimates per geologic unit. Variability in V_{S30} estimates becomes a significant issue when the estimates span the boundary between site classifications.

Subsurface soil properties beneath Chilean strong-motion stations were relatively unknown until recently [13]. The central part of Chile has been subjected to notable periodicity of large $M_W \geq 7.8$ earthquakes, with an average (one standard deviation) recurrence interval of 82 (6) years [14] due to rapid convergence of the oceanic Nazca plate beneath the continental South America plate. Prior to the 2010 M_W 8.8 Maule earthquake, no site-specific subsurface information was available for Chilean strong-motion stations outside of Santiago. As such, the University of Chile (UCH) Research and Material Testing Institute (Instituto de Investigación y Ensayo de Materiales, IDIEM) Civil Engineering Department (Departamento de Ingeniería Civil, DIC) conducted an invasive borehole testing campaign at 11 strong-motion stations in central and southern Chile (Fig. 1) following the M_W 8.8 Maule earthquake. The UCH–IDIEM–DIC invasive testing campaign provides a detailed comprehensive assessment of the subsurface column of drilled material at each strong-motion station. Conversely, the University of British Columbia (UBC) Earthquake Engineering Research Facility (EERF) of Vancouver, British Columbia, Canada, performed a rather crude non-invasive field testing campaign at these same 11 Chilean strong-motion stations. The UBC-EERF campaign was optimized for efficiency and budget by minimization of equipment, personnel, and time; however, a state-of-the-art probabilistic (Bayesian) inversion technique [7] is used to resolve subsurface V_S structure from the non-invasive dispersion data.

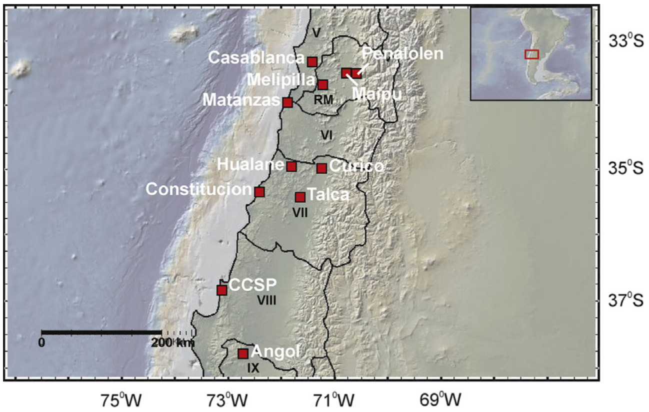

Fig. 1. Locations of 11 investigated Chilean strong-motion stations (squares) with regional districts (V–IX) marked by solid lines.

Table 2
Site classification based on site period [25].

Site class	Description	Natural period range
I	Rock/Stiff soil	T < 0.2 s
II	Hard soil	0.2 s ≤ T < 0.4 s
III	Medium soil	0.4 s ≤ T < 0.6 s
IV	Soft soil	T ≥ 0.6 s
V	Generic rock	Flat H/V, *T* not identifiable.
VI	Generic soft soil	Broad amplification/multiple peaks above 0.2 s
VII	Unclassifiable	Multiple peaks over 0.2 s, T not identifiable.

Rather than measure shear-wave velocity to classify subsurface ground conditions to predict site response, measured earthquake site response itself may be used to classify site conditions at strong-motion stations. Empirical earthquake site response is ideally determined from a multitude of weak to strong earthquake recordings at a variety of azimuths via standard bedrock-reference [15] and/or single instrument horizontal-to-vertical (H/V) [16] spectral ratios. The empirical spectral ratio is a measure of the amplification spectra (transfer function) resulting from the site-specific subsurface ground conditions. Microtremor H/V ratios have been shown to reliably measure predominant site period in comparison with weak to strong earthquake recordings e.g., [14,17–19]. Site classification based on the predominant period of the average H/V ratio has been proposed for strong-motion stations in Iran [20,21], Taiwan [22], Japan [23,24], and Italy [25]. Table 2 lists seven proposed period-based site classifications [25]; a short site period corresponds to rock or stiff soils, whereas a long site period corresponds to soft soils. Generic rock or soil classifications are proposed in the case of no predominant period or multiple peaks, respectively. For the 11 Chilean strong-motion stations, available earthquake recordings, as well as the non-invasive microtremor recordings, provide additional and unique datasets to evaluate site classification based on predominant site period.

This paper presents a blind comparison of the subsurface V_S-depth structure determined via invasive and non-invasive microtremor array method techniques at 11 strong-motion stations in central and southern Chile that recorded strong ground shaking from the 2010 M_W 8.8 Maule earthquake. The invasive testing results [26] were not made available to the first author until the microtremor data were processed and inverted for V_S structure, i.e. a blind test. The comparison of invasive and non-invasive V_S-profiling methods is performed in terms of the average relative difference in V_S for particular depth ranges and the resulting site classification based on V_{S30}. The non-invasive microtremor recordings, in combination with available earthquake recordings at the 11 Chilean strong-motion stations, allows for a