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New Chilean seismic code and the use of Nakamura period for assessing damage potential

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ABSTRACT: The proposed new Chilean Building Code introduced the Nakamura site period, T_N, as a parameter for classifying sites into the Site Classes A, B, C, D and E that are used widely in current building codes. The period is based on analysis of ambient vibration data recorded by a single instrument on the surface at the site, typically for a duration of 20 minutes.

The procedure for developing a site classification system based on T_N, is described in detail. Initially studies were conducted on 26 sites for which the following information was available: V_{s30}, 30m site stratigraphy, Nakamura Period, and damage patterns from past earthquakes in surrounding region. The studies were later extended to many other sites with similar data.

Finally, a country wide hazard map was developed for Chile based on data from 670 widely dispersed locations in terms of the Site Classes A, B, C, D and E.

1 INTRODUCTION

The objective of this study is to examine the correlation between the Nakamura period T_N and the damage potential of sites to subduction earthquakes. T_N has been adopted in the proposed new building code for Chile. T_N is calculated using the H/V spectral ratio, the ratio between the Fourier amplitude spectra of the horizontal and the vertical component of microtremors. The H/V spectral ratio was first introduced by Nogoshi & Igarashi (1971), and widespread by Nakamura (1989, 1996, 2000). These authors have pointed out the correlation between the H/V peak frequency and the fundamental resonance frequency of the site. (Bonnefoy-Claudet 2006).

According to SESAME (2004), the method has proven to be useful to estimate the fundamental period of soil deposits, while the peak amplitude cannot be directly linked to the low strain amplification factor.

This surface based Nakamura method is very convenient and inexpensive compared to the traditional methods using boreholes or penetration tests. This method is now widely used in practice. The Nakamura period is an economic parameter to get preliminary estimates of structural damage potential without getting into a full scale soil exploration.

2 CHILEAN CODE

2.1 *Current Code*

Experience with earthquakes and associated ground motions since 2010 provided a motivation to update the current Chilean code. The current Code, shown in Table 1a, is similar to ASCE7-16 or NBCC 2010 in defining site classes of seismic intensity based on V_{s30} (the time

Table 1a. Site classification according to the current code

Site Class	Soil description	Vs30 (m/s)	RQD	qu (Mpa)	N1 (blows/ft)	Su (Mpa)
A	Rock	≥ 900	≥ 50%	≥ 0,10 (Ɛqu≤2%)	-	-
B	Soft rock and very dense soil	≥ 500	-	≥ 0,40 (Ɛqu≤2%)	≥ 50	-
C	dense/stiff soil	≥ 350	-	≥ 0,30 (Ɛqu≤2%)	≥ 40	-
D	Medium dense soil	≥ 180	-	-	≥ 30	≥ 0,05
E	Soft soil	< 180	-	-	≥ 20	< 0,05
F	Special soils	-	-	-	-	-

averaged shear wave velocity over the top 30m) SPT value for sands, and undrained strength (S_u) or unconfined compression resistance (q_u) value for soft clays and fines. However, the ranges in velocities for the various site classes are different from the Canadian code. Site classification in the current Chilean code requires 2 parameters to define site class, V_{s30} and S_u or q_u (fines) or SPT (sands).

Site F is a site prone to liquefaction, collapsible soils, sensitive soils, organic soils and others. For a site class F the code requires a site specific seismic response analysis.

2.2 *New Code SOCHIGE proposal*

Since 2013 the SOCHIGE (Chilean Geotechnical Society) geotechnical engineering committee has been working on updating the current Chilean Code. The new Code keeps the V_{s30} and a borehole as mandatory requirements. The new site classification chart is shown in Figure 1b classifying the site with V_{s30} and T_N. The categories are the same as in the current code, except that the use of soil properties in classifying sites has been replaced by T_N, the Nakamura site period. When T_N and V_{s30} characterize a site differently, the lower classification is accepted for design. In Table 1b, T_N flat means no predominant frequency is observed which is typical of hard rock and very dense soil sites.

T_N is an indicator of potential damage (Ruz & Finn 2017). The evidence in Chile of strong subduction earthquakes such as the Coquimbo Mw8.4 (2015), the Iquique Mw8.2 (2014), the Maule Mw8.8 (2010) and the Valparaiso Mw8.0 (1985) is that damage is observed in soft soils where the site period T_N shows a deeper soil deposit. On the other hand, limited or no damage was reported at stiff sites. With only the T_N you can "screen" or quickly determine if the site has a potential damage.

3 DATABASE

The database supporting the proposed new Chilean code was developed by RyV Ingenieros for their geotechnical projects. The company made the database available to the national code committee to support the development of a new updated building code. The database consists of 1850 sites with shear wave velocity V_{s30} and 670 sites with shear wave velocity V_{s30} and site period measurements T_N. In addition, 309 of these latter sites have borehole stratigraphy and SPT values. At all of these sites a minimum of 3 measurements of T_N were made and at least 2 measurements of V_{s30} as shown in Table 2.

3.1 *Shear wave velocity and T_N maps*

Within the length limitations of this paper, it is not possible to show plots of the data for all instrumented sites in Chile. Therefore, 3 widely distributed sites are shown; Iquique in the north, Santiago in the center and Concepcion in the south to illustrate the nature of the database and how T_N was calibrated to Site Class and damage. Calibration of the T_N period ranges

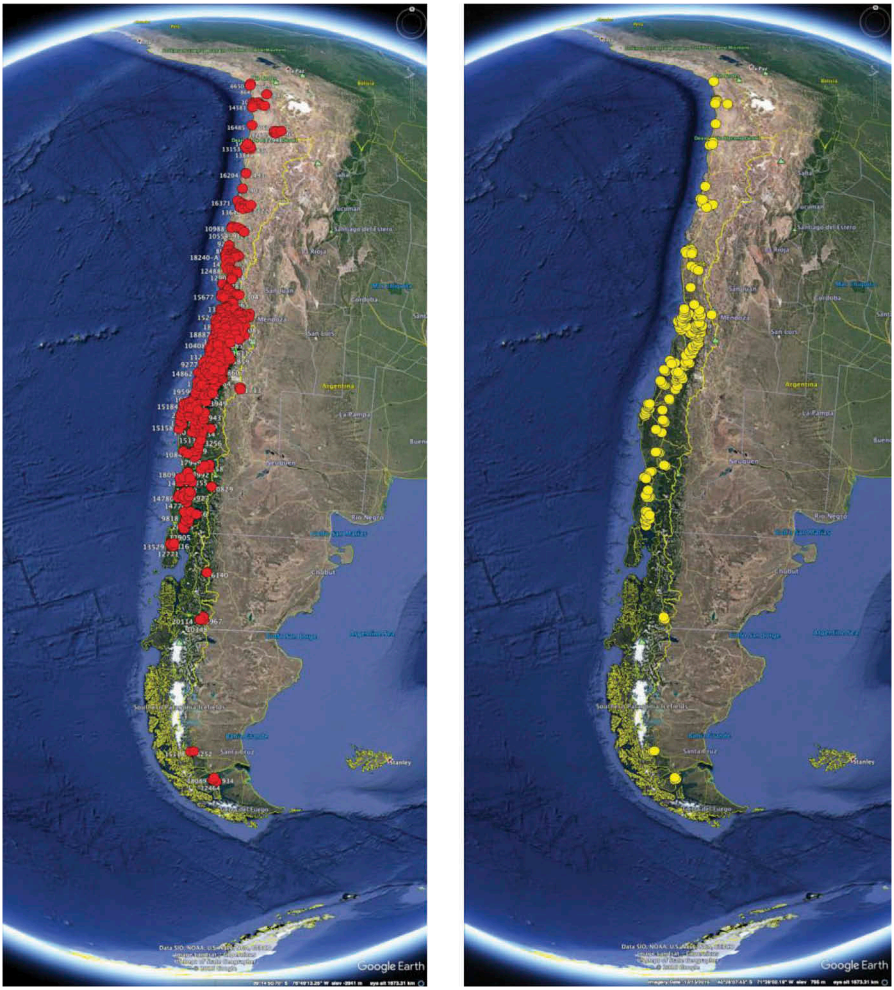

Figure 1. Distribution of sites with V_{s30} in Chile shown on the left and distribution of sites with T_N on the right.

Table 1b. New Chilean Code

Site Class	Soil description	Vs30 (m/s)	Tnak (seconds)
A	Rock	≥ 900	< 0,15 (o H/V Flat)
B	Soft rock and very dense soil	≥ 500	< 0,30 (o H/V Flat)
C	dense/stiff soil	≥ 350	< 0,40 (o H/V Flat)
D	Medium dense soil	≥ 180	< 1,0
E	Soft soil	< 180	-

were made in accordance with the V_{s30} ranges of the site Classes A, B, C, D and E as defined in the Chilean Code (Table 1a) and performance of the sites during the past earthquakes.

Iquique sites are mainly stiff soils resting on shallow rock. The shear wave velocity ranges from 350m/s to more than 900m/s and the T_N from flat response to 0.2s as shown in Figure 2. No significant damage was reported in this area during the Iquique earthquake Mw8.2 (2015). The left figure shows the corresponding V_{s30} measurements, most of which indicates velocities

Table 2. Data base

	V_{s30}	Borehole	T_N	$V_{s30} + T_N$	V_{s30} + Borehole + T_N
N of sites	1850	612	670	670	309
N of measurements	3600	612	2000	670	309

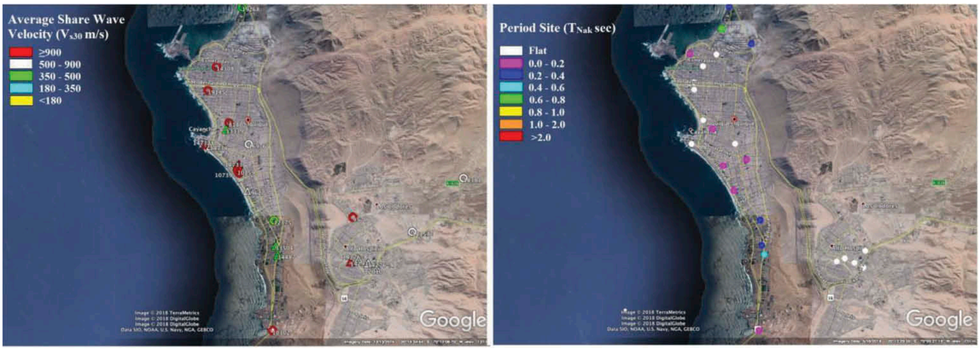

Figure 2. The V_{s30} hazard map for Iquique-Alto Hospicio is shown on the left and the T_N hazard map on the right.

greater than 900m/s indicating very stiff soils. These sites will classify as Site Class A. The five white data points indicate velocities within the range of 500m/s to 900m/s these sites classify as Site Class B. The five green data points indicate velocities within the range of 350m/s to 500m/s these sites classify as Site Class C.

The T_N of all the natural deposits are less than 0.4 seconds. The white data points indicate a flat frequency response and the purple points indicate T_N less than 0.2 seconds. The green data point is located in a man-made fill and is not included in the overall assessment.

The Santiago basin is primarily composed of pebbles, gravels, clays, and pumice or volcanic ash (Morales & Jerez 2002). The pebbles and gravels are mainly located in the eastern and southern part of the basin; clayey material is mostly present in the north, whereas a transition zone, between the gravel and clay zones is encountered in the center of the valley. The data points are shown in Figure 3.

The left side of Figure 3 shows the distribution of shear wave velocities, V_{s30}. The white data points within the boundaries of the blue curve indicates V_{s30} in the range of 500m/s to 900m/s typical of site Class B. The red curve encloses the majority of the soft clay sites (blue data points) with shear wave velocities 180m/s to 350m/s typical of site

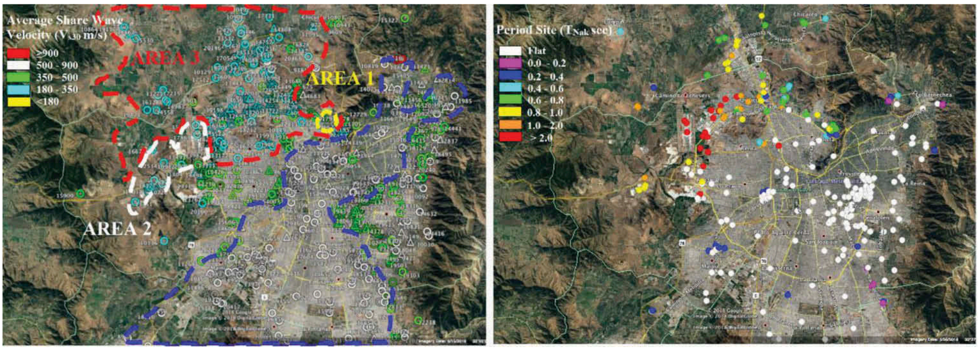

Figure 3. The V_{s30} hazard map for Santiago is shown on the left and the T_N hazard map on the right.

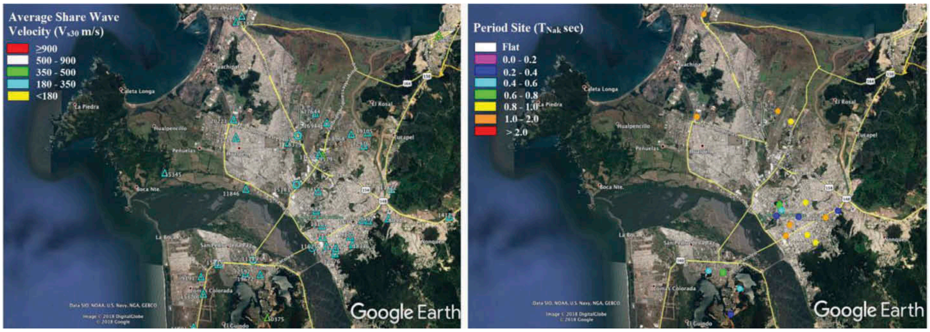

Figure 4. The V_{s30} hazard map for Conception is shown on the left and the T_N hazard map on the right.

Class D. At both sides of the blue curve boundaries are green data points indicating V_{s30} in the range 350m/s to 500m/s, which is site Class C. At the top center there is a small area, Ciudad Empresarial (Area 1), underlain by clays and on the North West portion which is underlain by pumice (Area 2). A third area, is the North Vespucio Ring. All three areas V_{s30} in the range 180 to 360m/s.

The right side of Figure 3 shows the Nakamura periods; the white data points indicate periods flat or less than 0.2 seconds. At the top center, Ciudad Empresarial (Area1), underlain by clays with periods in the range 0.6 to 1.0 seconds and on the north west portion (Area 2) is Pudahuel underlain by pumice and has T_N in the range of 1.0 to 2.0 seconds. The North Vespucio Ring (Area 3) indicates periods also in the range 1.0 to more than 2.0 seconds.

Concepcion region is mostly composed of poorly graded sands and silty sands, in layers of varying thicknesses and very uniformly deposited. The sands have non- plastic fines content of 22%, according to information collected from several boreholes throughout the city. Non plastic silts and silts of low plasticity can be found in layers 1 m to 4 m thick at slightly different depths in the entire basin, which suggests that they were deposited during a low velocity period of the Bio-Bío river (Montalva et al 2016).

The left side of Figure 4 illustrates the distribution of shear wave velocities V_{s30}. Most of the velocities are in the range of 180m/s to 360m/s. Although V_{s30} is fairly uniform over the entire area, the T_N varies from the edge of the basin to the center in the range of 0.2 seconds to 2.0 seconds. The variability in the T_N reflects the varying depth of bedrock from the edge of the basin to the center and therefore is more representative of site conditions than V_{s30}.

The deep blue data points in the right plot indicate periods in the range 0.2 to 0.4 seconds. The light blue points indicate 0.4 to 0.6 seconds. The green points indicate periods of 0.6 to 0.8 second, the yellow points periods of 0.8 to 1.0 seconds and the orange points periods of 1.0 to 2.0 seconds.

3.2 *Correlation of damage with T_N*

In the earlier study by Ruz & Finn (2017) they showed that the Nakamura site periods greater than 0.4 seconds indicated potential for significant structural damage on the basis of data from 80 sites. In the present study the database has been extended to 670 sites and the T_N 0.4 seconds threshold was confirmed to be a good indicator of the threshold for damage potential.

In the context of this paper, damage implies significant structural damage that needs to be repaired. No serious damage was observed at sites where T_N less than 0.4s, this finding was true irrespective to the intensity of the shaking or the type of structure. Damage structures varies from 1 story homes to tall buildings and overpasses. The correlation between T_N and damage potential was investigated for three areas; Iquique in the north, Santiago in the middle and Concepcion in the south. The damage data is based on the excellent reconnaissance reports of Assimaki et al (2012) and Motalva et al (2016).

Figure 5. Damage patterns in Cuidad Empresarial.

Iquique area has more than 300.000 habitants and incredibly it was subject to the Iquique M8.4 (2014) and no damage was reported. This is consistent with T_N showing flat frequency response or periods less than 0.2 seconds as shown in Figure 2.

The damage in Santiago was correlated with T_N for 3 areas with significant damage after the Maule earthquake Mw 8.8 (2010). The 3 areas are Ciudad Empresarial shown as Area 1 in Figure 3, Vespucio North Ring shown as Area 2 and Pudahuel shown as Area 3. Typical damage pattern in Ciudad Empresarial is shown in Figure 5. This damage has been associated with T_N in the period range of 0.6s to 1.0s.

Damage in the Vespucio North Ring (area 2) involved the collapse of 2 overpasses Miraflores and Lo Echevers shown in Figure 6a and b respectively. This damage was associated with T_N of 2 seconds.

Figure 6a. Overpass Lo Echevers

Figure 6b. Overpass Miraflores.

In the Pudahuel district, designated as area 3 in Figure 2, a 40m thick layer of pumice is known to sit on top of the sedimentary column. The Mw 8.0 Valparaíso earthquake in 1985 showed that this area was susceptible to heavy damage because of the soft soil conditions. The recent damage patterns there due to Maule Mw8.8 (2010) were correlated with the T_N=1.0s to 2.0s.

Concepción was severely hit by the Maule earthquake Mw8.8 (2010). There was extensive damage in the downtown area and some bridges collapsed catastrophically. Figure 8 shows damage to a collapsed bridge and shows an apartment building in the downtown area. The areas of these damage events had site periods in the range of 0.6 to 1.2 seconds. The T_N varied across the basin because the depth of the rock was changing across the area and therefore, could differentiate between damage at different sites. On the other hand, the V_{s30} was constant across the basin and could not make a distinction between sites with damage or no damage. In this area T_N is clearly a better indicator than V_{s30}. These findings are in agreement with T_N=0.4 seconds as threshold for damage potential (Ruz & Finn 2017).

Figure 7a. Ciudad de los Valles Pudahuel.

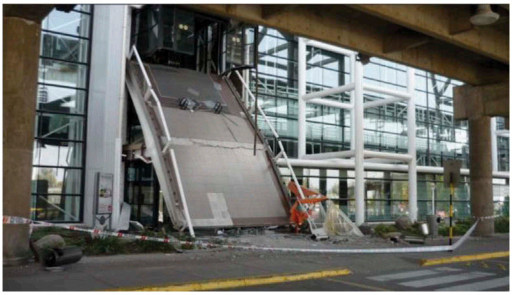

Figure 7b. Pudahuel Airport.

Figure 8. Collapsed bridge in Concepcion shown on the left and damaged apartment building on the right.

Studies of the type described above were conducted for all sites were T_N was available and damage was reported. A critical study of the data resulted in the development of a site classification based on T_N that was accepted by the code committee and are shown in Table 1b.

4 CONCLUDING REMARKS

Maps of V_{s30} and Nakamura site periods, T_N, were developed using data from more than 1850 sites distributed all over Chile. The Nakamura site period, $T_N = 0.4$ seconds threshold was confirmed as a reliable threshold for damage potential. The proposed new Chilean Code has incorporated T_N as an additional parameter to V_{s30} as shown in Table 1b.

The impact of T_N on site classification is shown in Table 3. Out of a total of 670 sites, the classifications of 167 sites (25%) were changed to a different category. According to the new Code, 15% are categorized to a superior category and 10% will correspond to a lower category.

Concrete examples of significant change in site categories are provided by Concepcion, Lo Echevers and Miraflores overpasses. Concepcion suffered severe damage during the Maule earthquake (Montalva et al 2016) and sites that were classified as D now are rated as E based on the T_N. It is important to note that a vulnerability study involving 269 structures (reinforced and over three storey structures) was conducted before and after the Maule earthquake. Results show that 18% of the structures suffered structural damage. The overall study suggests that T_N may be a more reliable indicator of damage potential than V_{s30} in cases where the depth to bedrock varies considerably with distance from the edge to the center of the Concepcion basin. The area of the Miraflores overpass and the Iloca area have the same V_{s30} but significantly different T_N. The Iloca period is 0.28 seconds and the Miraflores T_N is

Table 3. Redistribution of sites classes

Nº of Site	Current Code	New Code
6	B	A
7	B	C
1	C	A
23	C	B
29	C	D
9	D	B
41	D	C
33	D	E
6	E	C
12	E	D

2.2 seconds but both has a V_{s30} of 312m/s. There was no damage in Iloca and the Miraflores overpass failed catastrophically. This example shows that V_{s30} may not be a reliable indicator for the many sites with varying depth to bedrock.

This study has shown that T_N leads to site classifications that are a better index of damage potential. This is particularly true for basin sites with varying depth to bedrock rock. A number of these sites in Chile had a constant V_{s30} over a considerable distance yet the recorded damage varied with location. Increased damage was associated with increasing values of T_N due to the varying depth to bedrock.

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