16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 3849
Registration Code: S- V1463084860

LIQUEFACTION TRIGGERING ANALYSIS IN MEGATHRUST EARTHQUAKES

G.A. Montalva[(1)], F. Ruz [(2)], J. Roncagliolo[(3)], E. Escare[(4)]

[(1)] *Assistant Professor, Dept. of Civil Engineering, University of Concepción, gmontalva@udec.cl*
[(2)] *Civil engineer, RyV Ingenieros, francisco@ryv.cl*
[(3)] *Graduate Student, Dept. of Civil Engineering, University of Concepción, jroncagliolo@udec.cl*
[(4)] *Undergraduate Student, Dept. of Civil Engineering, University of Concepción, eescare@udec.cl*

Abstract

Recent megathrust events in Chile have provided the engineering community, with case studies that allow the evaluation of current state of practice, regarding liquefaction triggering analysis. This evaluation is performed in the context of long duration and high frequency content ground motions. Field observations show an apparent mismatch between observed and predicted liquefaction behavior during the 2010 Mw 8.8 Maule and the recent 2015 Illapel Mw 8.3 earthquakes. We speculate on the reasons for these differences. Partial drainage during the strong shaking could lead to a frequency dependence of the liquefaction behavior, we concur with studies that suggest that soil stiffness (i.e. shear-wave velocity or site period) are relevant parameters to be included. Also the results show that for the case of megathrust events, PGA is not the best-suited intensity parameter to proxy earthquake demand. We conclude that more research is needed in this relevant issue.

Keywords: Liquefaction triggering analysis, Megathrust earthquakes, Chilean case histories.

1. Introduction

The first widely used procedure for liquefaction triggering assessment was proposed by [1], it is the basis for most of the methodologies used today and an important reference framework. The main idea is a simple assessment procedure, which compares capacity versus demand. The capacity, or soil resistance against liquefaction, is proxied by the energy corrected blow count (N_{60}), and the demand, or seismic loading required to initiate liquefaction, is a function of the shear stress induced by the earthquake, the cyclic stress ratio (CSR).

This work has been extended using alternative resistance parameters, as CPT, BPT and Vs, for the different authors along the past century and afterwards were reviewed, summarized, and merged by the most important contributors to the matter in the 1996 and 1998 NCEER-NSF Workshops [2].

Recent updates to SPT and CPT based procedures include [3, 4, and 5], and for Vs case [6, 7, and 8].

Furthermore, to better characterize the damage potential Iwasaki et al. [9] proposed a liquefaction potential index (LPI). This is because the simplified liquefaction evaluation procedure discussed above, do not predict the severity of liquefaction manifestation on the ground surface, but rather it provides an estimated factor of safety (FS) along the soil profile. The usefulness of this tool is twofold, first liquefaction manifestation on the ground surface is more directly correlated to damage potential, and second available methodologies are fitted using ground surface liquefaction manifestation. In this line Sonmez and Gokceoglu [10] proposed to use a previous work [11] of probability of liquefaction, and not FS, as integrator parameter to compute a liquefaction severity index (LSI).

The purpose of this paper is to compare the different procedures listed above for Chilean data from the Maule (2010) and Illapel (2015) earthquakes, along with and assessing their accuracy.

2. Chilean Liquefaction Data

The historical evidence of liquefaction in Chile begins in 1906 following the Valparaíso earthquake, where the reported observations match those of surface manifestation of liquefaction. The largest megathrust earthquake, Valdivia 1960, left abundant evidence of soil liquefaction [12], as it also occurred in the 1985 Valparaiso earthquake [13]. After the 2010 Mw 8.8 Maule earthquake, evidence of liquefaction was observed along several sites in the country, for an extension of about 600 km [14]. In order to analyze the sites, using some of the available methodologies, three inputs where needed. First, a borehole with detailed stratigraphy identifying the amount of fine contents per layer, its plasticity, and N_{60} values. Secondly, the shear-wave velocity (Vs) profile at each site. And third, whether evidence of liquefaction at the surface was observed or not.

Thirty sites with all the three conditions described previously where selected for this study, along with 33 additional sites for which only Vs profile is available. The dataset for this work focus on the evidence observed after the 2010 Mw 8.8 Maule and the recent 2015 Illapel Mw 8.3 earthquakes. These observations were performed by government agencies (i.e. U. of Chile, and Servicio Nacional de Geología & Minería), the Geotechnical Extreme Events Reconnaissance (GEER) association, other universities (e.g. U. of Concepción, P. Catholic Univ. of Chile), among others. The area for this study extends from the Valparaíso region (5^{th}) up to the Los Ríos region (14^{th}) for the Maule Earthquake; and for the Illapel earthquake the area covered the Coquimbo region (4^{th}).

2.1 Evaluated sites

Detailed site investigation was carried out in order to select sites containing both SPT (N values) and Vs profiles, see Table 1. The first 30 sites have complete stratigraphy report containing fine content per layer, water table, and SPT values, along with Vs profiles which were available or measured for this study by the research team. For the remaining 33 sites only Vs profile is available. Out of the 63 sites, in 27 of them evidence of liquefaction was observed, and in the other 36 liquefaction was expected but not observed. The geographic distribution of the sites is shown in figure 1. In SPT profiles the applied energy was assumed to be 60% in all the cases where there was not available data.

Table 1 – Summary of studied sites.

N°	Site	Earthquake	Liq. evidence	Latitude	Long.	Data
1	Cárcel el manzano, Concepción	Maule 2010, Mw=8.8	NO	-36.805635	-73.0222	Vs-SPT
2	Copec palomares, Concepción	Maule 2010, Mw=8.8	NO	-36.817956	-72.989042	Vs-SPT
3	Centro comercial torreones, Concepción	Maule 2010, Mw=8.8	NO	-36.785923	-73.037979	Vs-SPT
4	Tottus Deck PTR el trébol, Concepción	Maule 2010, Mw=8.8	NO	-36.789785	-73.063577	Vs-SPT
5	Hotel Atton, Concepción	Maule 2010, Mw=8.8	NO	-36.833323	-73.057647	Vs-SPT
6	Edificio Irarrázaval, Concepción	Maule 2010, Mw=8.8	NO	-36.819283	-73.035344	Vs-SPT
7	Teletón San Pedro, Concepción	Maule 2010, Mw=8.8	NO	-36.84285	-73.107067	Vs-SPT
8	Planta Reloncaví, Valdivia	Maule 2010, Mw=8.8	NO	-39.834819	-73.254837	Vs-SPT
9	Edificio Consistorial, Los Ángeles	Maule 2010, Mw=8.8	NO	-37.469483	-72.351441	Vs-SPT
10	Centro comercial, Los Ángeles	Maule 2010, Mw=8.8	NO	-37.471828	-72.35566	Vs-SPT
11	Edificio Consistorial, Arauco	Maule 2010, Mw=8.8	Yes	-37.246933	-73.316788	Vs-SPT
12	Centro cultural, Arauco	Maule 2010, Mw=8.8	Yes	-37.24639	-73.320941	Vs-SPT
13	Ampliación retiro sur, Los Ángeles	Maule 2010, Mw=8.8	Yes	-37.483372	-72.371281	Vs-SPT
14	Edificio consistorial, Constitución	Maule 2010, Mw=8.8	NO	-35.330813	-72.412276	Vs-SPT
15	SBA Constitución, Constitución	Maule 2010, Mw=8.8	NO	-35.335446	-72.404316	Vs-SPT
16	Escuela Donn Muller, Constitución	Maule 2010, Mw=8.8	NO	-35.333559	-72.407067	Vs-SPT
17	Edificio Empresa Portuaria, San Antonio	Maule 2010, Mw=8.8	NO	-33.574833	-71.62706	Vs-SPT

N°	Site	Earthquake	Liq. evidence	Latitude	Long.	Data
18	Centro comercial, Valparaíso	Maule 2010, Mw=8.8	NO	-33.042705	-71.608427	Vs-SPT
19	Laguna Tres Pascualas, Concepción	Maule 2010, Mw=8.8	Yes	-36.815075	-73.04679	Vs-SPT
20	Puente Llacolén, Concepción	Maule 2010, Mw=8.8	Yes	-36.830108	-73.067991	Vs-SPT
21	Puente Juan Pablo II, Concepción	Maule 2010, Mw=8.8	Yes	-36.815864	-73.083674	Vs-SPT
22	Condominio Los presidentes 2, Concepción	Maule 2010, Mw=8.8	Yes	-36.791026	-73.081235	Vs-SPT
23	Condominio Los Presidentes, Concepción	Maule 2010, Mw=8.8	Yes	-36.79089	-73.08131	Vs-SPT
24	Muelle coronel 1	Maule 2010, Mw=8.8	Yes	-37.027639	-73.149957	Vs-SPT
25	Muelle coronel 2	Maule 2010, Mw=8.8	Yes	-37.032465	-73.14739	Vs-SPT
26	Santa Margarita del Mar, La serena	Illapel 2015, Mw=8,4	NO	-29.905427	-71.274077	Vs-SPT
27	Faro monumental de La Serena, La serena	Illapel 2015, Mw=8,4	Yes	-29.897083	-71.268572	Vs-SPT
28	Paso Inferior Chada	Maule 2010, Mw=8.8	Yes	-33.869894	-70.72642	Vs-SPT
29	Paso superior Hospital	Maule 2010, Mw=8.8	Yes	-33.86125	-70.745863	Vs-SPT
30	Av. Brasil, Valparaíso	Maule 2010, Mw=8.8	NO	-33.04498	-71.619365	Vs-SPT
31	Cementerio up	Maule 2010, Mw=8.8	NO	-36.824875	-73.072675	Vs
32	Cementerio Down	Maule 2010, Mw=8.8	NO	-36.825966	-73.072077	Vs
33	Cerro Chepe	Maule 2010, Mw=8.8	NO	-36.81379	-73.06483	Vs
34	Plaza Condell	Maule 2010, Mw=8.8	NO	-36.81773	-73.043729	Vs
35	Plaza Jurásica	Maule 2010, Mw=8.8	NO	-36.815457	-73.031275	Vs
36	Plaza Mayor	Maule 2010, Mw=8.8	NO	-36.816344	-73.053894	Vs
37	Concepción Centro	Maule 2010, Mw=8.8	NO	-36.828166	-73.048548	Vs
38	Angol-Cochrane	Maule 2010, Mw=8.8	NO	-36.83162	-73.053155	Vs
39	Salas-Freire	Maule 2010, Mw=8.8	NO	-36.827797	-73.057139	Vs
40	Janequeo-Barros A.	Maule 2010, Mw=8.8	NO	-36.822926	-73.04062	Vs
41	Anibal Pinto - Barros Arana	Maule 2010, Mw=8.8	NO	-36.826356	-73.050072	Vs
42	Ongolmo - Maipú	Maule 2010, Mw=8.8	NO	-36.82169	-73.045025	Vs
43	Carrera - Colo Colo	Maule 2010, Mw=8.8	NO	-36.82263	-73.050837	Vs
44	Angol - Prieto	Maule 2010, Mw=8.8	NO	-36.820335	-73.060206	Vs
45	Rosas - Salas	Maule 2010, Mw=8.8	NO	-36.823902	-73.059538	Vs
46	Condominio Valle noble, casa No126	Maule 2010, Mw=8.8	Yes	-36.816784	-73.006269	Vs
47	Ribera Andalién	Maule 2010, Mw=8.8	Yes	-36.79811	-73.030184	Vs
48	Lomas San Andrés	Maule 2010, Mw=8.8	Yes	-36.789906	-73.053946	Vs
49	Estero Nonguén	Maule 2010, Mw=8.8	Yes	-36.820722	-73.016897	Vs
50	Laguna Lo Custodio	Maule 2010, Mw=8.8	Yes	-36.806826	-73.04166	Vs
51	Tranque de relave Coihueco	Maule 2010, Mw=8.8	Yes	-36.637166	-71.79753	Vs
52	Hospital Curanilahue	Maule 2010, Mw=8.8	Yes	-37.473219	-73.348168	Vs
53	Las Palmas Mine, Talca	Maule 2010, Mw=8.8	Yes	-35.18525	-71.758671	Vs
54	San Pedro	Maule 2010, Mw=8.8	Yes	-36.843662	-73.114347	Vs
55	Ribera Bio-Bío	Maule 2010, Mw=8.8	Yes	-36.827016	-73.071667	Vs
56	Laguna Tres Pascualas	Maule 2010, Mw=8.8	Yes	-36.815326	-73.046062	Vs
57	San Pedro	Maule 2010, Mw=8.8	NO	-36.843662	-73.114347	Vs
58	Ribera Bio-Bío	Maule 2010, Mw=8.8	NO	-36.827016	-73.071667	Vs

N°	Site	Earthquake	Liq. evidence	Latitude	Long.	Data
59	Condominio Los Presidentes	Maule 2010, Mw=8.8	NO	-36.79089	-73.08131	Vs
60	Laguna Tres Pascualas	Maule 2010, Mw=8.8	NO	-36.815326	-73.046062	Vs
61	Casino, La Serena-Coquimbo	Illapel 2015, Mw=8,4	Yes	-29.950177	-71.29404	Vs
62	Costanera, La Serena-Coquimbo	Illapel 2015, Mw=8,4	Yes	-29.953601	-71.301278	Vs
63	Puente ruta D.240, Tongoy	Illapel 2015, Mw=8,4	Yes	-30.260335	-71.481146	Vs

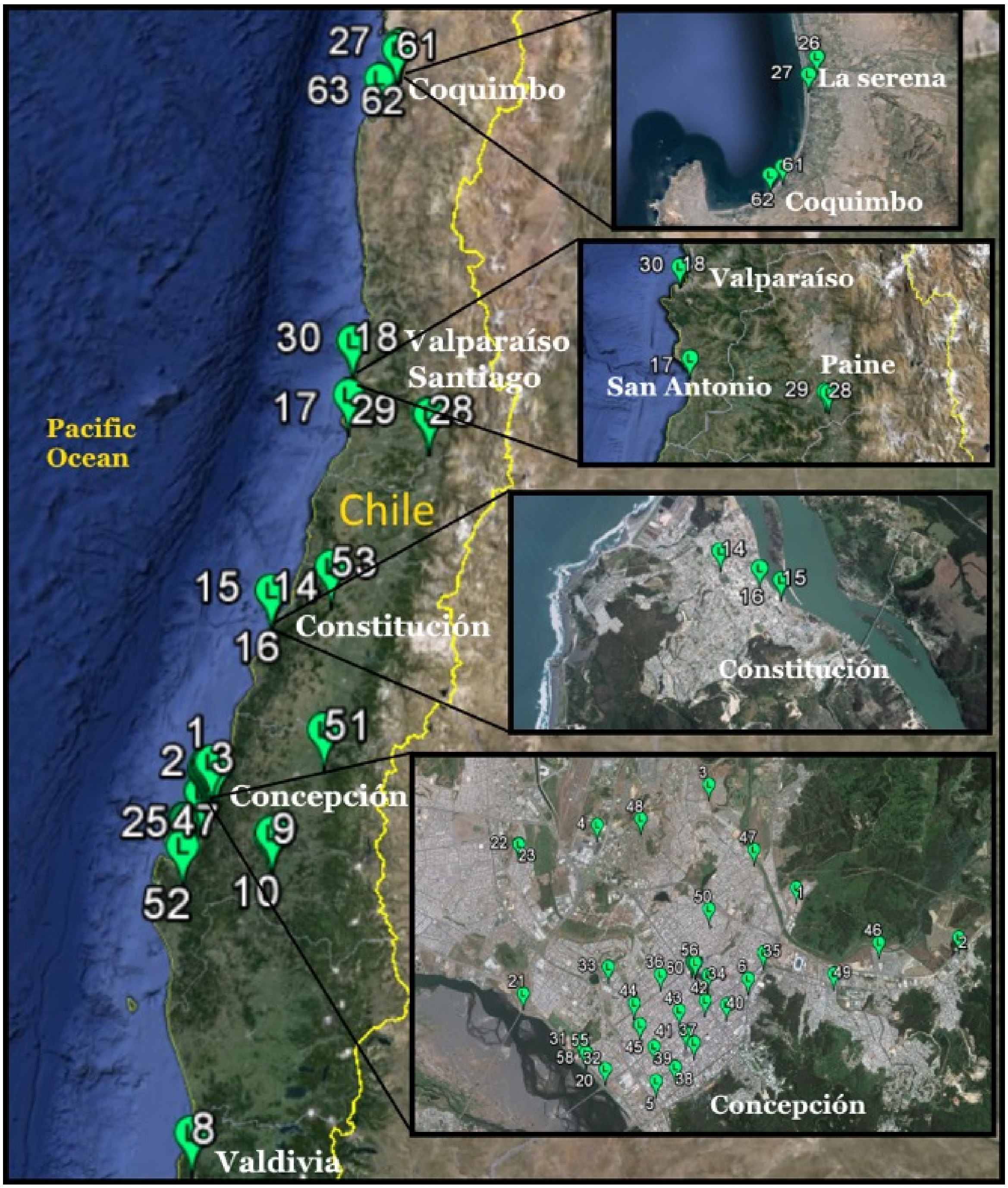

Fig. 1 – Geographical distribution of the sites.

2.2 Ground Motion Parameters

The most widely used demand parameter is the Peak Ground Acceleration (PGA). Although preliminary analyses [e.g. 15] have shown that PGA produces poor results for a few Chilean sites, in this work we do not propose alternative intensity parameters, to focus on the evaluation of existing methodologies only.

Due to the impact of seismic demand on the results, the criteria to estimate these parameters was to use the recorded value from the closest station to the site, or to use an event corrected ground motion prediction equation [16] to obtain the best possible estimate for each site. The associated deviation: deviation between events, deviation between stations, residual deviation, and total deviation, are shown in Table 2.

Table 2 – Logarithmic deviations of [16] GMPE.

τ	ϕ S2S	ϕ SS	σ
0	0.564363734	0.39902942	0.838449184

3. Analysis

3.1 Methodologies based on Standard Penetration Test (SPT)

Four methodologies were chosen for the evaluation of the data, due to their extensive use in recent years (Figure 2). These are [2, 3, 4, and 5]. Since the main purpose of this article is to evaluate the predictive capability of the methodologies mentioned, it must be said that each parameter is calculated strictly according to the recommendation of the authors of each methodology, including the magnitude scaling factors (MSF).

It should also be noted that the MSF applies to only 2 different sites from Maule earthquake of 2010, so a different MSF can only translate the entire set of data, and not changing the level of dispersion (Figure 2).

To address how well each methodology [i.e. 2, 3, 4, and 5] performs for the data presented herein, Equation 1 is used. The errors for each methodology are 36.7%, 43.3%, 43.3%, and 43.3%, respectively.

$$Error = \frac{\#\ of\ misclassified\ sites}{\#\ Sites} \tag{1}$$

As the main purpose of this work is not strictly to compare methods with each other, the critical layer was chosen as the most likely to liquefy according to each methodology. Hence, in Figure 2 different methodologies show slight differences in the distribution of points due to critical layer selection differences. Note that if the same critical layer were to be selected for all methods, the errors computed using (Equation 1) vary slightly, while the strong dispersion does not.

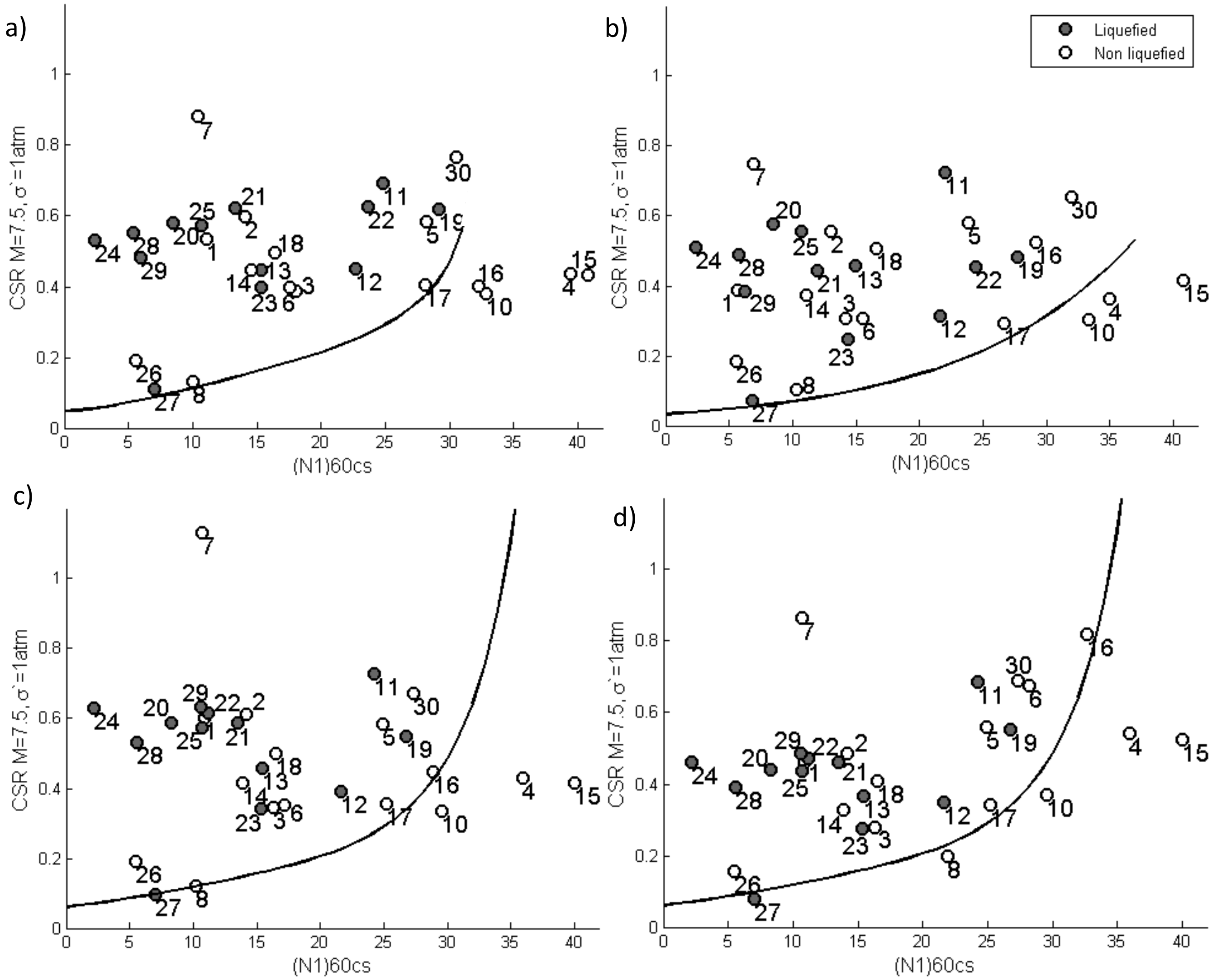

Fig. 2 – Liquefaction triggering analysis using PGA as demand proxy. (a) NCEER ws [2]; (b) Cetin et al [3]; (c) Idriss and Boulanger [4]; (d) Boulanger and Idriss [5].

We also perform the analyses using [9] and [10] to assess the liquefaction potential and liquefaction severity indexes (Figure 3). As a way to display best this information, on the horizontal axis a site stiffness parameter is used, the site shear wave velocity over the top 12 meters (Vs_{12}).

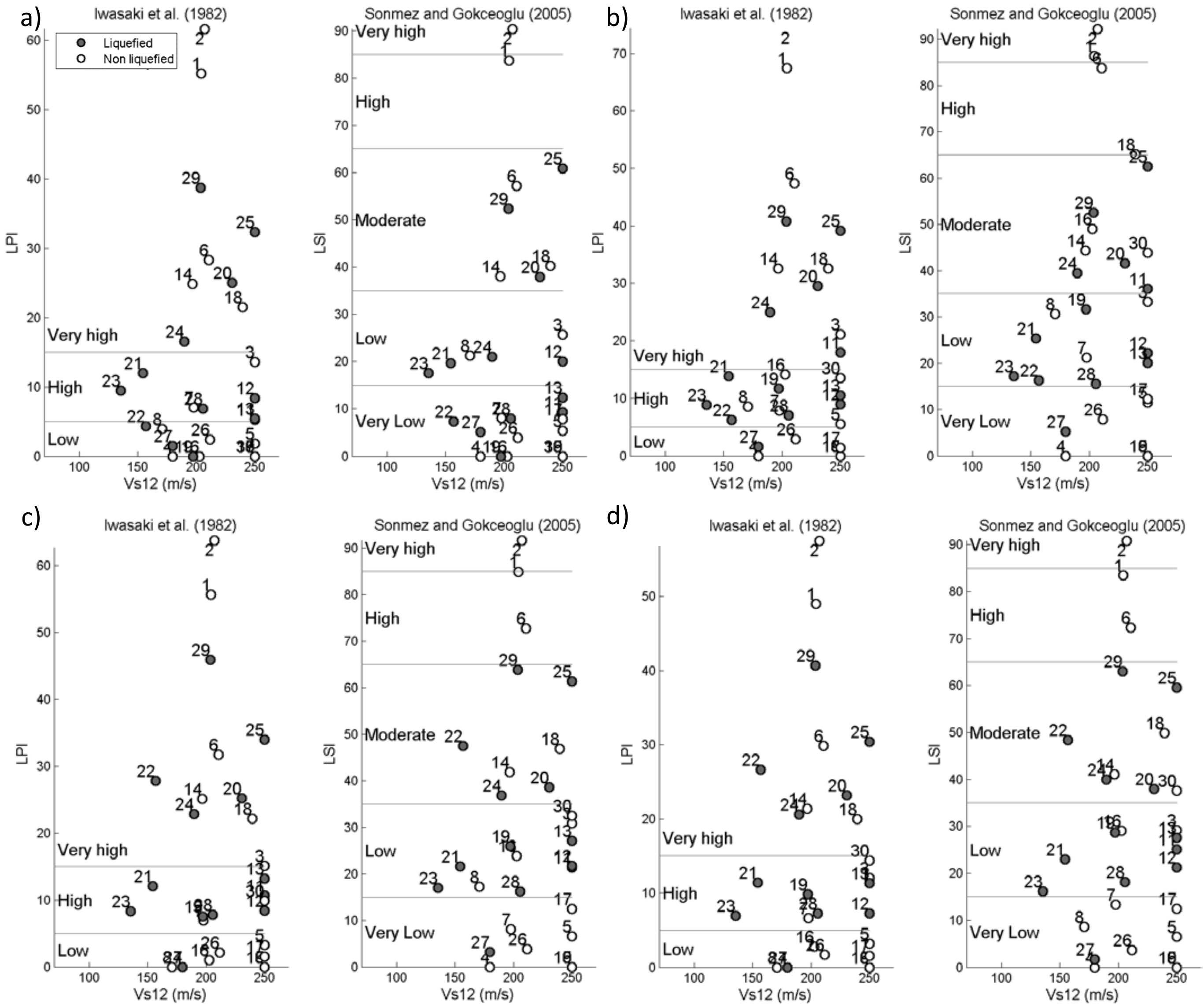

Fig. 3 – Liquefaction potential and severity index: (a) NCEER ws [2]; (b) Cetin et al [3]; (c) Idriss and Boulanger [4]; (d) Boulanger and Idriss [5].

3.2 Methodologies based on shear-wave velocity (Vs)

Three methodologies were chosen for the evaluation of the data with the available Vs profiles (i.e. all the data presented in this work), based on their relevance and use in practice the selected methodologies are [6, 7, and 8]. Figure 4 shows the results.

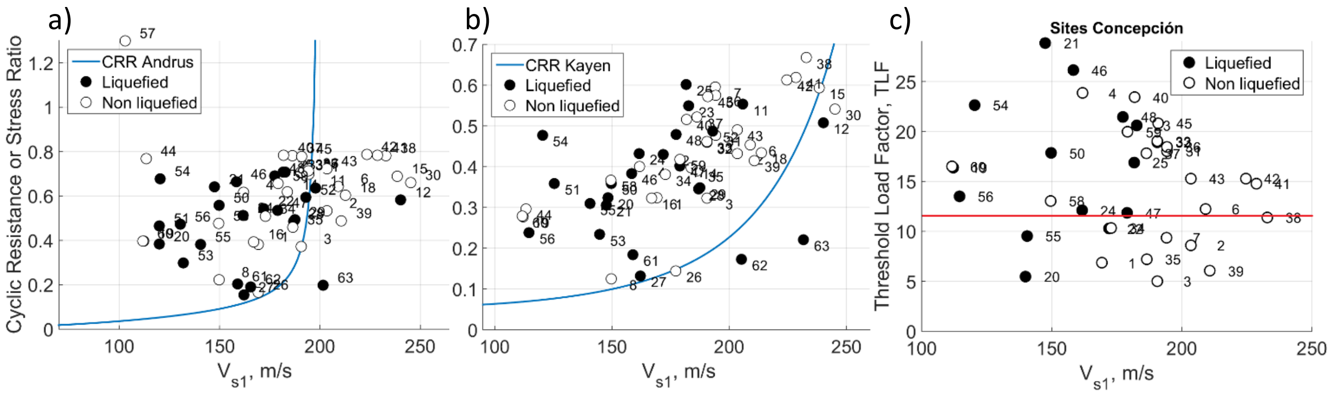

Fig. 4 – Liquefaction triggering analysis using PGA as demand proxy: (a) Andrus et al. [6]; (b) Kayen et al. [7]; (c) Dobry and Abdoun, [8]. Blue lines are the deterministic boundary proposed by each methodology, and the red line for [8] is a preliminary estimation of the division of classes made by the authors.

The analysis of TLF (Figure 4.c) was made exclusively for the city of Concepción using the critical layers given by [7]. The critical value of TLF = 12 was chosen arbitrarily to estimate a factor of safety to be used in the LPI and LSI methodologies (Fig. 5).

Similarly to the analysis for the SPT-based methodologies, for the Vs-based methodologies the same equation is used to assess the predictive capability of each method. The errors for each methodology are 46.0%, 57.1%, and 48,9% for methodologies [6, 7, and 8] respectively.

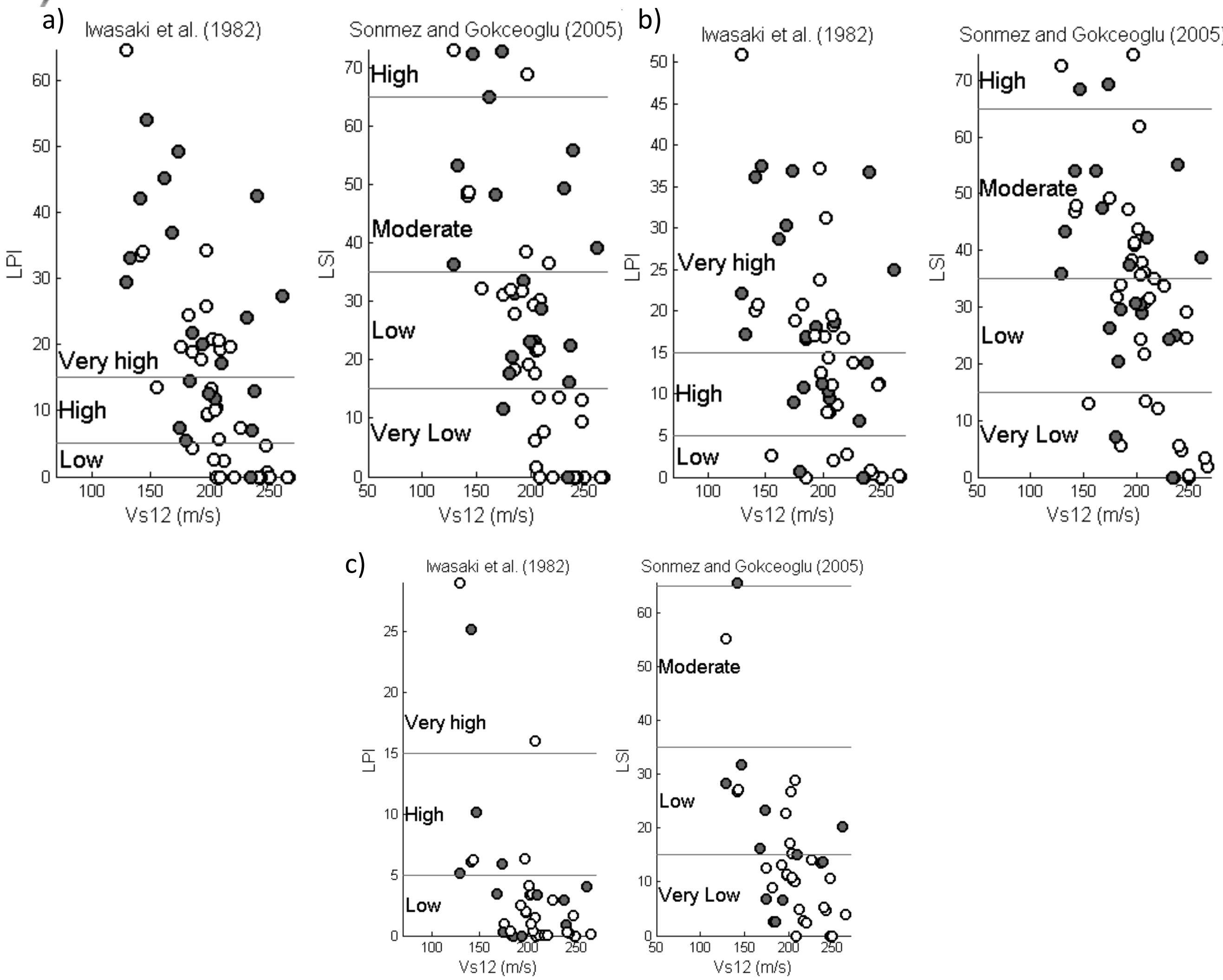

Fig. 5 – Liquefaction potential and severity index: (a) Andrus et al. [6]; (b) Kayen et al. [7]; (c) Dobry and Abdoun, [8].

Note that [8] cannot be assessed rigorously by its performance in the LPI and LSI methodologies by the unconventional way of estimating a safety factor. Even so it may be noted that the indices do not decrease the level of dispersion.

4. Discussion

The results for both the SPT- and Vs-based methodologies provide limited predictive capability for the dataset presented herein. False positives (i.e. there was no liquefaction yet the methodologies predict liquefaction) are abundant, while no false negatives were found. This implies that when we predict no liquefaction the likelihood of being correct is high, and when the prediction is that liquefaction will be triggered the likelihood of being wrong is high. The determination of LPI and LSI does not generate further improvements, obtaining similar levels of dispersion.

The error in the estimation of liquefaction triggering using the above mentioned methodologies varies from 11% for the shallow crustal dominated databases [4] to more than 35% for this study's database. Hence, the main conclusion from these analyses is that more research is needed to properly assess liquefaction triggering in subduction environments. A more comprehensive catalog of sites and events, including case histories from similar events (e.g. Tohoku, 2011; Ecuador, 2016; or Peru, 2001, 2007) should be analyzed together to get a better understanding of liquefaction triggering in subduction environments. Observations and analyses following Tohoku, 2011 [17] find exactly the same results (i.e. no false negatives and several false positives), that were attributed to lack of soil profile information. The results presented herein suggest and alternative explanation might be plausible.

We speculate that the long duration of ground shaking and the large size of the rupture area, compared to the events that control the database used in the available methodologies, provide partial drainage and high frequency content that may play a relevant role in liquefaction triggering analyses. We also believe that using PGA, a highly variable intensity parameter, and a magnitude scaling factor as proxies for the entire ground motion is likely not enough and partly responsible for the large dispersion in the results.

5. Copyrights

6. References

[1] Seed HB, Idriss IM (1971): Simplified procedure for evaluating soil liquefaction potential. *J. Soil Mechanics and Foundations Div*., ASCE 97(SM9), 1249–273.

[2] Youd TL, Idriss IM, Andrus RD, Arango I, Castro G, Christian JT, Dobry R, Liam Finn WD, Harder Jr LF., Hynes ME, Ishihara E, Koester JP, Liao S, Marcuson III WF, Martin GR, Mitchell JK, Moriwaki Y, Power MS, Robertson PK, Seed RB, Stokoe II KH (2001): Liquefaction resistance of soils: Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils." J. Geotech. Geoenviron. Eng., 12(10), 817–833.

[3] Cetin K, Seed R, Der Kiureghiuian A, Tokimatsu K, Harder Jr, Kayen R, Moss R (2004): Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential. Journal of Geotechnical and Geoenvironmental Engineering Vol. 130, No. 12, pp. 1314-1340.

[4] Idriss I, Boulanguer R (2008). *Soil Liquefaction During Earthquakes*. Oakland, California, USA: Earthquake Engineering Research Institute.

[5] Boulanger R, Idriss I (2014): CPT and SPT based liquefaction triggering procedures. Resport UCD/CGM-14/01

[6] Andrus R, Stokoe K (2000): Liquefaction resistance of soils from shear-wave velocity. J. Geotech. Geoenviron. Eng., 2000, 126(11): 1015-1025.

[7] Kayen R, Moss RE, Thompson EM, Seed RB, Cetin KO, Der Kiureghian A, Tanaka Y, Tokimatsu K (2013): Shear-wave velocity-based probabilistic and deterministic assessment of seismic soil liquefaction potential. Vol. 139, No. 3, March 1, 2013. DOI: 10.1061/(ASCE)GT.1943-5606.0000743

[8] Dobry R, Abdoun T (2015): Threshold Load Factor for Liquefaction Triggering Evaluations. *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)GT.1943-5606.0001399, 02815003.

[9] Iwasaki T, Tokida K, Tatsuko F,Yasuda S (1978): A practical method for assessing soil liquefaction potential based on case studies at various sites in Japan, Proceedings of 2nd International Conference on Microzonation, San Francisco, 885–896.

[10] Sonmez H, Gokceoglu C (2005): A liquefaction severity index suggested for engineering practice. Environ Geol (2005) 48: 81–91 DOI 10.1007/s00254-005-1263-9

[11] Juang CH, Yuan H, Lee DH, Lin PS (2003): A simplified CPT-based method for evaluating liquefaction potential of soils. J Geotech Geoenviron Eng 129(1):66– 80

[12] *Manual de Carreteras Vol. 3*. (2015). *Instrucciones y Criterios de Diseño*. Dirección de Vialidad, Ministerio de Obras Públicas, Chile.

[13] The Chile Earthquake of March 3, 1985—Geotechnical Effects. Earthquake Spectra: February 1986, Vol. 2, No. 2, pp. 273-291.

[14] Report of the NSF Sponsored GEER association (2010): Team Geo-Engineering Reconnaissance of the 2010 Maule Chile Earthquake. GEER Association Report Nº. GEER-022.

[15] Montalva Gonzalo A, Leyton F (2014). Discussion to: "Shear-Wave Velocity-Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential. *Journal of Geotechnical and Geoenvironmental Engineering*, 140 (4), 407-419.

[16] Montalva GA, Bastías N, Rodriguez-Marek A (2016): Ground Motion Prediction Equation for the Chilean Subduction Zone. Submitted to *Bulletin of the Seismological Society of America.*

[17] Cox BR, Boulanger RW, Tokimatsu K, Wood CM, Abe A, Ashford S, Donahue J, Ishihara K, Kayen R, Katsumata K, Kishida T, Kokusho T, Mason HB, Moss R, Stewart JP, Tohyama K, Zekkos D (2013): Liquefaction at Strong Motion Stations and in Urayasu City during the 2011 Tohoku-Oki Earthquake. Earthquake Spectra, Volume 29, No. S1, pages S55–S80. DOI: 10.1193/1.4000110