CHILEAN EMERGENCY SEISMIC DESIGN CODE FOR BUILDING AFTER EL MAULE 2010 EARTHQUAKE

T. Guendelman
Chairman Chilean Seismic Code Committee

G.R. Saragoni
Coordinator Chilean Seismic Code Calibration Subcommittee

R. Verdugo
Coordinator Chilean Seismic Code Soil Subcommittee

SUMMARY:
The main modifications to Chilean Seismic Design Code for building Nch 433 of 96 due to the lesson of 2010 earthquake are presented. These modifications are included in a complementary emergency seismic guide DS61 and it was the result of the work of more than 70 engineers.
The main modifications refer to the soil classification and the design spectra. The new soil classification is dynamic using V_s30 and increase the number of soil types from 5 to 6.
Acceleration and displacement design response spectra are defined for only 4 soil types. The more soft soil was not included in this stage due to limitation of the classification based only in V_s30.
The conditions of minimum base shear of the Chilean code Nch 433 of 96 was considered the main reason of the good performance of tall buildings, however this requirement was increased for soft soils in the new guide.

Keywords: Chile, 2010 Earthquake, Code, Building.

1. INTRODUCTION

The El Maule, Chile 2010 MW = 8.8 earthquake struck the main cities of Santiago, Concepcion and Viña del Mar where there are many tall building of reinforced concrete. The earthquake was characterized by the collapse of one tall building in Concepción and two five stories concrete buildings in Santiago. Despite the few catastrophes, it appears that tall buildings performed well and the vast majority of those buildings that did incur damage provided at least life safety as it was recommended by the Chilean code Nch 433 of 96 “Earthquake resistant design of buildings”. Only 2.8% of the analyzed of 1939 buildings of more than 8 stories with permit between 1985 and 2009 shown failure, which was a very pleasant outcome, since the tall buildings were subjected to strong ground shaking and long shaking duration that have not been experienced before. However this reduced amount of failures of shear wall concrete buildings was concentrated in the last 10 years generation of buildings, which produced great concern about the satisfy of the code. One reason of the observed damage in tall building was due to lacks of the soil classification of the Chilean Code Nch 433 of 96 which leads to important difference in the demand of design response spectra for stiff and soft soils in the range of periods of tall buildings T > 1.0 sec. The other reason of the failures was the underestimate of the design spectra of the Chilean Code Nch 433 of 96 for long periods.

In this paper are presented the corrections to these detected problems included in the Chilean complementary emergency seismic design guide DS61 of the Ministry of Housing and Planning (MINVU) of December 2011.

2. THE 2010 CHILE EARTHQUAKE

The offshore Maule, Chile earthquake occurred at 3:34:15 local time with a moment magnitude of 8.8 as determined by the United States Geological Survey (USGS 2010). The location of the epicenter was at latitude of 35.909°S and longitude 72,733°W, which is 95 Km northwest of Chillan, 105 Km north-northeast of Concepción and 335 Km Southwest of Santiago, the capital of Chile.This subduction interplate thrust earthquake occurred at the convergence of the Nazca oceanic plate with the South American continental plate. The focal depth was 35 Km. this is the sixth largest magnitude earthquake recorded in the world and therefore considered to be a mega earthquake. This mega earthquake is characterized to have a rupture length of 500 Km with the release of the seismic energy from two main dominant asperities, one located near Concepción and the other near Pichilemu .

The Chilean Deputy Interior Secretary confirmed the fatalities in 521 from the earthquake, among them 124 due to the subsequent tsunami; the number of people classified as missing is 56. The earthquake and tsunami left some 800.000 people injured or displaced. The government estimated that the damage was U$ 30.000.000.000. Private estimation reduces this value to only U$ 24.000.000.000.

3. ACCELEROGRAPHIC DATA

The earthquake was recorded by 35 accelerographs, obtained for the first time in the world accelerograms for Mw = 8.8 earthquake. The characteristic of these accelerograms is the long duration around 2.5 minutes in agreement with the rupture length of the source of the earthquake. Accelerograms were obtained at ground level in most of the important damaged cities, in instrumented buildings, isolated buildings, isolated bridges dams and elevated metro.

A record obtained in Angol was close to 1g, which was confirmed by USGS as well recorded. However the most important accelerogram was obtained in downtown Concepción, close to the site where the high rise concrete building collapsed. In Figure 1 is shown the acceleration response spectra of downtown Concepción record showing an important record peak at the period of 2.0 sec due to the sandy soil (Saragoni et al. 2010).

The earthquake produced important soil amplification effects which were detected in the acceleration response spectra. One important effect of soil response was the disagreement between the peaks of the design response spectra of the Chilean Code Nch 433.of 96 according to its soil classification. The peak is supposed to be located at the natural period of the soil, however most of the time the peak of response spectra of recorded accelerograms exhibits the peaks at higher periods. This is one of the reasons of the failure observed in many high rise buildings which is covered in the next section.

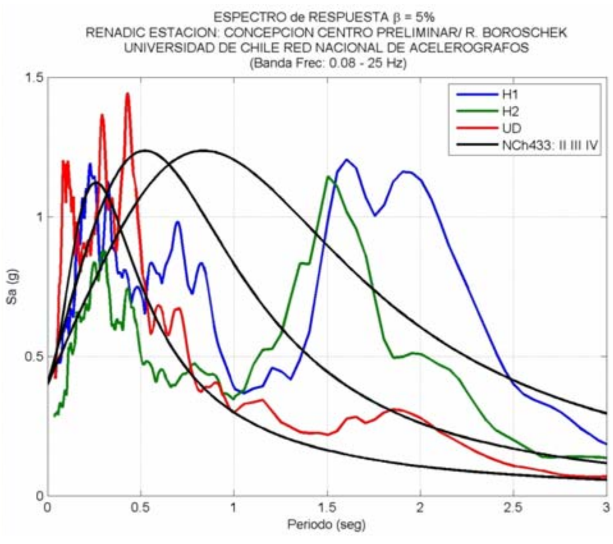

Figure 1. Acceleration response spectra for the Concepcion downtown station showing an important second peak at the period of 2.0 sec due to soil amplification. Comparison with Nch 433. of 96 Code design spectra for soil Types II, III and IV showing the disagreement, (Boroscheck et al. (2010)).

4. PERFORMANCE OF TALL BUILDINGS

There are many tall building in Santiago, Concepción and Viña del Mar that there are for office and residential, most of them are of reinforced concrete. The 55 story Titanium was just completed that year and a height of 191.7 m is currently the tallest building in South America; the building has seven subterranean levels. The nearby Gran Torre Costanera concrete building was currently under construction and will be 300m in height at its spire and it is now the tallest building in South America.

Despite the few catastrophic, it appears that tall buildings in Chile performed quite well and the vast majority of those buildings that did incur damage provided at least life safety as it is recommended by the Chilean code Nch 433 of 96. "Earthquake Resistant Design of Buildings". Table 1 summarizes the performance of the buildings with construction permits granted for 9,974 residential buildings with three stories or greater from 1985 to 2009 in Chile (Lew et al. 2010). That is the buildings built after the important 1985 central Chile earthquake which inspired the Chilean Code Nch 433 of 96 based on the successful results of its former version of 1972.

Table 1. Performance of Residential Buildings permitted from 1985 to 2009.

Building that collapsed	:	4 (approximate)
Building to be demolished	:	50 (estimate)
No of building 3 + stories	:	9,974
No of building 9 + stories	:	1,939
Failures in 3 + story buildings		0.5%
Failures in 9 + story buildings		2.8%

The Nch 433 of 96 building code of Chile is very similar to the codes used in the United States, so the seemly good performance of tall building is a very pleasant outcome, especially since the tall buildings in Chile were subjected to strong ground shaking and long shaking duration that have not been experienced before. Since the last important earthquake of 1985 Central Chile, buildings in Chile, like buildings all over the world, have increased in height. In the meantime, the walls in these buildings have decreased in thickness due to various reasons such as architectural and parking needs. Walls in basements get reduced in length from walls above in the structure and vertical loads can be very high in these walls. Shear failures were not the dominant failure mode as compression failures of these walls were observed in most of the damaged tall buildings in Santiago, Viña del Mar and Concepción. Examples of this type of failure are illustrated in Figures 2 and 3.

The failure was characterized by a horizontal narrow strip on the vertical concrete shear walls under the slabs of the first basement (see Fig. 2). The vertical reinforcement steel was cut without extrusion (see Fig. 3). Other reason of the observed damage in tall buildings was due to the soil classification of the Chilean Code Nch 433 of 96 which leads to important difference in the demand of design response spectra between soils II and III in the range of periods of tall buildings, $T > 1.0$ sec (see Fig.1). Most of these failures were due to the lack of confinement of the boundary of shear walls required by ACI code but eliminated by the Chilean code Nch 433 of 96. This allowance of the Chilean code was deleted in the 2009 version of the code, and in 2008 reinforcement concrete Chilean code.

Figure 2. Horizontal failure strip in basement shear walls.

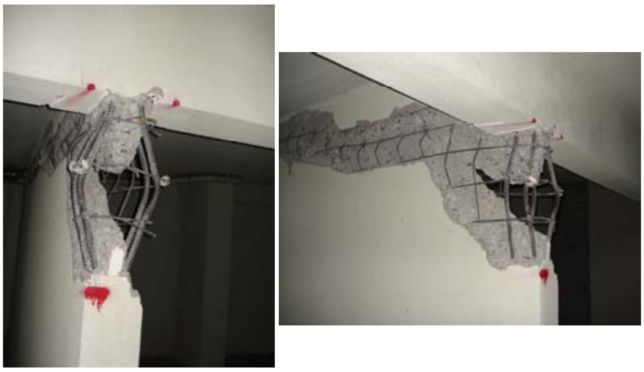

Figure 3. Head of the shear wall in the zone of the horizontal strip failure.

5. MODIFICATION OF DESIGN SPECTRA

The design response spectra used to calculate the seismic resistant of the structure was modified to

$$S_a = \frac{SA_o\alpha}{\left(R^*/I\right)} \tag{1}$$

By introducing the factor S of dynamical soil amplification of Table 2
The factor S increases the design spectra considered in the previous Chilean Code Nch 433 of 1966, mod. 2009 and the new spectra is shown in Figure 4.
The amplification factor α is estimated for each vibration mode n according to the following equation.

$$\alpha = \frac{1+4.5\left(\dfrac{T_n}{T_o}\right)^p}{1+\left(\dfrac{T_n}{T_o}\right)^3} \tag{2}$$

Where Tn = vibration period of mode n, and T_0 and p , parameters related with the properties of the soil and given in Table 2.
The values I and A_0 are the same of Nch 433 of 1966, mod. 2009.
The R* of Eq. (1) is the response modification coefficient, which that in the Chilean code is not constant, it depends of T* the natural period of the mode with the largest translation mass in the

direction of analysis. As it is shown in Eq. (3).

$$S_{de}\,(T_n) = R^* = 1 + \frac{T^*}{0.10T_o + \frac{T^*}{R_o}} \tag{3}$$

Where R_0 is a value depending of the type of structure and T_0 of the soil type.
This is an important difference of the Chilean Code with respect to other code that considers R constant.

Table 2. Parameters depending of soil type.

Soil Type	S	T_0	T'	n	p
		S	s		
A	0.90	0.15	0.20	1.00	2.0
B	1.00	0.30	0.35	1.33	1.5
C	1.05	0.40	0.45	1.40	1.6
D	1.20	0.75	0.85	1.80	1.0
E	1.30	1.20	1.35	1.80	1.0
F	*	*	*	*	*

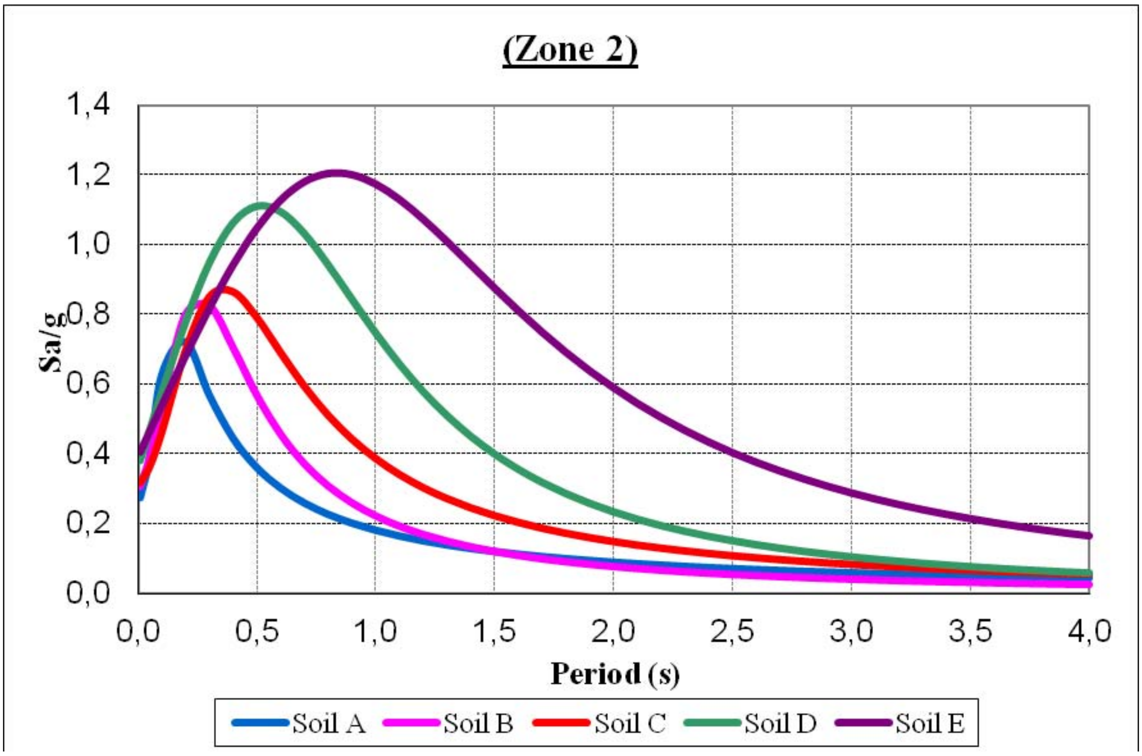

Figure 4. Elastic Acceleration Spectra for zone 2 (Ao = 0.30g); R*=1, I=1, showing the effect of the new soil classification

6. ELASTIC DISPLACEMENT SPECTRA

The new guide define the elastic displacement response spectra S_{de} (cm) required to calculate the building roof lateral displacement as

$$S_{de}\,(T_n) = \frac{T_n^{\,2}}{4\pi^2}\,\alpha\, A_0\, C^*{}_d \tag{4}$$

In this equation A_0 is given cm/s^2 and the displacement amplification factors C^*_d are the values given in Table 3.

Table 3. Deflection Amplification Factor C_d^*

Soil Type	C_d^*	Period Range
A	*1.0*	$T_n \leq 0.23$ s
	$-0.055T_n^2 + 0.36T_n + 0.92$	0.23 s $< T_n \leq 2.52$ s
	$0.08T_n^2 - 0.9T_n + 3.24$	2.52 s $< T_n \leq 5.00$ s
B	*1.0*	$T_n \leq 0.47$ s
	$0.95T_n + 0.55$	0.47 s $< T_n \leq 2.02$ s
	$0.065T_n^2 - 0.75T_n + 3.72$	2.02 s $< T_n \leq 5.00$ s
C	*1.0*	$T_n \leq 0.65$ s
	$0.57T_n + 0.63$	0.65 s $< T_n \leq 2.02$ s
	$0.055T_n^2 - 0.63T_n + 2.83$	2.02 s $< T_n \leq 5.00$ s
D	*1.0*	$T_n \leq 0.90$ s
	$1.1T_n$	0.90 s $< T_n \leq 1.75$ s
	1.93	1.75 s $< T_n \leq 5.00$ s

The values of C_d^* of Table 3 were obtained from an analytic adjustment with the elastic response spectra obtained from the accelerographic records of the Chilean earthquake of February 27, 2010.

It must be noticed that C_d^* values are given only for the first four type of soils. For soil type E, special studies are required.

The value of Sde is used to calculate the lateral building roof displacement of reinforced concrete buildings δ_u according to the following equation

$$\delta u = 1.3 S_{de}(Tag) \tag{5}$$

Where Tag is the period of the mode with the largest translational mass in the direction of analysis, considering the effect of reinforcement steel and the stiffness of the cracked concrete.

7. LIMITATION OF MINIMUM BASE SHEAR Q_{MIN}

The condition of minimum base shear of the Chilean Code Nch 433 of 96 was considered the main reason of the good performance of tall buildings during the 2010 earthquake, however in the new guide the minimum base shear was increased by the soil factor S to correct the few building failures observed in softer soils. The base shear resulting from the spectral modal analysis must be equal or greater than $Q_{min} = ISA_0P/6g$.

If the base shear is less than Q_{min} the displacements and rotations of the horizontal diaphragms and the action on the structural elements must be multiply by a factor such that base shear reaches the required minimum value.

This requirement of Q_{min} implies the use of a less value R* for high rise building call R_1, in the code.

$$R_1 = \begin{cases} R^* \dfrac{Q_o}{Q_{\min}}; Q_o \le Q_{\min} \\ R^*; Q_o \ge Q_{\min} \end{cases} \tag{6}$$

Where Q_0 = base shear.

The use of R_1 values implies a more elastic response for high rise buildings which is part of the success of the Chilean Code in the 2010 mega earthquake.

8. SOIL CLASSIFICATION

The Chilean code Nch 433 of 96 that was operative before the earthquake of 2010, classified the sites, from a seismic point of view, using soil parameters mainly associated with their resistance, such as RQD, unconfined strength, N-SPT, undrained resistance. This approach resulted in that several sites were wrongly classified, underestimating they response spectra. Especially catastrophic were the cases occurred in deep deposits of saturated dense to medium sandy soils such as the recorded in downtown Concepción, see Figure 1.

To overcome this situation a new seismic soil classification was developed. Firstly, six different soil types were defined and the main soil parameter adopted was the shear wave velocity of the upper 30 m of the ground. To ensure a rather smooth transition to the use of the new provision, the former resistance parameters were also included and some of them slighted increased. The resulting seismic soil classification is presented in Table 4.

It is well known that the seismic soil response at the surface is definitely dependent of the entire soil deposit, being insufficient the evaluation of the soil properties only in the upper 30 m. However, for practical purposes is a depth that can be realistically achieved in normal projects. Nevertheless, in the next version of the soil classification the fundamental period of the site is going to be introduced, which can be easily obtained using ambient noise measurements by means of the H/V spectral ratio.

Table 4. Seismic Soil Classification

Type of Soil		V_{s30} (m/s)	RQD (%)	q_u (MPa)	(N_1) (blows/ft)	S_u (MPa)
A	Rocks, cemented soils	≥ 900	≥ 50	≥ 10 $(\varepsilon_{qu} \le 2\%)$		
B	Soft or fractured Rocks, very dense or very firm soils	≥ 500		≥ 0.4 $(\varepsilon_{qu} \le 2\%)$	≥ 50	
C	Dense or Firm Soils	≥ 350		≥ 0.3 $(\varepsilon_{qu} \le 2\%)$	≥ 40	
D	Medium Dense or Medium Firm Soils	≥ 180			≥ 30	≥ 0.05
E	Medium Loose Soils	< 180			≥ 20	< 0,05
F	Special Soils	*	*	*	*	*

V_{s30} : Shear wave velocity of the upper 30 m of the ground

N_1 : Standard Penetration Index normalized at 0.1 MPa of confining pressure. Applicable only to soils that classify as sands.

RQD : Rock Quality Designation, according to ASTM D6032.

q_u : Simple Compression Resistance.

$\boldsymbol{\varepsilon_{qu}}$: Strain developed at peak resistance of the simple compression test.

S_u : Undrained strength.

9. SEPARATION BETWEEN BUILDINGS.

The distance of a building to the vertical plane of the extreme of the lot at any level can not be less than $2R_1/3$ the seismic displacement at that level calculated according to the static or spectral modal analysis of the code. This distance can not also be less than one thousandth of the height of the same level neither 1.5cm.

10. CHILEAN SEISMICITY AND THE CALIBRATION OF SEISMIC CODE

Chile is characterized by the largest seismicity in the world which produces strong earthquakes every 83 ± 9 years in the central part of Chile (Compte et al. (1986)). This high seismicity allows calibrating the Chilean Seismic Code with the observed performance of buildings after each large quake. The last calibration was due to the Central Chile earthquake of March 3, 1985, M = 7.8 earthquake and it was introduced in Chilean Codes Nch 433 of 96 and Nch 433 of 96. mod. 2009.

This new El Maule earthquake of February 27, 2010, $M_W = 8.8$ has required to recalibrate again the code, especially for tall concrete buildings, after 15 years. A Subcommittee XI named "Calibration of Actual Code" was in charge to calibrate the recommendation of the commented emergency code. The committee was integrated for more than 14 engineers and analyzed the response of more than 2000 existing buildings undamaged and damaged by the earthquake (Guendelman and Lindenberg (2010)).

The conclusions of this subcommittee lead to the recommendations of the Supreme Decree 61 (DS61) of the Chilean Ministry of Housing and Planning. (MINVU) of December 13, 2011.

Supreme Decree DS 61 required derogating supreme Decree DS117 of 2010 which was the emergency seismic code for buildings since February 25, 2011. The DS 117 was derogated mainly due to the fact that it produced oversized building not accepted by the Chilean structural engineer community.

The emergency code DS 61 considers the simultaneous application of DS60 which gives the new requirements for the seismic design of reinforced concrete walls.

AKCONOWLEDGEMENT
Authors want to express their gratitude to the members of subcommittees II Soil Effects and XI Calibration of Seismic Code of the Emergency Seismic Code Committee.

REFERENCES

Boroscheck, R., Soto P. León, R y Comte, D. “Terremoto Centro Sur de Chile, 27 febrero 2010. Informe Preliminar N°5”. Departamento de Ingeniería Civil, Universidad de Chile, Facultad de Ciencias Físicas y Matemáticas <http: //www.renadic.cl> 6/4/2010.

Comte. D.A. Eisenberg, E. Lorca, M. Pardo, L. Ponce, R. Saragoni, S.K. Singh, G. Suarez (1986). “The 1985 Central Chile Earthquake: A Repeat of Previous Great Earthquake in the Region?, Science,Vol.23. pp 393-500.

DS N°60 MINVU (2010), Reglamento que fija requisitos de diseño y cálculo para el hormigón armado y deroga Decreto N°118, de 2010 (in Spanish), Ministerio de Vivienda y Urbanismo. Diario Oficial 13 de Diciembre de 2011.

DS N°61 MINVU (2011), Reglamento que fija el diseño sísmico de edificios y deroga Decreto N° 117, de 2010 (in Spanish), Ministerio de Vivienda y Urbanismo. Diario Oficial 13 de Diciembre del 2011.

Guendelman T. and Lindenberg J., Cambio en Solicitaciones Sísmicas en Edificios, Seminario Efectos del Terremoto en el Nuevo Diseño Sísmico y Estructural en Chile, ICH Nov. 2010.

Lew, M., Naeim, F., Carpentier, L., Youssef, N., Rojas, F., Saragoni, G.R. & Schachter, M. 2010. “The Significance of the 27 February 2010 Offshore Maule, Chile Earthquake”, Proc. 2010 Los Angeles Tall Building Structural Design Council Annual Meeting, 2010.

Official Chilean Standard Nch 433. of 96 (1996) “Earthquake Resistant Design of Buildings”. (In English). Instituto Nacional de Normalización INN. 43 pp.

Official Chilean Standard Nch 433. of 96 modificada 2009 (2009) “Earthquake Resistant Design of Buildings”. (In Spanish). Instituto Nacional de Normalización INN.

Saragoni, G.R., Lew, M. Naeim F., Carpenter L.D., Youssef N.F., Rojas F. y Schachter M. “Accelerographic Measurements of the 27 February 2010 Offshore Maule. Chile Earthquake” The Structural Design and Special Buildings 19(8): 886-875, 2010.

U.S. Geological Survey. 2010. Earthquake Hazard Program-Magnitude 8.8-offshore Maule, Chile. http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/