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# SITE RESPONSE STUDIES IN SITES WITH SEISMIC RECORDS FOLLOWING THE CHILEAN EARTHQUAKES OF 2010 AND 2014.

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## Abstract

Following the earthquakes of 27th of 2010 and April 1st of 2014 a good deal of information resulted because of the records obtained from the main shocks and the aftershocks. This data was complemented in some sites with a program of soil exploration and characterization that allowed modeling the subsoil profile.

This model was then used to characterize the response of the soil using some records obtained in rock in nearby locations and to compare the absolute acceleration spectra obtained from the original record and from the response of the soil model and with the design spectra of the DF 61 issued by the Ministry of Housing in Chile.

The purpose of this research was to find if there are substantial differences between these three spectra to explain them and to discuss their consequences in the analysis and design process.

*Keywords: Earthquakes, Site Response, Response Spectrum,*

## 1. Introduction

This work aims to compare the response spectra obtained at different stations for the latest earthquakes in Chile. The earthquake of February 27, 2010 [1], [3], and the earthquake of April 1, 2014 [2]. The stations chosen for this comparison are those that have the underlying soil characterized and the values of the soil parameters known and with a profile of the different layers up to the depth where a strong soil or rock is found. The compared spectra includes the design spectra for the sites according to the Chilean Code NCh433 of 96 Mod 2009. And DF 61 from the Ministry of Housing.

Several authors have describe methodologies for site response evaluation, for Santiago the work of Godoy [4] was revised, as well as the work by Matasovic, N & Hashash [5]

## 2. Profiles of Soils

To carry out this research, the following places were selected in different locations near or at the earthquake recording station and with different geotechnical characteristics and properties. Sites selected were Peñalolén and Melipilla, Las Americas School, Santa Lucia Hill, in the metropolitan region, Los Angeles in the Bio-Bio region, Constitución in the Maule Region, Iquique in the Tarapacá region and Valparaiso an Viña del Mar.

The spectra were obtained computing the response of the site modeled as a shear beam with different layers, using for this the earthquake accelerograms obtained at the same station, and acceleration records registered at rock outcrops nearby, For example at Rapel. These records obtained at rock locations were used as input at basal rock to obtain the site response. The records used were from the earthquake of the central zone in March 1985; records of the Maule Earthquake in February 2010; and the Iquique Earthquake of 2014.

The comparisons were made among spectra obtained at the sites with the spectra computed from the soil column model and the design spectra of Chilean design codes, NCh433 [6] and DF61 [7].

## 3. Site description

In Table 1, the soil properties and the strata profile are presented. This includes the density, shear wave velocity, thickness for each layer of soil and in each site. These were the properties used to model each site. In addition to the table some qualitative description is made for each site.

**Peñalolén**: The place where the recording instrument is located corresponds to the Luis Tisne Hospital. This instrument belongs to RENADIC. This place has a superficial layer that has a larger velocity than the layer below it. The rock in this site is located at 170 m below the surface, this agrees with the observed natural period of vibration of the site computed using the expression $T = 4H/v_s$, where H is the depth of the stratum, and $v_s$ is the shear wave velocity in the stratum.

Accordingly, the model for this site is a shear column of soil with the geotechnical properties obtained from testing and exploration, such as the shear wave velocity, density d plasticity. The damping and the shear modulus were modeled with cyclic degradation for each type of soil. However, for the Chilean gravel, the curves available do not match because Santiago gravel is composed of granite rock of high strength, and the clasts are in contact with each other and cemented with finer soil that makes the ensemble high rigidity. This makes that amplification in this types of soils is very low. The curves of degradation for the shear modulus and the damping for this material were the curves proposed by Idriss y Sun[8].

The site was subjected to the record obtained in rock at the Rapel station for 2010; this record is the one that adjust better to the model.

**Los Angeles**: The site considered in this city corresponds to the City Building, because it has a complete geotechnical study. For this site, the natural period of vibration of the soil was determined using the Nakamura method, giving a natural period of 0.18 sec. In this way the rock can be assumed to be at 39.0 m. Again, for this site the record of Rapel obtained during the Maule Earthquake of 2010 was used.

**Table 1 Different Sites Properties**

| **Place** | **Description** | | | |
|---|---|---|---|---|
| **Peñalolén** | 0 a 28 m: clay, Vs = 380 m/s, c=0,2 ton/m$^2$, φ=5,35° | 28 a 170 m: gravel, Vs=800 m/s, c=1,5 ton/m$^2$, φ=45° | 170 m: basal rock, Vs = 900 m/s, c=18 ton/m$^2$, φ=40° | |
| **Los Angeles** | 0 a 8,1 m: Sandy Silt, Vs=282 m/s, c=1,5 ton/m$^2$, φ=33° | 8,1 m a 40 m= Volcanic, Vs=1500 m/s, c=10 ton/m$^2$, φ=39° | 40 m: Basal Rock, Vs=1800 m/s, c=18 ton/m$^2$, φ=40° | |
| **Constitución** | 0 a 3,5 m: Sandy with clay and silt, Vs=180 m/s, high plasticity, water table at 1 m, c=1,2 ton/m$^2$, φ=27° | 3,5 a 23 m: Silty Clay, Vs=400 m/s, High Plasticity, c=2,5 ton/m2, φ=18° | 23 a 41 m: Sand rock, Vs=700 m/s, c=3 ton/m$^2$, φ=33°<br>41 a 47 m: Conglomerate, Vs=700 m/s, c=1,5 ton/m$^2$, φ=45° | 47 a 90 m: Arcillolite, Vs=700 m/s, c=5 ton/m$^2$, φ=33°<br>90 m: Basal Rock, Vs=2500 m/S, c=18 ton/m$^2$, φ=40° |
| **Iquique** | 0 a 4 m: Sand, Vs=330 m/s, c=0 ton/m$^2$, φ=34° | 4 a 25 m: High rigidity rock, Vs=1000 m/s, c=18 ton/m$^2$, φ=40° | 25 m= basal rock, Vs = 1250 m/s, c=18 ton/m$^2$, φ=40° | |
| **Melipilla** | 0 a 60 m: Gravell, Vs=650 m/s, c=2,5 ton/m$^2$, φ=45°, napa freática 3,7 m | 60 m: Calcareous Conglomerate, Vs=1250 m/s, c=7 ton/m$^2$, φ=50° | | |
| **Antumapu** | 0 a 5 m: Sand, Vs=400 m/s, c=0,5 ton/m$^2$, φ=37° | 5 a 10 m: Clay, Vs=300 m/s, c=1 ton/m$^2$, φ=23° | 10 a 200 m: Gravel, Vs=700 m/s, c=1,5 ton/m$^2$, φ=45° | |
| **Santa Lucia Hill** | Low Rigidity Rock, vs=1100, c=4 ton/m$^2$, φ=42° | | | |
| **Las Americas School** | 0 a 2 m: Clay, Vs=245, c=1,5 ton/m$^2$, φ=25° | 2 a 60 m: Gravel, vs=650, c=1,5 ton/m$^2$, φ=42° | | |
| **Valparaíso UTFSM** | High Rigidity Rock, vs=1100, c=8 ton/m$^2$, φ=55° | | | |
| **Valparaíso Almendral** | 0 a 40 m Sand, Vs=343, c=0,5 ton/m$^2$, φ=37° | | | |
| **Viña del Mar Centro** | 0 a 3 m: Clay, Low Consistency, and low Plasticity, High Humidity, c=1,8 ton/m$^2$, φ=22° | 3 a 30 m: Sand with quartz, High Compsctness, High Humidity, c=0,2 ton/m$^2$, φ=38° | | |
| **Viña del Mar el Salto** | 0 a 40 m:Sand with low contents of Silt, High Compactness, Medium Humidity, c=0,4 ton/m$^2$, φ=36° | | | |

**Constitución**: This site also was chosen because it had a complete geotechnical characterization, In this case wave velocities in the superficial layers was 700 m/seg, and at the basal rock 2500 m/seg. The profile of soil is characterized by limes and clay of very high plasticity, and is located on top of a conglomerate of rocks and argillite. The velocity registered at the basal rock is 2500 m/sec and it is located at 92 m. The phreatic level is at 1 m depth. Here the Maule earthquake record obtained at Rapel was used again.

**Iquique**: This city had an earthquake of Mw = 8.2 on the 1st of April 2014. During this event several records were obtained in different stations. This site chosen this time is called T05A, in the city of Iquique. The site in the neighborhood of the station is a layer of sand of 4.0 m of depth that lies on top of rock of very high rigidity. This rock rests over the basal rock at 25 m approximately. The records were deconvoluted to the basal rock

**Antumapu:** Located in Santiago, Antumapu is highly cemented gravel similar to Melipilla. Antumapu has a thick stratum of gravel 200 m deep, very stiff because is well cemented.

**Melipilla**: has a thin layer of sand with clay of about 6 m thick after which starts a strong layer of cemented gravel up to a depth of 60 meters, below this gravel there is a conglomerate of calcareous rock with no determined depth. The spectrum of the records obtained at Melipilla and Antumapu were computed and compared.

**Valparaiso UTFSM station**: This station is located on strong rock. The record obtained here for the earthquake of 2010 is measured in rock. Nearby there other record obtained in softer soils. One is located a Valparaiso at the Almendral district and at Viña del Mar Centro and Viña at el Salto. These records are relatively close among them. The soil in Viña del Mar is basically sand with clay that extends up to 30 meters at least. Almendral and el Salto has a deposit of sand of at least 40 m.

## 4. Results

As a first step, all sites have been grouped in three broad groups, rock sites, gravels and sand with gravel, without looking at other parameters such as depth of the deposit. In figures 1, 2 and 3 the spectra normalized to the peak ground acceleration of the acceleration record obtained for the soils is presented, and compared to the spectra for similar soils according to the Norm NCh433 plus the DF61 classification.

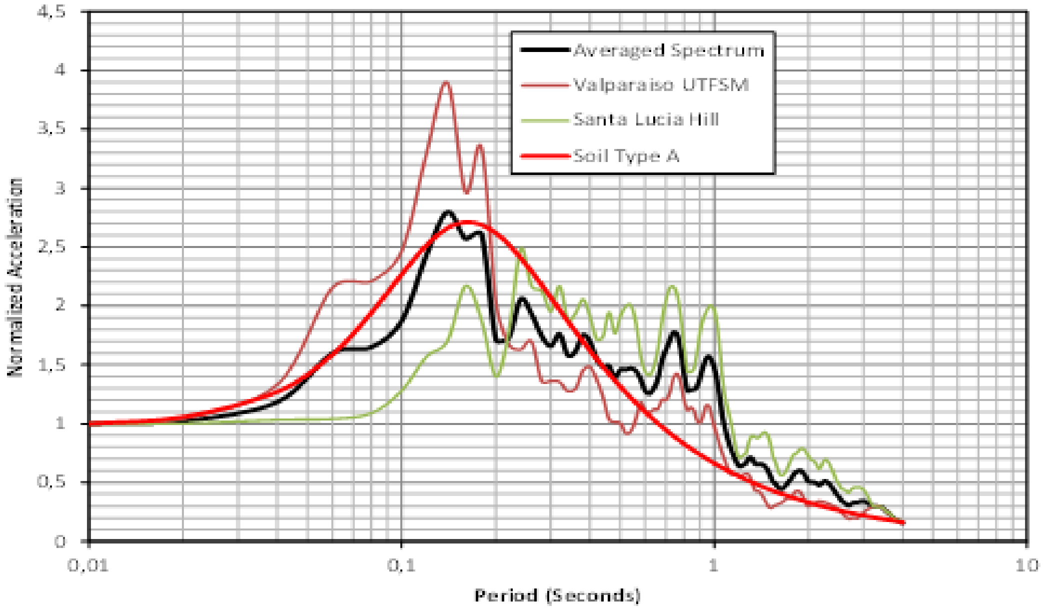

Figure 1. Spectrum in rock

In figure 1, it can be observed that the Santa Lucia Hill does not present a frequency content typical of a rock recorded earthquake, instead, the record obtained at UTFSM for the 2010 earthquake has a content of high frequency waves that is more typical for rock terrains.

In figure 2, that corresponds to soils deposits of sand with fines there is a good variation of the predominant frequency, this is because the depth of the soil deposit is not considered in the parameters that define the spectrum. However, the predominant frequency range is from 0.3 to 1.0 seconds.

In figure 3, the result for soil deposits of graves and sand are shown, in this case there is a good resemblance with soil type C, but again there is not consideration of the depth of the deposit.

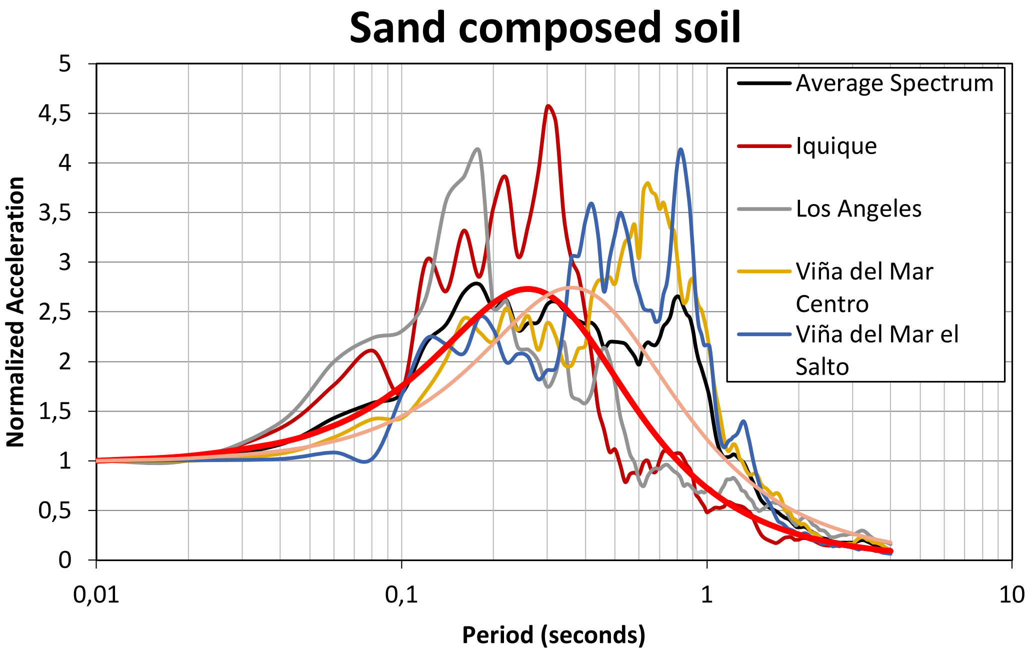

Figure 2. Spectrum computed for sand soil

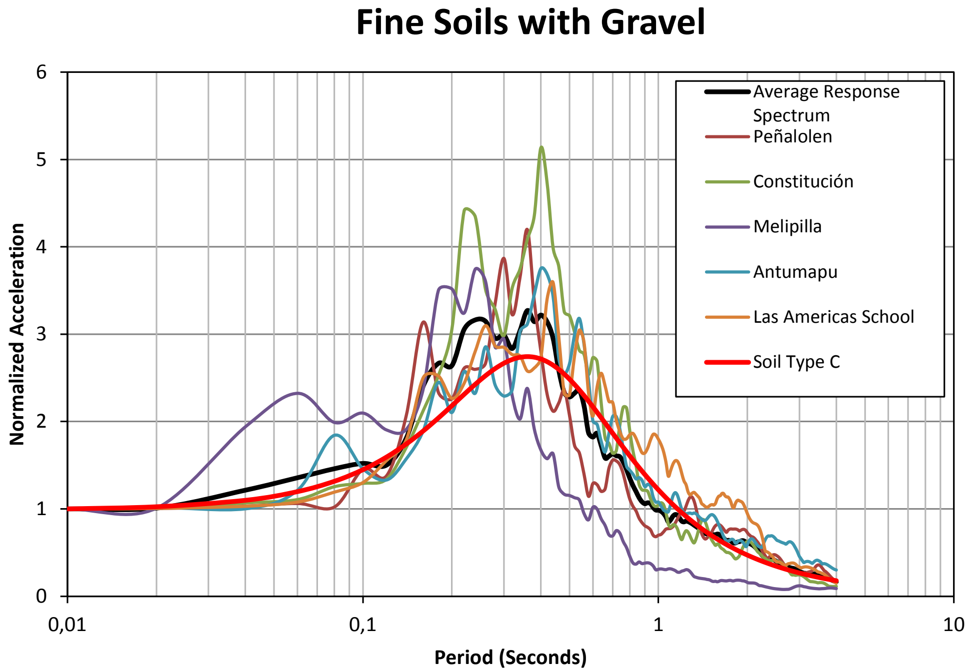

Figure 3. Spectra for different sites with sand and gravel.

**Peñalolén**: For this site, the curves of Idriss for the degradation of the Shear Modulus and the damping were used to model the gravel stratum, and we computed the response for the earthquakes of 1985 and 2010. The result is shown in figure 4. In Peñalolen, the record used was the record obtained at the Peñalolen station.

Parallel to the computation of the spectrum, the natural period of vibration of the site was measured using the Nakamura method. The obtained period was 0.18 seg, this coincides with the predominant period of the response spectrum for Peñalolen. This spectrum is presented in figure 4 along with the spectra of the DF61.

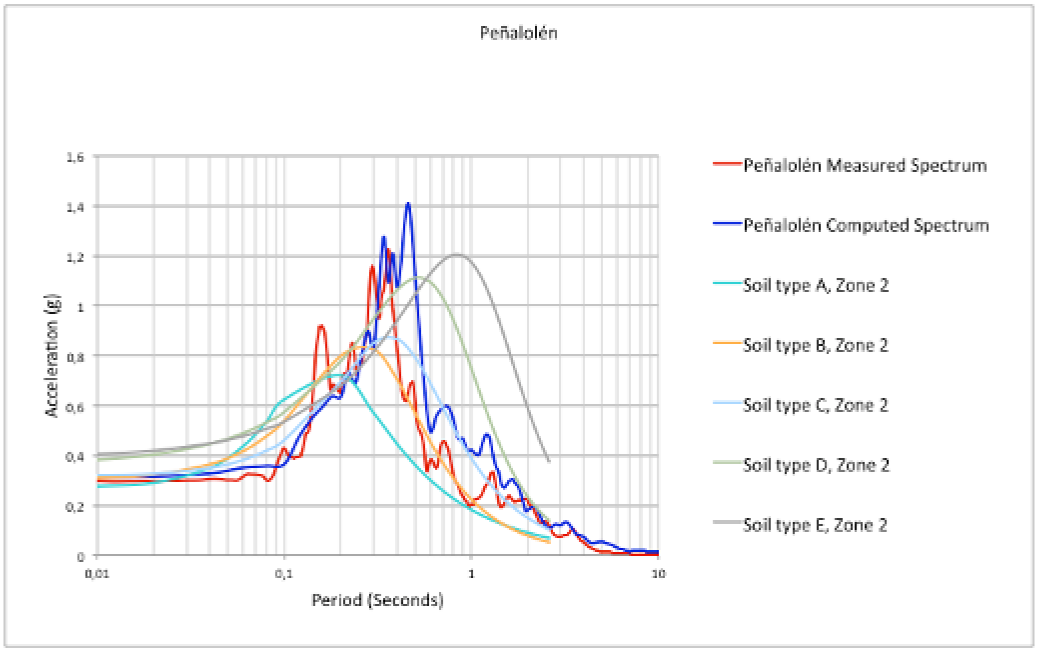

Figure 4. Measured Spectrum at Site and computed using Rapel Record

**Constitution:** For Constitución, the site used is located at the City Hall because there was a good soil study with the stratigraphy and soil properties. This was close to the seismological station. The acceleration record used to compute the response was the record obtained at Rapel (Rock) and was used as an outcrop record that was deconvoluted a used as input at the basal rock for Constitución. The layers that form the soil were modeled using the data reported on Table 1. Results of this model are presented in figure 5. Shows the Spectrum obtained at the site, and the spectrum obtained by computing the response of the site to the Rapel earthquake record of 2010, all of them compared with the spectra of DF61.

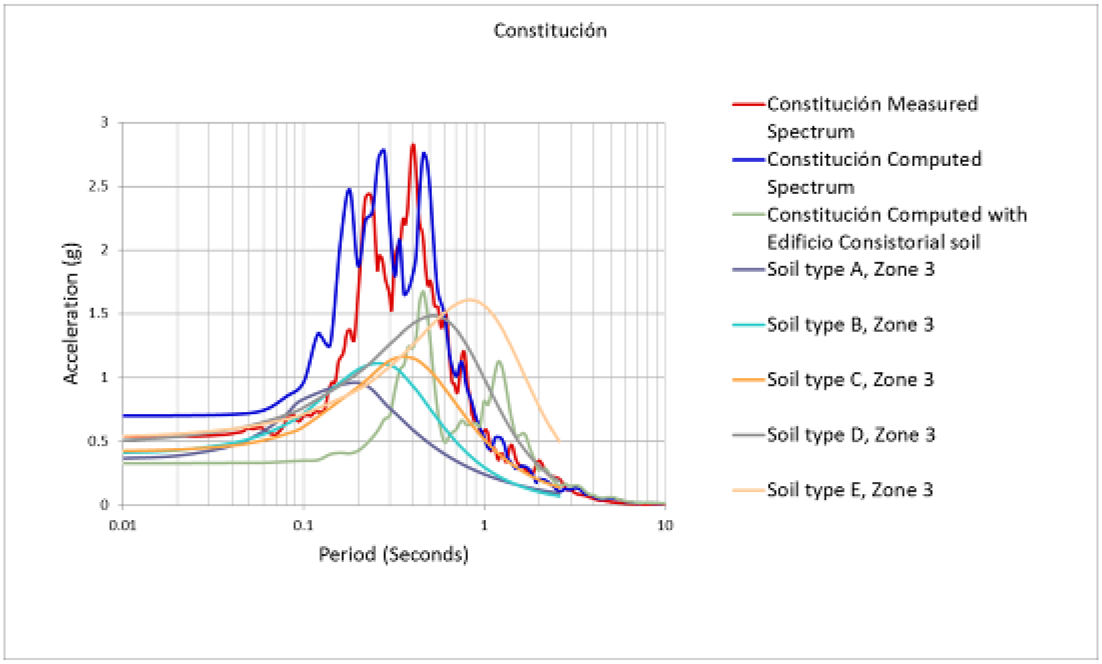

Figure 5. Measured Spectrum at Site and computed using Rapel Record.

**Iquique:** The spectrum of Iquique was computed using the record obtained at station T06A registered in rock. With this record, the soil profile of station T05A was modelled accordingly to the properties listed in table 1 and used to compute the site response. This was computed using the record obtained at T05A directly and the response using the acceleration record obtained at T06A as input at the level of the basal rock. The results are plotted in figure 6 along with the spectra of DF61.

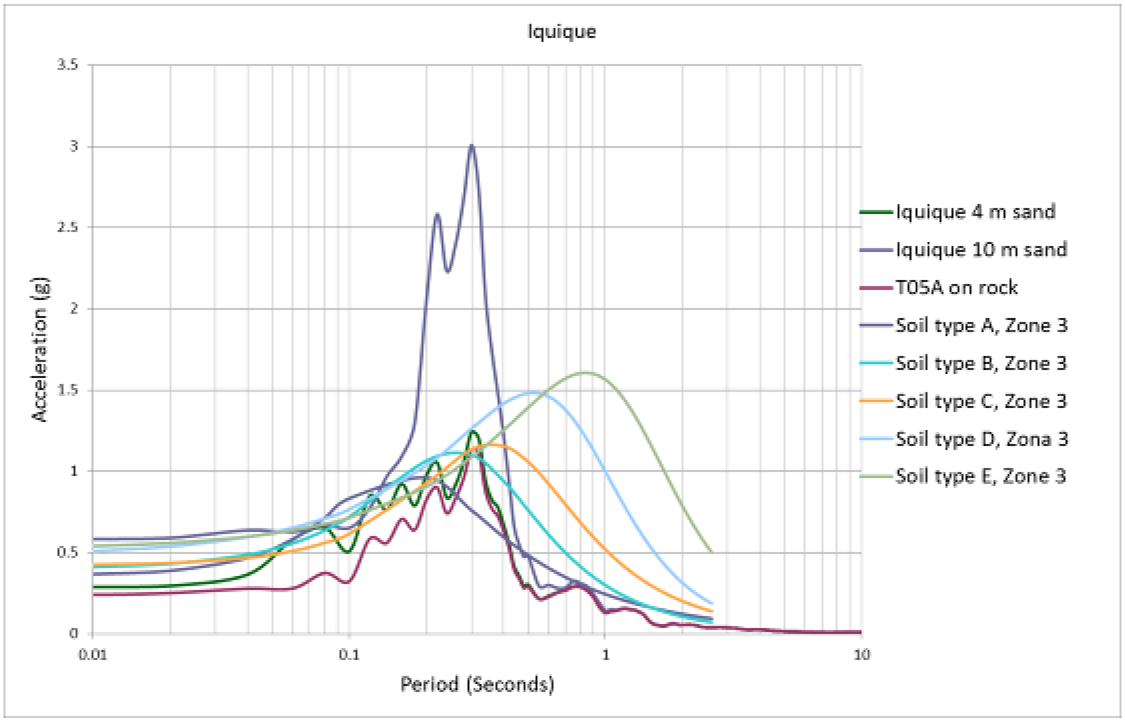

Figure 6. Response at Iquique site.

The results in figure 6 shows that the spectra grows when the depth of the sand deposit grows and it shows a maximum for a sand layer of 10 m then it reduces again. It is possible to see that these spectra has their predominant periods matching the predominant periods of the DF61 spectra for soil A and B.

**Melipilla:** Like Peñalolen and Antumapu, and the station at Colegio Las Americas in Santiago, Melipilla is founded un gravel. The gravel of Maipo and Mapocho river are similar in their composition, and can be modelled using the curves for rock because the high contents of large size granitic clasts that are present in the soil deposit. The response of these sites are presented in figure 7, and compared to the spectra of DF61. Is easy to se that these spectra agree in its predominant period with spectrum A and B of the DF61, Except Antumapu that has a larger period of about 0.4 sec. This can be attributed to the fact that the soil deposit is about 200 m depth. In Melipilla the depth of the gravel deposit is only about 60 m.

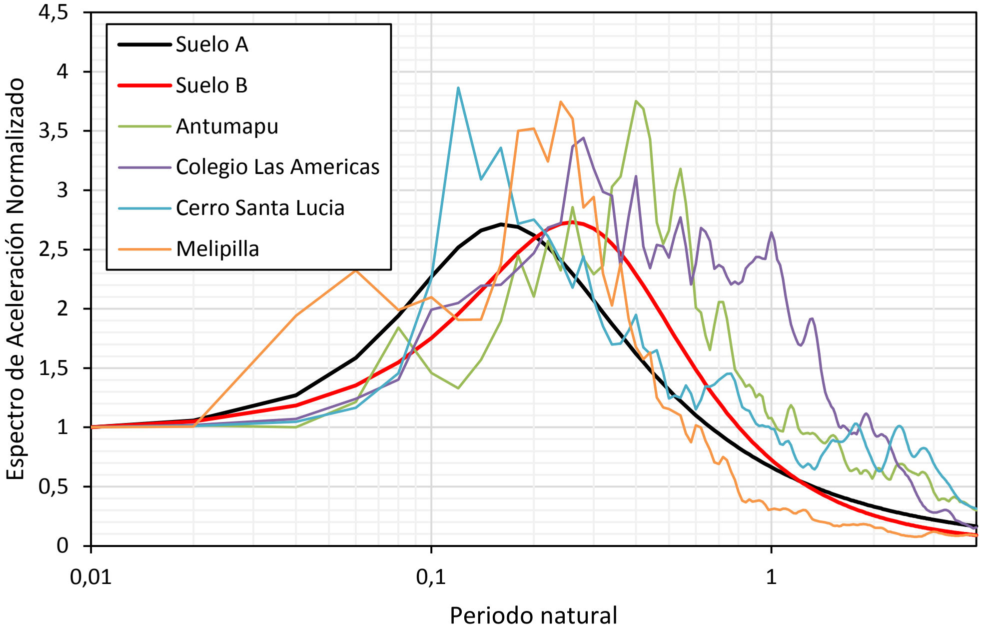

Figure 7. Several spectra in Rock and Gravel

The Melipilla and Antumapu sites were modelled accordingly to the properties listed in Table 1; the response of these sites to the acceleration record obtained at Rapel for 2010 was computed. The result is shown in figure 8, Again, Melipilla shows a predominant period that ranges from 0,15 to 0,3 seconds, and Antumapu is around 0.4 seconds. The amplitude obtained for Antumapu is larger than Melipilla. This is due to the deeper deposit of gravel for Antumapu, 200 m against 60 for Melipilla.

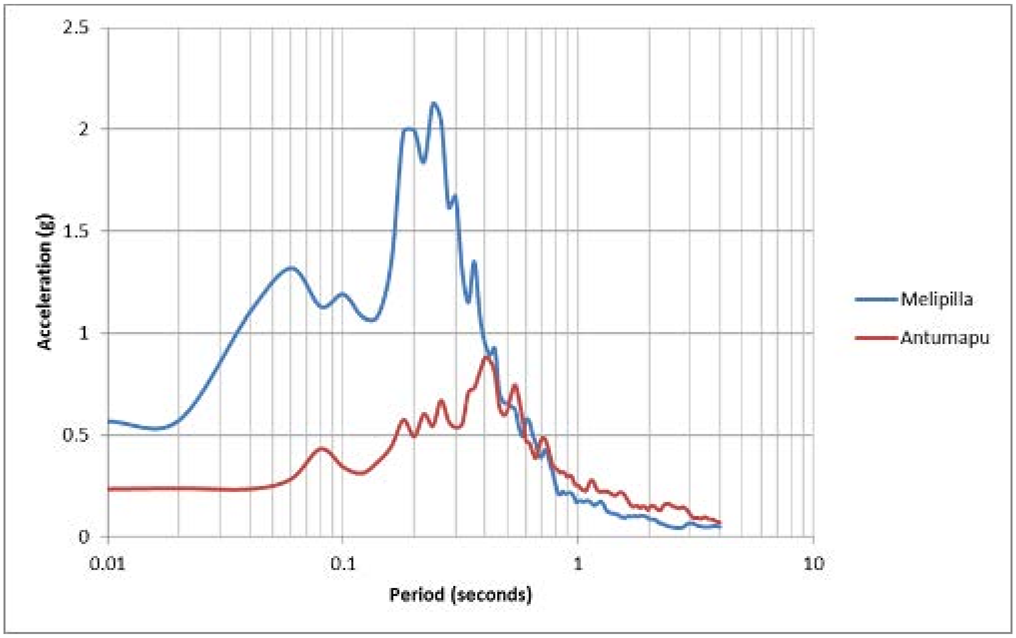

Figure 8. Spectra for Melipilla and Antumapu

A comparison between the response of the sites of Antumapu, Santa Lucia Hill and Las Americas School is shown in figure 9. These are the spectrums obtained at the sites mentioned.

A comparison between the sites of Antumapu, Santa Lucia Hill and Las Americas School is shown in figure 9, for the record obtained in this sites for the 2010 Maule Earthquake. Between Antumapu and Las Americas School the difference is the depth of the soil deposits, 60 m of gravel below las Americas and 200 meters below Antumapu, this gives the difference in both predominant period and amplitude. Regarding Santa Lucia Hill, behavior is like rock but also there are components of the structure of the hill (Topographic Effect).

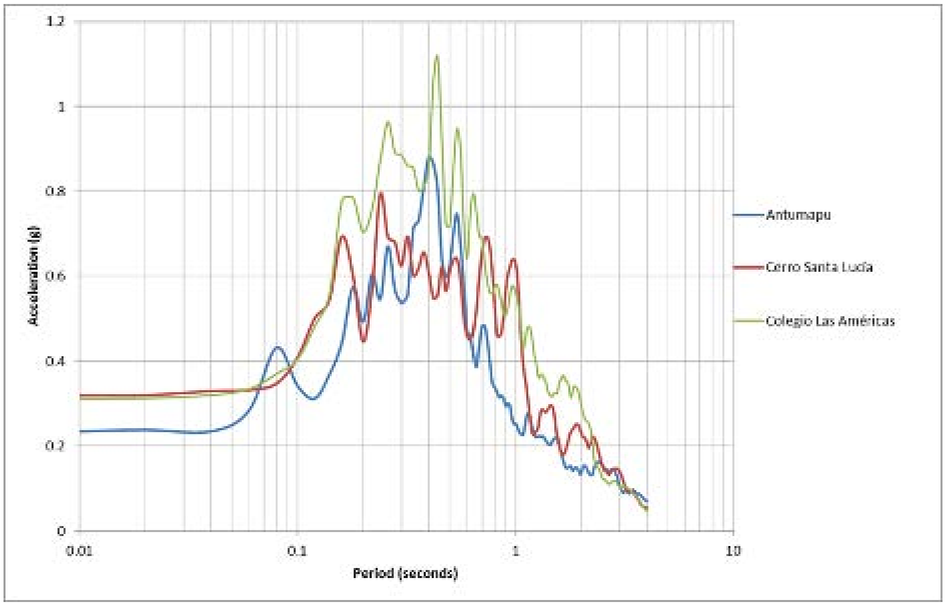

Figure 9. Spectra for Antumapu, Las Americas School and Santa Lucia Hill

## 5. Comparison between Viña del Mar and Valparaiso

One of the places affected by the Maule 2010 earthquake are the cities of Valparaiso and Viña del Mar. In Valparaiso is a station at the Technical University Federico Santa María, In this station the instrument is located at an outcrop of rock, so the registered accelerogram for the Maule earthquake in this station is in rock. Other station in Valparaiso at the Almendral Neighborhood, which is in sand. In Viña del Mar there are two sites: Viña del Mar Centro and Viña del Mar el Salto. Both of them in sand. The spectra for these sites are shown in figure 10. Again the same conclusion can be drown, this are: the type of material and the depth of the soil deposit control the frequency content and the amplitude of the spectra.

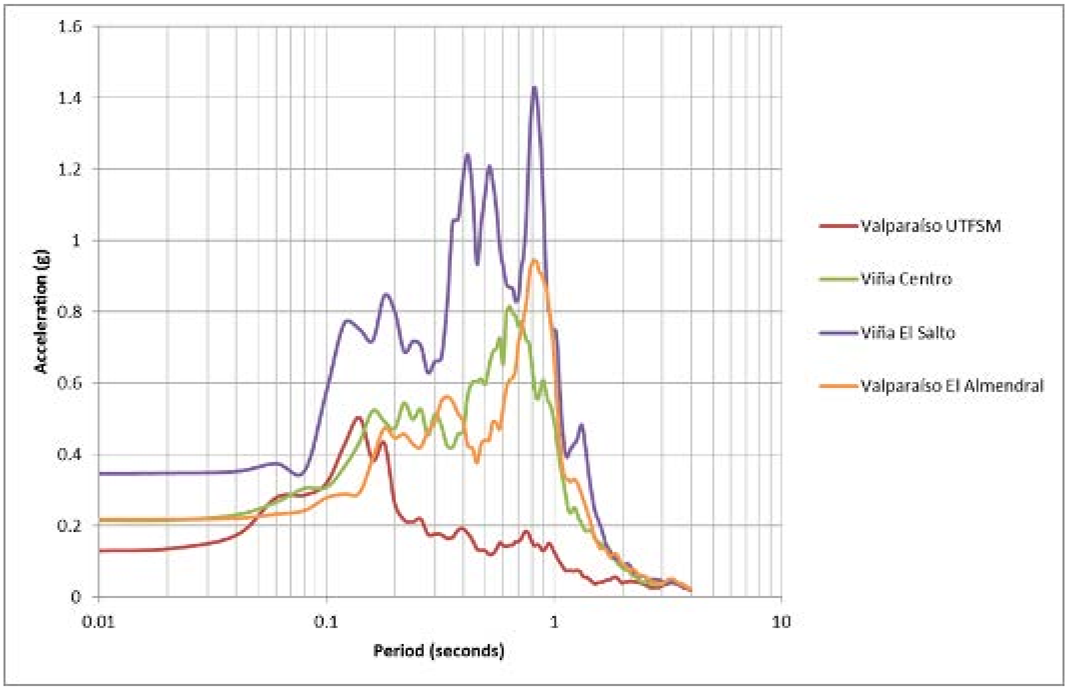

Figure 10. Spectra at Viña del Mar and Valparaiso

## 6. Conclusions

The characteristics of the design acceleration spectrum not only should include the parameters of the type of soil but also the stratigraphy of the different layers and the depth up to the basal rock. For this reason is better to compute the site response rather than use the spectra proposed in the norm. Other parameters that show influence in the behavior of the site is the rigidity of the soil, as in the case of UTFSM and Almendral, sites that are 2.4 km apart, and the response is quite different, the stiffer rock at UTFSM produces a lower spectrum and with a smaller predominant period of vibration.

The degradation of the Shear Modulus and the damping with the deformation is important when computing the site response. The Chilean gravels need to have a degradation curve as well as clays, because when using the curves from other places like the Idriss curves for graves for the sites of Melipilla, the results do not agree with the observed behavior. This make important to consider the plasticity index and the over consolidation ratio because the degradation curves depends on these parameters. The influence of the OCR and the PI can be seen in the response of Viña del Mar Centro and Viña del mar el Salto because the difference are these two parameters, However, more research need to be done in this case.

If the earthquake is long in time duration earthquake that it has a zone that can be considered stationary in amplitude and frequency content, then it is possible that the response shows the influence of the predominant frequency of the excitation.

In places where there are layers of fine soil like clay and silt, an amplification can be expected as it is shown in the comparison of Las Americas School and Antumapu.

In reality to use the SPT or the Vs30 as parameters to define the parameters of the spectrum are not enough, and the best is to model the soil with the degradation curves and all the other parameters which can tell much more than the velocity or the STP.

## 7. Aknowlegements

The earthquake records from the 2010 earthquake are from the RENADIC network of the Department of Civil Engineering at the University of Chile. The Records of the 2014 Iquique Earthquake were published by the National Seismological Center of the University of Chile.

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