TWO PEAKS RESPONSE SPECTRA (2PRS) FOR SUBDUCTION EARTHQUAKES CONSIDERING SOIL AND SOURCE EFFECTS

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ABSTRACT :

Two peaks design response spectra (2PRS) for Chilean seismic code are proposed considering soil effects and seismic source effects. These spectra consider the source effects of interplate thrust and intraplate of intermediate depth earthquakes that are characteristic of Chilean subduction seismicity. These types of earthquakes present different characteristic periods of seismic source. The proposed spectra are the envelope of one of the source seismic spectra of the two considered types of earthquakes and one soil spectra. In the soil spectra the effect of soil damping is introduced explicitly, this condition produces higher decay than the actual one for the high periods. The spectra is obtained using the accelerograms from epicenter zones of large magnitude earthquakes close to the design magnitude, avoiding to mix with small amplitude accelerograms corresponding to earthquakes of small and moderate magnitudes, because the energy in seismic source periods is observed only in epicenter accelerograms of large earthquakes. The periods and dampings for the soil and the source seismic periods are proposed for different types of soil, according to Vs dynamic classification, for spectra of Chilean subduction earthquakes. The proposed designs 2 PRS consider the subduction due to Nazca plate, but it can be expanded to other subduction or non subduction zones.

KEYWORDS: Two peaks response spectra, Chile, Subduction, Seismic source, Soil period.

1. INTRODUCTION

In general, design response spectra for different world seismic code have been obtained from dynamic amplification functions by averaging normalized absolute acceleration response spectra, being majority of considered accelerograms of small amplitude due to the lack of ones in epicenter zone for large earthquakes.

The accelerograms of small amplitude are in general produced by small to moderate earthquakes, in which the soil free vibrations are predominant (Ruiz and Saragoni, 2008). This condition is in accordance with the seismic code common practice that considers only the fundamental period of soil in design spectra. However, the described previous steps for the design condition may be incorrect since in destructive earthquakes, it can be observed that dynamic amplification functions have more than one representative peak: one due to soil free vibrations and one peak due to source seismic waves.

Therefore in order to be able to understand the real behavior of soil during design earthquakes it is necessary to study accelerograms registered in epicenter zones for destructive earthquakes, since the different properties observed during large earthquake are not always present in small magnitude earthquakes.

Due to these limitations of response spectra based on averaging functions it has been suggested (Lobos, 1999; Gomez-Bernal, 2002; Ruiz and Saragoni, 2005a) to use more than one peak in design spectra to represent both soil and source seismic characteristics effects.

2. ACCELEROGRAMS OF LARGE CHILEAN SUBDUCTION EARTHQUAKES

Chile, in contrast with other seismic countries, has many important accelerograms from large magnitude earthquake registered in epicenter zones. This has permitted the study of the seismic behavior of soil and the influence of seismic source waves in large epicenter accelerograms.

With this accelerographic information it has been possible to measure the fundamental period and higher modes of soil and seismic source period from large magnitude earthquakes (Saragoni and Ruiz, 2004). On the other hand, the study of accelerograms from thrust and intraplate earthquake has permitted to establish the differences between them. These different characteristics will be included in the proposed spectra that will be the envelope of these types of subductive Chilean earthquakes.

3. ANALYSIS OF RESPONSE SPECTRA OF CHILEAN ACCELEROGRAMS

The study of important response spectra of Chilean earthquake has allowed to observe that this one present more than one characteristic peak. Lobos (1999) observed the presence the more than one peak and proposed response spectra with two peaks for the records of 1985 March 3 Central Chile earthquake. Later Ruiz and Saragoni (2004) proposed that one peak is associated to soil response and the other peak is associated to influence of seismic source.

In Fig. 1 is presented the elastic response spectra for 0 % damping for different earthquakes recorded at Papudo station (S40°E). In this figure is possible to observe two characteristic peaks, one being associate to soil and other to seismic source (Ruiz and Saragoni, 2004).

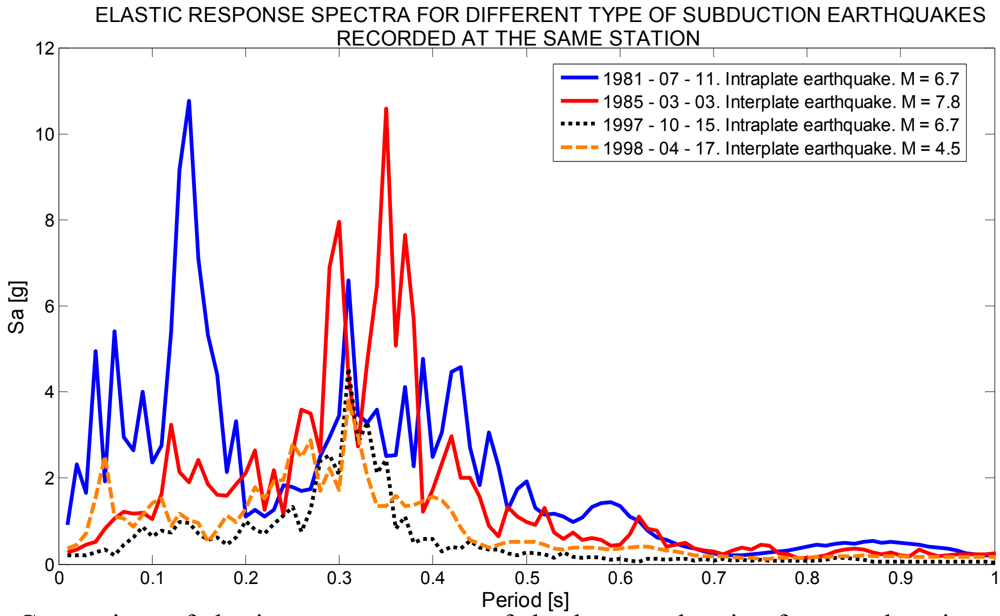

Figure 1. Comparison of elastic spectra response of absolute acceleration for zero damping of Chilean earthquake interplate type thrust and intraplate of intermediate depth, recorded at Papudo (S40°E) station, showing more than one predominant peak, consequence of soil response and seismic source.

In this figure it can appreciate that the response spectra of Papudo S40°E accelerograms for Papudo 1981 intraplate of intermediate depth earthquake (Ms = 6.7), obtained at few kilometers from the epicenter, shows one peak of absolute acceleration around of 0.33 s of period and other peak at approximate 0.15 s, this second peak it not observed in the other records of Papudo obtained for 1985 interplate type thrust earthquake (Ms = 7.8). In the accelerogram of 1985 interplate type thrust earthquake only one predominant peak is observed at 0.33 s, this period is associated to free vibration of soil (Ruiz and Saragoni, 2008). This period of 0.33 s is also observed in Fig. 1 in the others earthquakes of small magnitude, registered at Papudo station.

From the accelerograms obtained at Papudo station for four earthquakes, it is possible to conclude that if it only consider the average of the dynamical amplification functions, the record obtained in far zone of the epicenter or the registers of small amplitude will have more influence. Since the far or small amplitude accelerograms are predominant in the data base, the obtained average response spectra would have only one peak representative of soil effect without consider the one due to the seismic source effect.

4. CHILEAN CODE

From 1985 Central Chile subductive interplate thrust earthquake of magnitude Ms = 7.8, when more than 20 important accelerograms were obtained, it was proposed a new response spectra for the code NCh 433 Of. 93 and that it was maintained in the actual code NCh 433 Of. 96. The spectra of Chilean code NCh 433 Of. 96 is:

$$S_a = \frac{I \cdot A_0 \cdot \alpha}{R^*} \tag{1}$$

Where
I : Coefficient associated to the importance and use of the building.
A_0 : Maximum effective acceleration, that is determinate according to seismic zonation.
R^* : Reduction factor, that is function of the periods of the structure and the soil.
α : Dynamic amplification function.

Consequently the elastic basic spectra are given by:

$$S_E(T_n) = A_0 \cdot \alpha \tag{2}$$

Where α depends of the characteristics of the soil and the period of the structure and it has the following expression:

$$\alpha = \frac{1 + 4.5 \cdot \left(\frac{T_n}{T_0}\right)^p}{1 + \left(\frac{T_n}{T_0}\right)^3} \tag{3}$$

Where: T_n = Period of vibration n mode of the structure and T_0, p = Parameters of foundation soil types

5. CHARACTERISTIC PERIODS OF SOIL AND SEISMIC SOURCE

Ruiz and Saragoni (2005b) proposed the four fundamental periods (T_0) for each type of soils of the Chilean code NCh433 Of. 96 indicated in Table 1. The characteristic periods of seismic source and soil of Chilean accelerograms are shown in the Tables 2 and 3 (Saragoni et al. 2005a and Saragoni et al. 2005b).

Table 1. Fundamental period T_0 proposed for Chilean Code Nch 433 of. 96 for Chilean soils types. (Ruiz and Saragoni, 2005b)

Soil Type	To [s]
I	---
II	0,35
III	0,60
IV	1,00

6. ACCELERATION RESPONSE SPECTRA WITH TWO PEAKS

The earlier idea of Lobos (1999) and Gomez-Bernal (2002), who proposed response spectra with two peaks for accelerograms of Chile Central 1985 and Mexico City, Mexico 1985 earthquakes, has been considered.

The spectra with two peaks proposed here, for the 5% damping, consider: the period of soil (T_S) with β soil damping and the other peak at the characteristic period of seismic source (T_F). Therefore it is proposed that the absolute acceleration elastic response spectra is the sum of the response spectra proposed for the soil effect (Sa_{soil}) gives by Eq (4) and the response elastic spectra due to the seismic source (Sa_{source}), Eq. (5), the proposed spectra is given by Eq. (6).

$$Sa_{soil} = \frac{\left(\left(A \cdot a_{\max}\right)^{0,8}\right) \cdot \left(2 \cdot \beta \cdot \frac{T_n}{T_S}\right)}{\left(\left(1 - \left(\frac{T_n}{T_S}\right)^2\right)^2 + \left(2 \cdot \beta \cdot \frac{T_n}{T_S}\right)^2\right)^{0,5}} \tag{4}$$

$$Sa_{source} = \frac{a_{\max} + \left(B \cdot a_{\max}\right) \cdot \frac{T_n}{T_F}}{1 + \left(\frac{T_n}{T_F}\right)^3} \tag{5}$$

$$Sa\left(T_n, 0.05\right) = Sa_{soil} + Sa_{source} \tag{6}$$

Where T_S = fundamental period of soil, β = soil damping, T_F = period of seismic source, A and B are constants and a_{max} = PGA.

Table 2. Period of soils T_S seismic source T_R estimated from accelerograms of Central Chile 1985 earthquake. (Saragoni et al, 2005a)

Station	Soil type	T_S (s)	T_R (s)
Valparaíso (UTFSM)	I	0.67	0.20
Quintay	I	0.50	0.20
Las Tórtolas	I	0.25	---
Rapel	I	0.40	0.30
Illapel	II	0.25	---
La Ligua	II	0.29	0.16
Papudo	II	0.34	---
San Isidro	II	0.33	---
Melipilla	II	0.30	---
Pichilemu	II	0.33	---
San Fernando	II	0.36	---
Iloca	II	0.33	0.16
Hualañe	II	0.38	0.23
Talca	II	0.33	---
Cauquenes	II	0.45	---
Zapallar	III	0.50	0.18
San Felipe	III	0.50	---
Llay Allí	III	0.67	0.25
Viña del Mar	III	0.67	0.22
Santiago, Endesa	III	0.65	---
Llolleo	III	0.53	0.23
Ventanas	IV	1.00	0.33
Valparaíso (Almendral)	IV	0.83	0.27
Constitución	IV	0.77	0.36
Chillán	IV	0.77	---

The spectra proposed in Eq. (6) are calibrated with accelerograms of different Chilean earthquakes and the found values of A and B are presented in Table 4. For the T_F values it is proposed to use the relationship between T_S and T_R, given by Eq. (7) and assuming that $T_F = T_R$. The constant values C are proposed in agreement with the observed values in Chilean earthquakes (Saragoni et al., 2005a, 2005b).

$$Ts = C \cdot T_F \tag{7}$$

Where Ts = Fundamental soil period, T_F = Seismic source period, C = constant presented in Table 4.

Table 3. Characteristic periods of soils T_S and seismic source T_R, obtained from accelerograms of different type of Chilean earthquakes. (Saragoni et al., 2005b)

Station	Earthquake	Soil Type	T_S (s)	T_R (s)
Papudo	07 – 11 - 1981	II	0.39	0.15
Papudo	14 – 10 - 1997	II	0.41	0.29
La Ligua	07 – 11 - 1981	II	0.40	0.18
Illapel	14 – 10 - 1997	II	0.23	0.24
Zapallar	14 – 10 - 1997	II	0.41	0.29
Punitaqui	03– 11 – 1997	II	0.29	0.40
San Fernando	03 -04 - 1985	II	0.41	0.18
Iloca	03 – 04 - 1985	II	0.29	0.13

Table 4. Constants used for elastic response spectra for each soil type.

Soil Type	A	B	C
I	2	8	1.5
II	5	6	2.0
III	3.5	6	2.5
IV	4	4.5	3.0

In Fig. 2 are presented 2PRS for 5% structural damping used for the best estimates of A and B constants.

In Fig. 2a, is presented the response spectra for UTFSM S20E for Central Chile 1985 interplate thrust earthquake, for soil type I, with a period of Ts = 0.15 s, as it considered by Chilean code NCh 433 Of 96, although the period of soil in UTFSM show in the Table II is Ts = 0.67s. A soil damping of 0.1 was arbitrarily chosen.

In the Figs. 2b, 2c, 2d, are presented the 2PRS of intraplate intermedia depth earthquake in soil type II, showing like the nearest epicentral accelerogram has the highest peak at the seismic source period (Papudo S40°E, Papudo 1981, Fig. 2d). The response spectrum in Fig. 2e is the corresponding to San Isidro Long. accelerogram of Central Chile 1985 interplate thrust earthquake, this accelerogram has the highest acceleration (0.7g) for this large earthquake and it was not included in the estimate of α of the Chilean Code (Arias, 1989). In these cases (Figs. 2b, 2c, 2d and 2e) a soil damping β of 0.12 was used, only for Papudo station exist measurement of soil damping and the values are between 0.056 and 0.165 (Saragoni and Ruiz, 2004) .

In Figs. 2f and 2g the 2PRS of soil type III are presented for Llolleo N10°E and Viña del Mar S20°W accelerograms of Central Chile 1985 earthquake, showing that the seismic source peak is higher in Llolleo and soil period peak is the highest in Viña del Mar, as a consequence that Llolleo is near to a seismic source (asperity) (Ruiz, 2008). The soil damping β used in these stations is 0.17, which it similar to that proposed by Saragoni and Ruiz (2004) for Viña del Mar S20W for Central Chile 1985 earthquake.

Finally, in the Fig. 2h is presented the response spectra, for Ventanas EW accelerogram of Central Chile 1985 earthquake, with a period Ts = 1 s and soil damping of 0.12, similar to that proposed by Saragoni and Ruiz (2004).

7. SOIL DAMPING EFFECT ON SEISMIC HIGH-RISE BUILDINGS

The second peak of the 2PRS of Fig.2 corresponds to natural period of the soil. In this figure it is observed a good matching between observed and proposed spectra for structure periods T greater than natural period of the soil T_S. In this zone of $T_n > T_S$ the proposed 2 PRS, $Sa(T_n, 0.05)$ amplitudes are controlled by the soil damping β experimentally measure by Saragoni and Ruiz (2004). This result implies that 2PRS values for $T > T_S$ is controlled by the soil damping, and would explain the fast decay of the Chilean response spectra with the structural period T_n. This physical interpretation is very important for the seismic demand of high-rise buildings, since it would be less than the values considered by the actual Chilean Code.

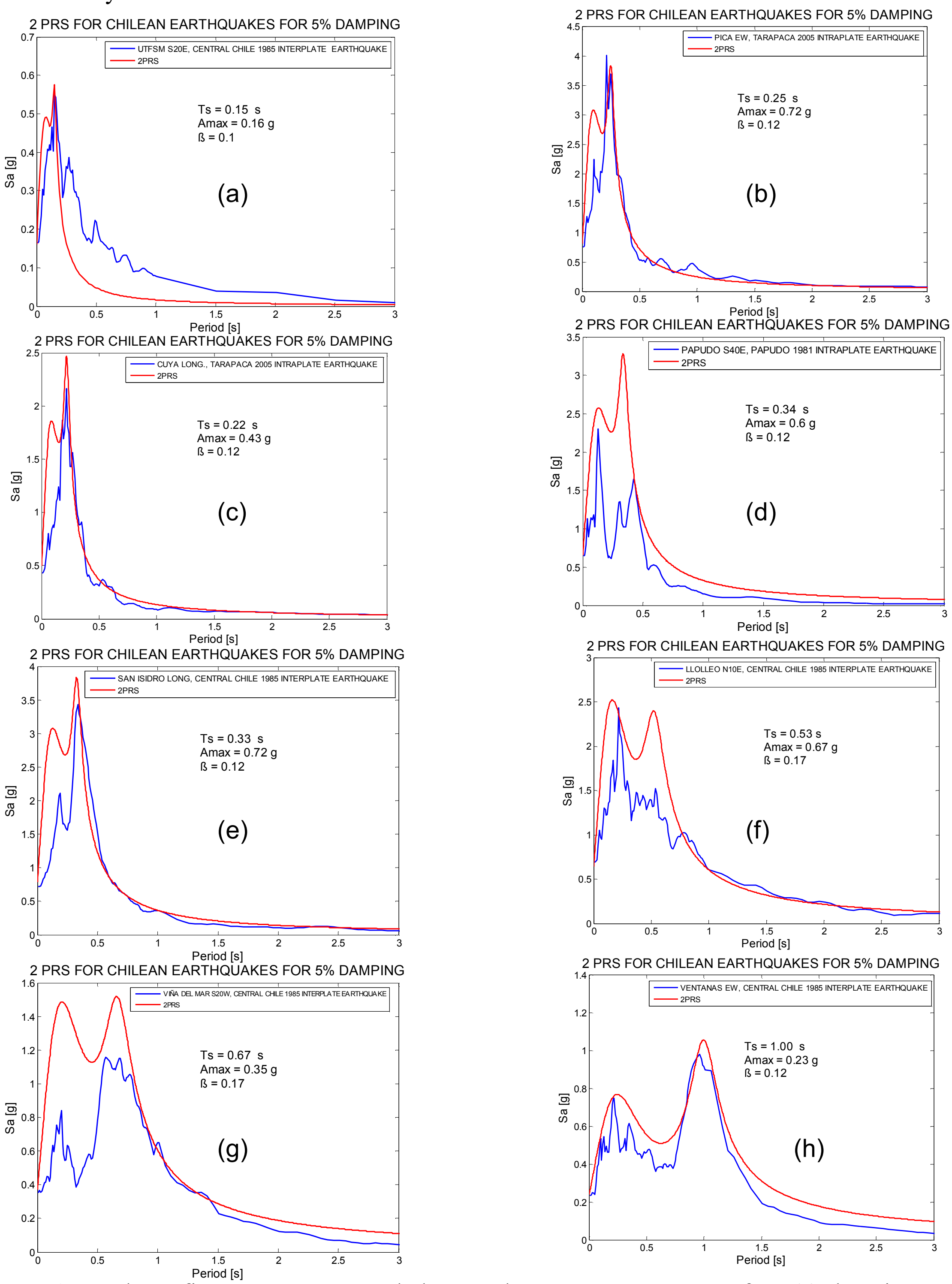

Figure 2. In these figures are presented the envelope response spectra for 5% damping used for calibration of constant A and B for two peaks spectra (2PRS), the values the PGA are in g, the soil period is T_S in sec and β is the soil damping.

8. CALIBRATION OF PROPOSED 2PRS FOR CHILEAN CODE

The satisfactory response of structures, designed according to seismic Chilean code during large Chilean subduction earthquakes, allows assuming that Chilean seismic code NCh 433 Of. 96 is

calibrated to real earthquakes. Therefore in this paper the shape of the proposed 2 PRS of Eq. (6) will be adjusted to the effective acceleration values A_0, considering as T_S the values of T_0 of Table 1 and T_S = 0.15 s for soil type I. The values of the soil damping β and the constants A and B are given in Table 5, keeping the C values considered in Section 6.
The proposed elastic basic 2 PRS is given by:

$$Se(T_n) = \frac{\left((A \cdot A_0)^{0,8}\right) \cdot \left(2 \cdot \beta \cdot \frac{T_n}{T_0}\right)}{\left(\left(1-\left(\frac{T_n}{T_0}\right)^2\right)^2 + \left(2 \cdot \beta \cdot \frac{T_n}{T_0}\right)^2\right)^{0,5}} + \frac{A_0 + (B \cdot A_0) \cdot \frac{T_n}{T_F}}{1+\left(\frac{T_n}{T_F}\right)^3} \tag{8}$$

Where:
A_0 = effective acceleration of Chilean code NCh 433 Of. 96. A and B constants given in Table 5. T_0 = Soil period given in Table 5. T_F = Seismic source period given in Table 5. β = Soil damping of Table 5.

Table 5. Constant of the elastic basic 2PRS by soil type.

Soil Type	A	B	β	T_0 [s]	T_F [s]
I	1	3.5	0.10	0.15	0.100
II	1.6	3	0.12	0.35	0.175
III	2.5	3.0	0.15	0.60	0.240
IV	2.8	2	0.15	1.00	0.333

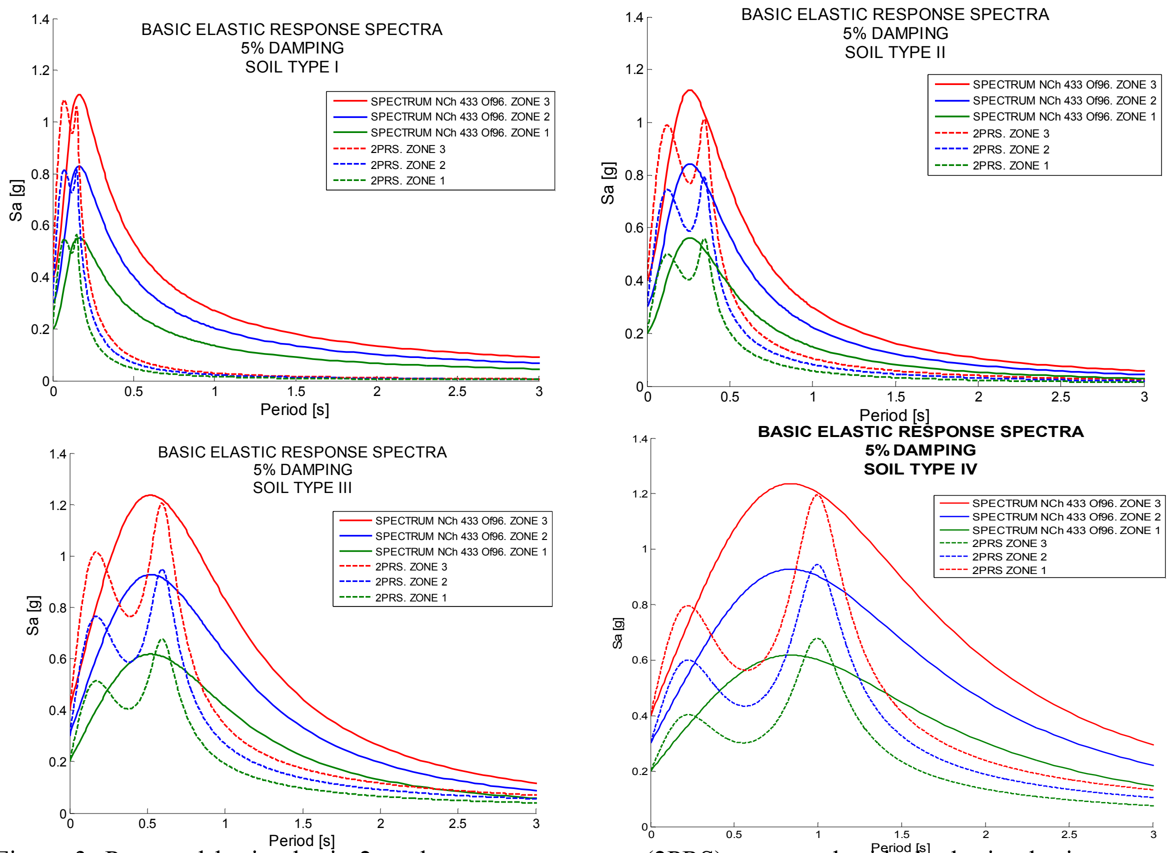

Figure 3. Proposed basic elastic 2 peaks response spectra (2PRS) compared with the basic elastic spectra of Chilean code NCh 433 Of 96 for different soil types and seismic zones.

It must be keep in mind that the proposed basic elastic 2PRS is an envelope that represent both interplate Ms = 8.5 and intraplate intermediate depth Ms = 8.0 earthquakes. This is an important difference with the desing spectra of the actual Chilean code that represent mainly interplate thrust type subduction earthquakes.

In general intraplate of intermedia depth earthquakes have higher frecuency content than interplate, therefore the intraplate control the amplitude of first peak of the seismic source of the 2 PRS, at least the site is close to an identified asperity of thrust earthquakes. The decay of the proposed 2PRS for structural periods larger than the period of the second peak is directly related with the commented effect of the soil damping and this zone of the 2PRS is generally controlled by interplate earthquakes.

In Fig. 3 are shown the proposed basic elastic 2PRS compared with the one of Chilean Code NCh 433 of 96 for each type of soil and seismic zone. It must be remembered that the considered soil classification corresponds to the dynamical one of UBC 1997 modified by Ruiz and Saragoni (2005). This classification considers the case of hard rock with $V_{S30} \geq 1500$ m/s, not considered in the actual Chilean code. This explains the observed differences between the proposed spectra and the Chilean code for soil type I.
The peak of the seismic source has a lower amplitude than the soil peak for soils types II, III and IV, since the soil damping controls the 2PRS for $T_n > T_0$.

9. COMMENTS AND CONCLUSIONS

It has been proposed two peaks response spectra for the Chilean code NCh 433 Of. 96, considering simultaneously the soil and the seismic source effects.
The proposed spectra consider the effects of the subductive earthquakes of interplate thrust and intraplate of intermediate depth types. However it has not been included at this stage the effect of crustal earthquakes.
The proposed design 2PRS considers the earthquake of the subduction due to Nazca plate, but it can be expanded to other subduction or non subduction zones.

REFERENCES

Arias, A., (1989). Proposal of design spectra for the new seismic design Chilean code. V Chilean Congress on Seismology and Earthquake Engineering, Santiago, Chile. (In Spanish)
Gómez Bernal, A., (2002).Interpretation of the soil effect in the Mexico valley using high density accelerographic networks, Ph.D. Thesis, Universidad Nacional Autónoma de México, México. (In Spanish)
Lobos, C., (1999), Effect of source mechanisms surface waves and soils on the accelerograms of Chile, March 3, 1985 earthquake, Thesis of civil engineer, University of Chile: Santiago, Chile. (In Spanish)
Ruiz, S. and Saragoni, G. R. (2004). Experimental measurements of the 1D dynamical response of soils using autocorrelograms of accelerograms of Ms = 7.8 Chile 1985 earthquake. V Chilean Congress of Geotechnique, Santiago, Chile. (In Spanish)
Ruiz, S. and Saragoni, G. R., (2005a). Proposal of 2 peaks acceleration response spectra for the Chilean seismic codes considering the effect of soils and subductive type earthquakes. IX Chilean Congress on Seismology and Earthquake Engineering, Santiago, Chile. (In Spanish)
Ruiz, S. and Saragoni, G. R., (2005b). Proposal of parameters and soil classification for seismic design codes considering the characteristics of accelerograms of Chilean earthquakes. IX Chilean Congress on Seismology and Earthquake Engineering, Santiago, Chile. (In Spanish)
Ruiz, S. and Saragoni, G. R. (2008). Soil Free Vibration in Large Earthquake. Soil Dynamic and Earthquake Engineering. In Press, Corrected Proof, Available online 14 March 2008.
Ruiz, S (2008). Characterization of high frecuency seismic waves in the near field. MSc Thesis on Geophysics, University of Chile. (In Spanish)
Saragoni, G. R., and Ruiz, S. (2004). Elastic 1D models for the seismic response obtained from accelerograms of Central Chile earthquakes. V Chilean Congress of Geotechnique, Santiago, Chile. (In Spanish)
Saragoni, G. R., Luppichini, N and Ruiz, S., (2005a). Study of free vibration soil waves and high frequency Rayleigh waves type of accelerograms of 1985 Central Chile earthquake. IX Chilean Congress on Seismology and Earthquake Engineering, Santiago, Chile. (In Spanish)
Saragoni, G. R., Modena, P. and Ruiz, S., (2005b). Study of free vibration soil waves and high frequency Rayleigh waves type of accelerograms of 1981 Papudo intraplate of intermedia depth earthquake. IX Chilean Congress on Seismology and Earthquake Engineering, Santiago, Chile. (In Spanish)