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EFFECTS OF LONG DISTANCE EARTHQUAKES ON TALL BUILDINGS: SEISMIC RISK IN BUENOS AIRES

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Abstract

The Chilean 8.3 Magnitude Earthquake of September 16 2015 produced panic of inhabitants of tall buildings in Buenos Aires, 1300 km away. The main event and its aftershocks were registered by a new seismometer of Universidad de Buenos Aires. Using these data, the response spectra, the frequency contents and significant duration of the ground motions and the Inter Story Drift index and RMS acceleration on Buenos Aires tall buildings were computed. Damping and period of these tall buildings had been measured during a previous study. The results show that similar spectra are obtained for the main shock and the aftershocks showing that soil period is one of the main parameters to explain the large amplification of pseudo acceleration computed for the tall buildings. This soil period in Buenos Aires was computed showing similar values that the measured tall buildings natural period. The frequency content of ground motion on rock, 300 m below the surface, is obtained from deconvolution of the acceleration measured on surface. Finally, from the Chilean seismicity and the new attenuation law obtained for distant earthquakes, the return period of human discomfort and non-structural damage is obtained for current practice in Buenos Aires tall buildings.

Keywords: Long Distance Earthquakes, Effects of Earthquakes on Tall Buildings, Seismic Risk in Buenos Aires

1. Introduction

Buenos Aires, the capital of Argentina and second biggest city of South America with 14,5 million inhabitants, is located in the mid-east region of the country, on the western shore of the Rio de la Plata river. The city lies in the center of the Pampas plain, over 1200 km away from the high seismicity area defined by the interface between the South American and Nazca plate. The recent seismic history of this area of South America, Chile and Argentina, can be seen in Ref [1].

On September 16, 2015 at 19:54:32 (UTC-03:00) a Mw 8.3 earthquake was recorded. The United States Geological Survey (USGS) reported the epicenter coordinates as 31.573°S, 71.674°W, about 230 km north-northwest of Santiago de Chile, Chile and 1280 km from Buenos Aires. Over the century prior to this earthquake, the region within 700 km of this event hosted 15 other Mw 7 and plus earthquakes and the largest earthquake on record, the 1960 Mw 9.5 earthquake in southern Chile.

The 2015 Mw 8.3 event was felt strongly, as in previous opportunities, in several Argentine provinces. In Buenos Aires, the higher buildings were self-evacuated due to the movement of hanging objects like lamps, curtains, plants and bookshelves. The director of the emergency medical services (SAME, in its Spanish acronym) reported that the earthquake was felt from the 8th floor and that there were no structural damages. The only casualty reported was a man who had a slight physical disability that died after falling down the stairs during the evacuation of a building after the earthquake. While in seismic zones cities the inhabitants are used to this phenomenon, in Buenos Aires this caused alarm and panic to building dwellers.

The Argentine codes for the design of structures in Buenos Aires do not take into account seismic loads except for facilities such that its failure could have catastrophic effects on large segments of the population. But as could be seen in terms of the repercussion of recent earthquakes, long period structures founded upon a significant depth of soil responded to distant earthquakes with a perceptible movement. In other parts of the world there have been several cases that reflect this [2], and the most significant is the Mexico earthquake of September 19, 1985. Major damage occurred in Mexico City due to large local soil amplification effects 350 km away the epicenter [3]. The March 11, 2011 Mw 9.0 Tohoku earthquake and its aftershocks caused motions on tall buildings at 770km [4] and 388km [5] from the epicenter of the mainshock. Further analysis was performed on instrumented buildings in Tokyo [6] to gain insight of closer large-magnitude earthquakes. Note that this work extends some conclusions of the above references to tall buildings at 1300 km away the epicenter.

2. Buenos Aires Geology and Soils

In Buenos Aires city, the crystalline basement with presence of gneiss (a foliated metamorphic rock) is found at a depth between 280 to 400 m. As a consequence of this differential faulting, the metamorphic basement can be observed on the surface of Uruguay, and at more than 20 m above sea level, on the Martín García Island in the Rio de la Plata river. The approximately 300 m of soil above the rock is composed mainly by 5 different formations (Fig. 2): “Post-Pampeano” (<10 m thick), “Pampeano” (25 to 45 m thick), “Puelche” (12 to 20 m thick), “Parana” (30 to 45 m thick) and “Olivos” (200 m thick) [7]. A brief description of each layer follows [8], where Vs is the average shear wave velocity of the stratum.

“Pampeano o Tosca” (Vs ≈220 m/s): In most of the urban area, the upper level of Buenos Aires presents rigid deposits of silty and clayey soils, strongly pre-consolidated by desiccation with layers of lenses of cemented soils by calcareous impregnation. The total thickness of these sedimentary deposits is about 25 to 45 m.

“Post-Pampeano” (Vs ≈115 m/s): Above the “Pampeano”, in a narrow strip (1000 to 2000 m) along the cost of Rio de la Plata and Riachuelo (Fig. 2), the upper level of the Pampeano is replaced by a stratum of variable depth (less than 10 m) of very soft fluvial deposits of clays and plastic silty clayey soils.

“Puelche” (Vs ≈347 m/s): Fine and dense sands are found underlying the Pampeano formation,. This deposit is mainly of fluvial origin, and reaches a thickness of 12 to 20 m. Their porosity is around 20% - 30% , almost totally lacking cementation, and their voids are filled with water. It is the largest aquifer not only in the area around Buenos Aires but in the Pampa region as a whole.

“Parana” (Vs ≈ 351 m/s): Below these dense sands there is a layer of plastic clayey silt or silty clay, approximately 30 to 45 m thick. These greenish clay or blueish clays of marine origin, are very stiff and normally consolidated under the loads imposed by the Pampeano profile.

“Olivos” (Vs ≈570 m/s): Below the Parana formation and above the fractured basement exists a layer of about 200 m of continental origin. The upper 100 m is mainly clay meanwhile in the lower 100 m sandy soils are predominant.

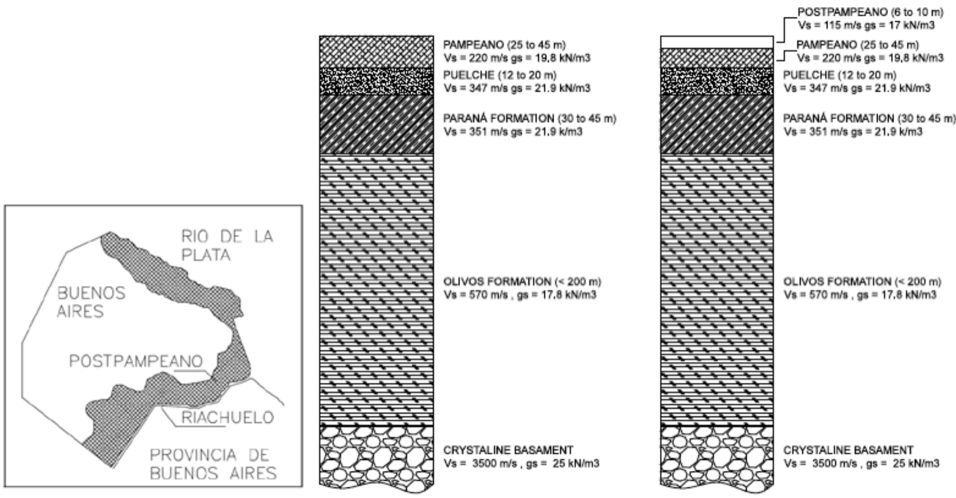

Fig. 1 Soils of Buenos Aires City. The crystalline basement is around 300 m below the surface. The left profile corresponds to the center of the city where the UBA (Universidad de Buenos Aires) seismometer is located. The right profile corresponds to the dashed zone in the left figure, near de Rio de la Plata and Riachuelo margins.

3. Recorded Ground Motions in Buenos Aires due to Chilean Earthquakes

Table 1 shows the 8.3 Magnitude Chilean earthquake of September 16, 2015 and 13 replicas equal or larger than 6.0 Magnitude recorded with the seismometer of Facultad de Ingenieria of the Universidad de Buenos Aires located close to the geometrical center of the city. The table shows the magnitude (M_w), the depth, the distance from the epicenter to the center of Buenos Aires (R), the peak ground velocity (PGV) and peak ground acceleration (PGA) recorded in Buenos Aires. Also are shown the significant duration (T_d), defined as the time interval between 5 and 95% of the integral of the square of the ground acceleration [9] and the mean square period of the record (T_g) defined as [10]

$$T_g = 2\pi \frac{\sum_{0.25Hz}^{20Hz} \mathcal{F}_{\ddot{u}i}^2 \frac{1}{\omega_i}}{\sum_{0.25Hz}^{20Hz} \mathcal{F}_{\ddot{u}i}^2} \quad (1)$$

where $\mathcal{F}_{\ddot{u}i}$ is the Discrete Fast Fourier transform of the accelerogram at the frequency ω_i. Some T_d values could not be computed because the records were truncated by the seismometer.

Table 1 - Recorded Ground Motion in Buenos Aires

Day	Time	Earthquake	M_w	Depth	R	PGV	PGA	T_d	RMS	T_g
				km	km	cm/s	cm/s2	s	cm/s2	s
2015-09-16	22:54:32	48km W of Illapel, Chile	8.3	23.3	1282	0.48690	1.10100	261.6	0.2453000	2.25
2015-11-07	07:31:43	39km SW of Ovalle, Chile	6.8	47.8	1289	0.05209	0.15340	301.8	0.0308360	1.95
2015-09-17	04:10:27	61km WNW of Illapel, Chile	6.7	40.7	1295	0.05657	0.12830	226.4	0.0287670	1.99
2015-09-26	02:51:18	26km SSW of Ovalle, Chile	6.3	40.2	1280	0.04062	0.12460	229.5	0.0337330	2.20
2015-09-21	17:40:00	22km WSW of Illapel, Chile	6.6	13.0	1250	0.03748	0.09565	316.8	0.0221920	2.30
2015-11-11	01:54:38	81km NW of Coquimbo, Chile	6.9	32.9	1401	0.03472	0.08107		0.0308360	2.38
2016-02-10	00:33:05	37km W of Ovalle, Chile	6.3	36.5	1314	0.02761	0.08085		0.0222920	1.99
2015-09-17	03:55:15	54km WNW of Illapel, Chile	6.5	45.0	1288	0.02258	0.06309	271.0	0.0122690	2.12
2015-09-21	05:39:34	55km W of Illapel, Chile	6.1	40.7	1288	0.01815	0.05786	263.2	0.0104630	2.08
2015-09-17	01:41:05	70km SW of Ovalle, Chile	6.4	45.0	1297	0.02299	0.05582		0.0116540	2.29
2015-09-18	09:10:44	93km NW of Valparaiso, Chile	6.2	33.0	1306	0.01605	0.03661	334.2	0.0064692	2.43
2016-02-22	06:37:03	105km WSW of Coquimbo, Chile	6.0	12.0	1383	0.01097	0.03464	200.2	0.0073619	2.26
2015-09-19	12:52:20	79km W of La Ligua, Chile	6.2	26.9	1292	0.01370	0.02798	256.8	0.0071569	2.21
2015-11-27	21:00:22	64km N of Taltal, Chile	6.2	34.0	1601	0.00384	0.00901		0.0016572	2.10

3.1 Significant Duration and Mean Square Period

Fig. 3 a) shows the significant duration of the recorded ground motions as a function of the magnitude. It can be noticed that their significant durations, in contrast to that of short distance earthquakes, is not dependent on the magnitude and is much larger (200 to 300 s). This has two important consequences: a) buildings in resonance with the main period of the soil motion significantly amplify the acceleration at the base and b) the inhabitants of those buildings are affected by high accelerations during several minutes increasing the discomfort and panic.

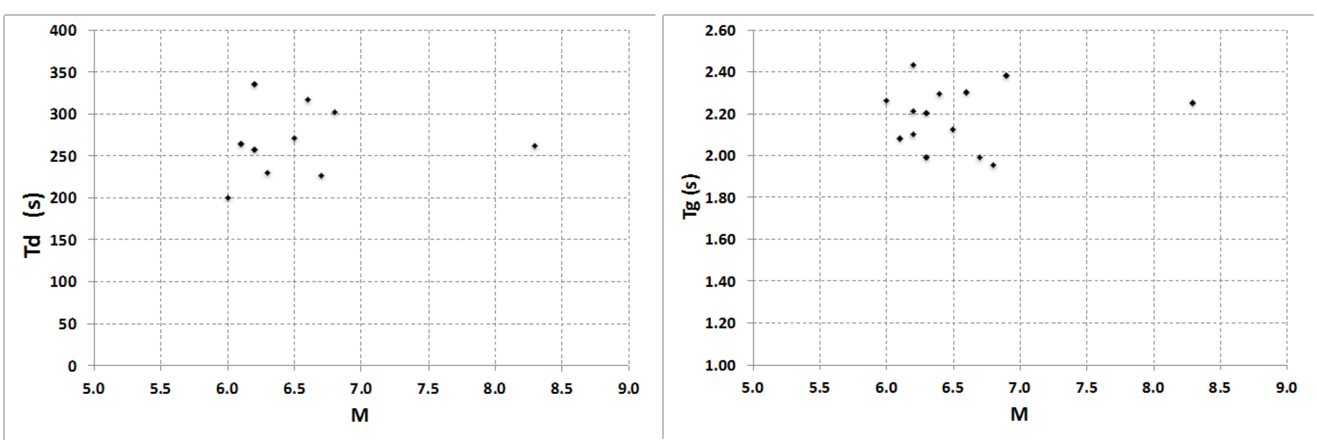

Fig. 2 a) Significant duration of recorded GMs (left) and b) Mean Square Period of recorded GMs (right)

Fig. 3 b) shows the Mean Square period of the recorded ground motions as a function of the magnitude. A mean value of 2.2 s, independent of the magnitude, is obtained. This result indicates that for long distance earthquakes the effect of the magnitude on the frequency content tends to be hidden by the influence of the soil period above the rock as it will be shown in the following section.

3.3 Response Spectra

The pseudo-acceleration response spectra of the 14 recorded ground motions normalized by the PGA are shown in Fig. 4 for 1% damping (the damping value obtained for Buenos Aires tall buildings using ambient vibrations). It is clearly noted the similarity among the response spectra of all ground motions with two resonance period around 2.5 s and 1 s. As it will be shown, these are the first and second natural periods of the 300 m of soil above the rock basement. Note also the large amplification of the PGA (about 10 times for the first period of resonance), typical of harmonic type of ground motion. Fig. 4 b) shows the mean and mean plus one standard deviation of the pseudo-acceleration response spectra of the 14 recorded ground motions normalized by the PGA.

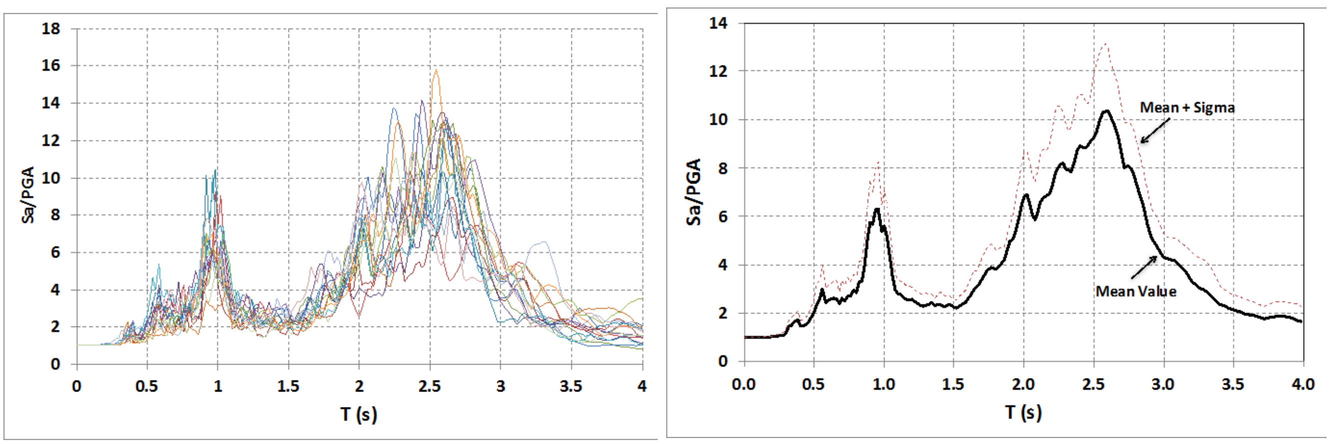

Fig. 3 a) Pseudo-acceleration response spectra normalized by PGA of 14 recorded ground motions in Buenos Aires (left) and b) Mean and Mean + Sigma of them (right)

3.4 Peak Ground Acceleration – Magnitude relationship

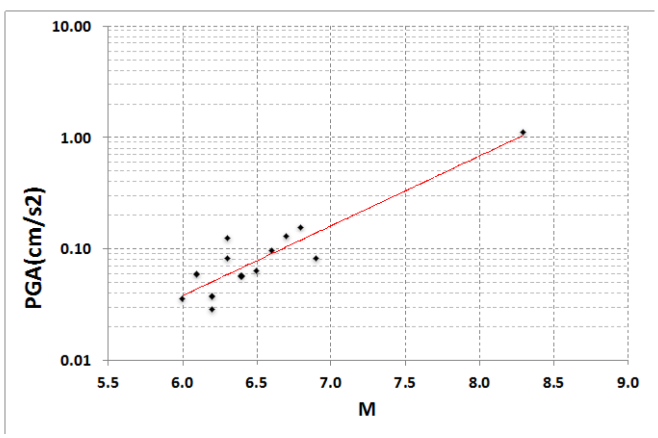

Fig. 4 PGA – Magnitude for the recorded ground motion in Buenos Aires

Fig. 5 shows that the exponential model is a very good representation of the relationship between PGA and Magnitude for the recorded ground motion in Buenos Aires. Therefore, using regression analysis the following equation was obtained with a $\sigma_{ln} = 0.34$ (note that this equation is valid for a very narrow distance range from R= 1250 to 1400 km and for the Buenos Aires soil),

$$\ln\left(\frac{PGA}{cm/s2}\right) = 24.537 + 1.408\, M_w - 5.052\, ln\left(\frac{R}{km}\right) \qquad (2)$$

3.5 Fourier Spectra on soil

Fig. 6 shows the acceleration history of the EQGM of September 16, 2015 recorded on soil in the center of Buenos Aires. Note the PGA of 1 cm/s2 and the long duration of the significant motion (260 s) recorded. Fig. 7

shows the Discrete Fast Fourier Transform of this record. The frequency content predominantly around T=2.5 s (f=0.4 Hz) and T=1 s, also shown in Fig. 4, are clearly recognized.

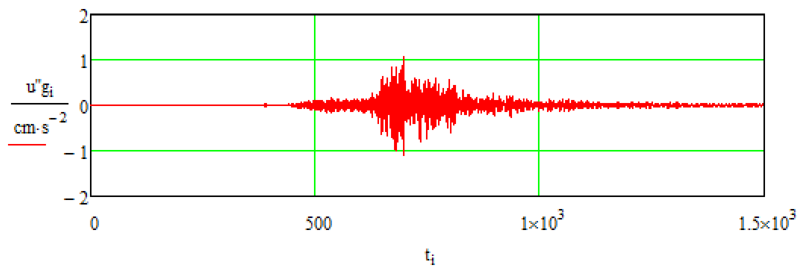

Fig. 5 Acceleration history of the EQGM of September 16, 2015 recorded in Buenos Aires

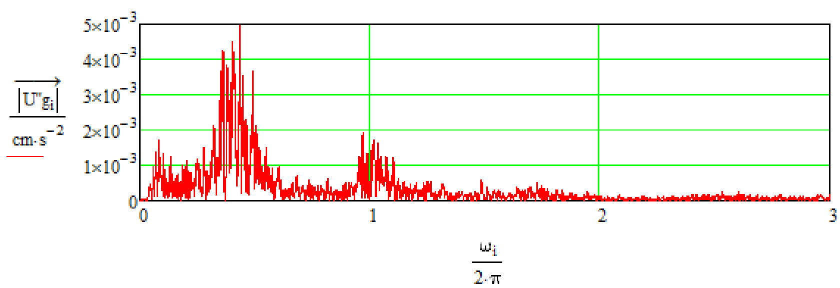

Fig. 6 Discrete Fourier Transform of the EQGM of September 16, 2015 recorded in Buenos Aires on soil

3.6 Fourier Spectra on rock by deconvolution

Considering the layer of soils shown in Fig. 2 on elastic rock and a damping factor $\xi = 0.03$ for all, soil layers and rock, the transfer function between the rock and the soil surface in Buenos Aires shown in Fig. 8 is obtained. The natural frequencies of the soil are f_1=0.4 Hz (T_1=2.5 s) and f_2= 1 Hz (T_2= 1 s) for the first and second period respectively. Using the transfer function of Fig. 8, the Fourier Transform of the EQGM on the rock basement is computed by deconvolution [11] (Fig. 9).

It is noted that on the rock basement, 1300 km away of the epicenter, the frequency content is larger in the range from 0 to 0.6 Hz. Therefore, only soils with their first mode in this range (i.e., with hundreds of meters of soils above the rock or very soft soils) could amplify the rock motion to a level that can be high enough to alarm the inhabitants. This is the situation in Buenos Aires where, beside that, an important inventory of tall buildings with natural period in this range exists.

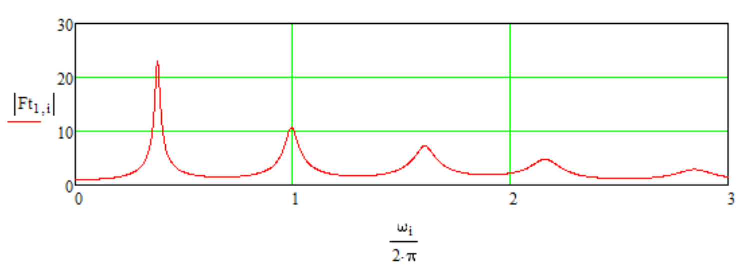

Fig. 7 Transfer function between the rock and the soil surface for the layers of soils in the center of Buenos Aires

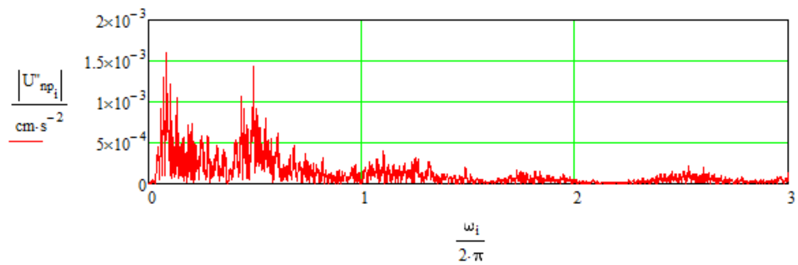

Fig. 8 Fourier Transform of the EQGM of September 16, 2015 in Buenos Aires on the rock basement obtained by deconvolution

4. Effects of Chilean Seismicity on Return Periods of Buenos Aires Ground Motions

As a result of the oblique subduction of the Nazca plate below the South America plate at a high convergence rate of about 7 cm/year, the main earthquakes in Chile that produce movement in Buenos Aires are associated with the large subduction (thrust) earthquakes, along the coupled zone of the interface between the subducting Nazca plate and the South American plate. Using the geographical category defined by Susa [12], zones 5, 6 and 7 (Fig. 10) are the most significant due to their epicentral distance to Buenos Aires (about 1300 km for the three zones). From the evaluation of the seismic recurrence for each zone obtained by Nuñez et al [13], the number of EQs by year with magnitude $M_w \geq m$ is obtained (Fig. 10).

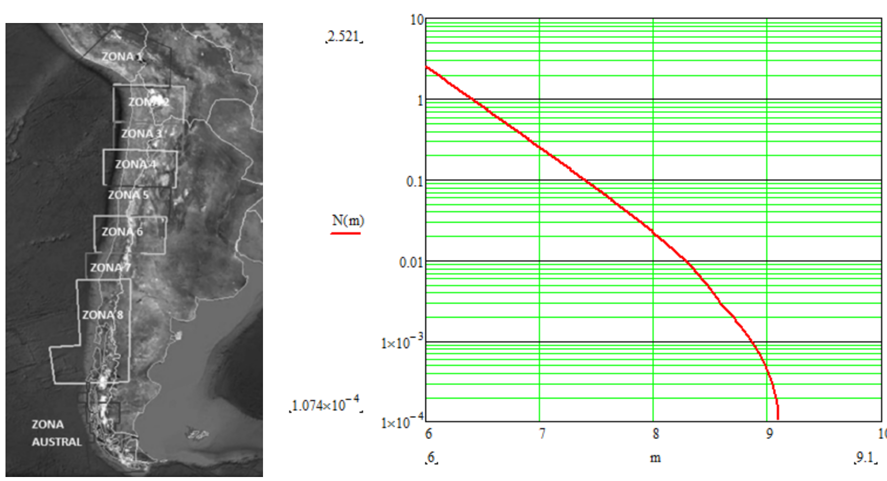

Fig. 9 Chilean seismic zones as defined by Susa [12] (left) and Number of EQs by year with magnitude $\boldsymbol{M_w} \geq$ m for zones 5, 6 and 7 (right)

Using the attenuation law of Eq. (2) and the results show in Fig. 10 right, the annual rate of EQs in Chile that produce GMs with $PGA \geq$ pga (cm/s2) in Buenos Aires is obtained (Fig. 11). Note that according to these results, a PGA≥1 cm/s^2 (as recorded on September 16, 2015 in Buenos Aires) has a return period of about 100 years (only for Chilean Earthquakes).

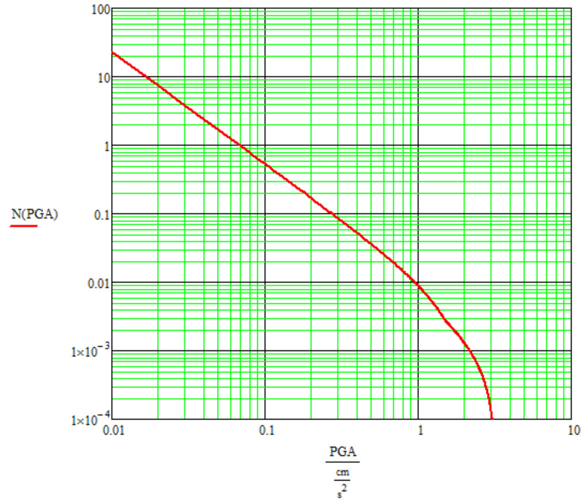

Fig. 10 Number of EQs by year in Chile that produce GMs with $\boldsymbol{PGA} \geq$ pga in Buenos Aires

5. Period and Damping of Tall Buildings in Buenos Aires

From a systematic survey to estimate the natural period and damping of tall buildings in Buenos Aires a relationship $T = 0.0187\,H/m - 0.0544$ was obtained using ambient vibrations [14] (Fig. 12). For example, for a 150 m height (50 story building) a natural period about 2.7 s was found. In the same study a damping about 1% was obtained, particularly for taller buildings (Fig. 12). Although this value could increase a little for a PGA about 1 cm/s^2 (100 years PGA return period), 1% damping should be used to estimate the tall building response in Buenos Aires until more data becomes available.

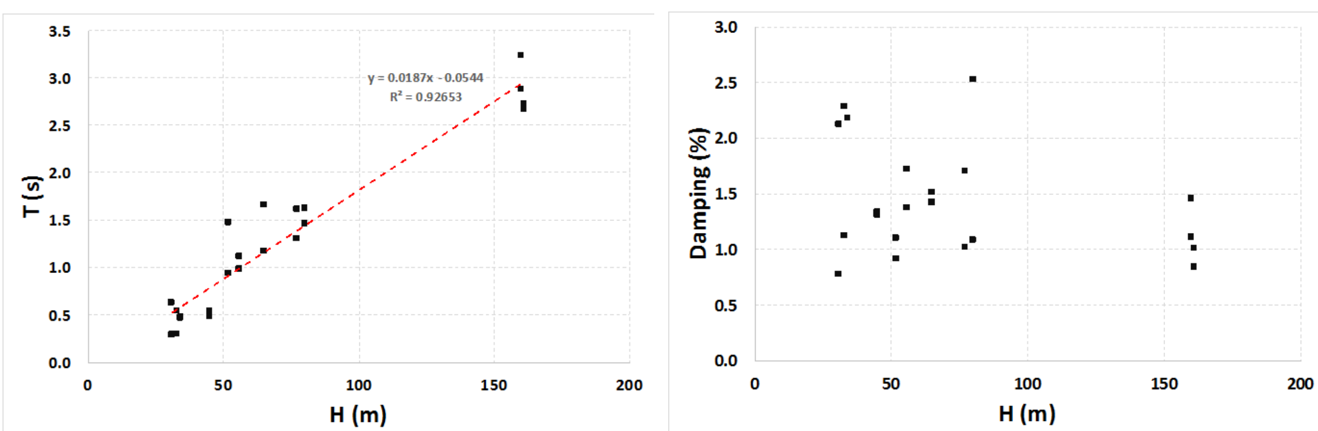

Fig. 11 Period and damping of Tall Buildings in Buenos Aires [14]

6. Return Period of Accelerations in Tall Buildings in Buenos Aires

Using PGAs with return periods of 1, 5, 20 and 50 years obtained from Fig. 11, the acceleration in the top floor of buildings with shear beam behavior (mean + sigma) was computed (Fig. 13). Also the evaluation curve for acceptable horizontal motions for residences specified for ISO 10137 in Annex D “Guidance for human response to wind-induced motions in buildings” is shown in the figure. The Guide specifies peak accelerations at the first natural frequencies in the principal structural directions of the building (normally, along-wind and cross- wind) and in torsion. This is derived from examinations of data for many actual buildings of general use.

As shown in the figure, the acceptable limit for wind is exceeded with a return period of about of 20 years for buildings with first mode period about 1 s and 2.4 s to 2.7 s. The worst situation in terms of inhabitant's comfort is for buildings between 100 to 160 m height (33 to 53 story buildings). It is also shown in the figure that for these buildings the average vibration perception threshold [15] has a return period of about 5 years.

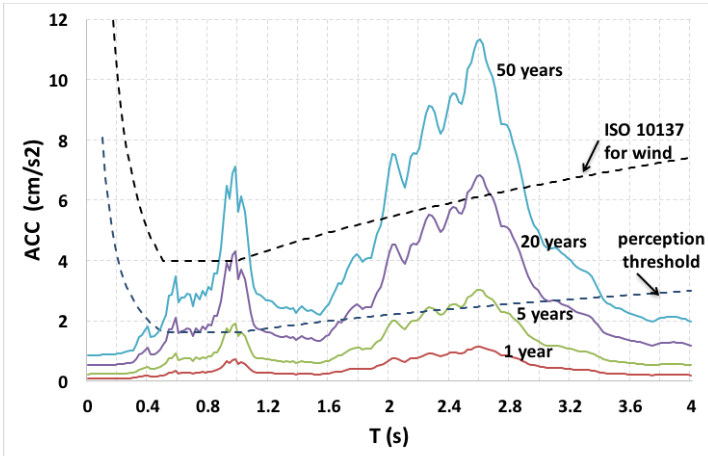

Fig. 12 Acceleration in the top floor of buildings with shear beam behavior in Buenos Aires

7. Return Period of Non-structural Damage in Tall Buildings in Buenos Aires

Damage to brick infills partitions are particularly sensitive to Interstory Drift Index (IDI) as shown in Fig. 14. Certain level of damage is achieved for IDIs as low as 0.0006 for certain type of brick infills [16].

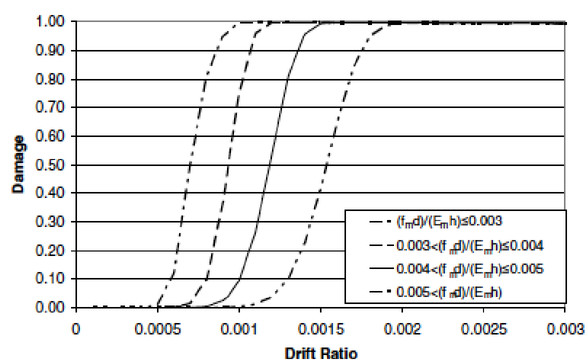

Fig. 13 Damage functions for brick infills [16]

From Fig. 11, a PGA= 1.65 cm/s^2 is obtained in Buenos Aires for a 475 years return period. Using this PGA, the response spectra of Fig. 4 and the relationship between T and H of Fig. 12, the IDI for the first floor of buildings with shear beam behavior is obtained. As shown in the figure, some level of nonstructural damage is possible for buildings about 130 to 150 m height (around 40 to 50 story buildings, T= 2.4 to 2.8 s), particularly for weak brick infills if any previous distortion is present as usual in tall building due to differential creep in columns.

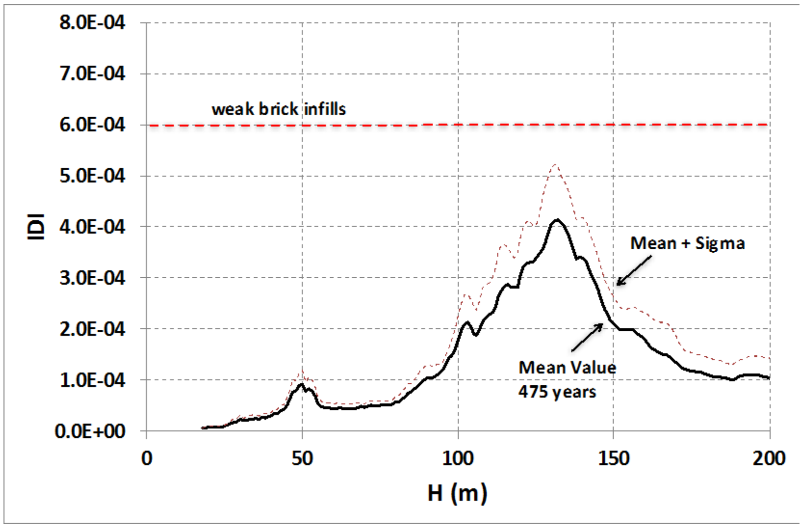

Fig. 14 IDI in the first floor of buildings with shear beam behavior for 475 years return period

8. Conclusions

From the analysis of the topics discussed in this paper, the following conclusions regarding the effects of long distance earthquakes on tall buildings (1300 km from the epicenter to Buenos Aires in this case) are obtained:

- The significant duration of EQGMs, in contrast to that of short distance earthquakes, is not dependent on the magnitude and is much larger (200 to 300 s). This has two important consequences: a) buildings in resonance with the main period of the soil motion significantly amplify the acceleration at the base and b) the inhabitants of those buildings are affected by high accelerations during several minutes increasing the discomfort and panic.
- For long distance earthquakes, the effect of the magnitude on the frequency content tends to be hidden by the influence of the soil period above the rock.
- The shape of the response spectra obtained for the main shock and for all the replicas (from magnitude 8.3 to 6.0) are similar with two resonance periods around 2.5 s and 1 s. These periods are approximately the first and second natural periods of the 300 m of soil above the rock basement in Buenos Aires. The pseudo-acceleration response spectra shows also a large amplification of the PGA (about 10 times for the first period of resonance), typical of harmonic type of ground motion.
- The frequency content obtained by deconvolution 1300 km away of the epicenter on the rock basement is much larger in the range from 0 to 0.6 Hz. Therefore, only soils with first mode in this range (i.e., with hundreds of meters of soils above the rock or very soft soils) could amplify the rock motion to a level that can be high enough to alarm the inhabitants. This is the situation in Buenos Aires, where an important inventory of tall buildings with natural period in this range exists.
- The acceptable limit for wind is exceeded with a return period of about of 20 years for buildings with first mode period about 1 s and 2.4 s to 2.7 s. The worst situation in terms of inhabitant's comfort is for buildings between 100 to 160 m height (33 to 53 story buildings). For these buildings, the average vibration perception threshold has a return period of about 5 years.
- Some level of nonstructural damage is possible for buildings about 130 to 150 m height (around 40 to 50 story buildings, T= 2.4 to 2.8 s), particularly for weak brick infills with a return period of 475 years.

9. References

[1] USGS, http://earthquake.usgs.gov/earthquakes/eventpage/us20003k7a#general

[2] Pan TC (1995): When The Doorbell Rings - A Case of Building Response To A Long Distance Earthquake. *Earthquake Engineering & Structural Dynamics*, Vol. 24, 1343-1353

[3] Celebi M, Prince J, Dietel C, Onate M and Chavez G (1987) The Culprit in Mexico City—Amplification of Motions. *Earthquake Spectra*: May 1987, Vol. 3, No. 2, pp. 315-328.

[4] Çelebi, M., Okawa, I., Kashima, T., Koyama, S., & Iiba, M. (2014). Response of a tall building far from the epicenter of the 11 March 2011 M 9.0 Great East Japan earthquake and aftershocks. *The Structural Design of Tall and Special Buildings*, 23(6), 427-441.

[5] Çelebi, M., Hisada, Y., Omrani, R., Ghahari, S. F., & Taciroglu, E. (2016). Responses of two tall buildings in Tokyo, Japan, before, during, and after the M9. 0 Tohoku Earthquake of 11 March 2011. *Earthquake Spectra*, 32(1), 463-495.

[6] Çelebi, M., Kashima, T., Ghahari, S. F., Abazarsa, F., & Taciroglu, E. (2016). Responses of a Tall Building with US Code-Type Instrumentation in Tokyo, Japan, to Events Before, During, and After the Tohoku Earthquake of 11 March 2011. *Earthquake Spectra*, 32(1), 497-522.

[7] Núñez E (1986): Geotechnical conditions in Buenos Aires City. *V Intern. Congress IAEG,* IV, 2623-2630.

[8] Codevilla M and Sfriso A (2011): Actualización de la información geotécnica de los suelos de la Ciudad de Buenos Aires. *Pan-Am CGS Geotechnical Conference.*

[9] Trifunac MD and Brady AG (1975): A study on duration of strong earthquake ground motion. *Bull. Seismol. Soc. Am.* 65, 581–626.

[10] Rathje ER, Abrahamson NA and Bray JD (1998): Simplified Frequency Content Estimates Of Earthquake Ground Motions, *Journal of Geotechnical and Geoenvironmental Engineering*, American Society of Civil Engineers, Vol. 124, No. 2, pp. 150-159, 1998.

[11] Kramer S (1996): *Geotechnical Earthquake Engineering.* Prentice Hall, 1st edition.

[12] Susa D. (2004): Evaluación del peligro sísmico asociado a sismos de tipo interplaca en Chile y sur del Perú utilizando una distribución bi-paramétrica de Weibull. Memoria de Título, Universidad de Chile, Departamento de Ingeniería Civil.

[13] Núñez I, Boroschek R, Comte D and Contreras V (2015): Nuevo Peligro Sísmico para Chile. *XI Congreso Chileno de Sismología e Ingeniería Sísmica ACHISINA 2015,* Santiago, Chile.

[14] Mustar J (2015): Determinación del Período Natural y Factor de Amortiguamiento a Partir de la vibración ambiente. Tesis para completar las exigencias del grado de Ingeniería Civil. Facultad de Ingenieria. Universidad de Buenos Aires.

[15] Kwok K, Hitchcock P and Burton M (2009): Perception of vibration and occupant comfort in wind-excited tall buildings. *Journal of Wind Engineering and Industrial Aerodynamics*. 97 (2009) 368–380

[16] Erduran E and Yakut A (2004): Drift based Damage Functions for Components of RC Structures. 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004