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# VIBRATIONS IN NEIGHBORHOOD BUILDINGS DUE TO ROCK CONCERT IN STADIUMS

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**Abstract.** *Rock concerts events in the River Plate Stadium in Buenos Aires (and other stadiums) has raised neighborhood complains due to molest vibrations felt by the inhabitants of some buildings at distances up to 3 km. In this paper are described the results of the studies conducted to determine the origin and the effects on buildings of vibrations generated during rock concerts in stadiums. First, are presented the equations for modeling: a) the coordinate jump of the public on the field and the generated load; b) the acceleration wave propagation over the surface of an elastic solid and c) the response of buildings at different distances from the stadium. The resulting equations are used to estimate the accelerations at top of buildings at distances inside a 3 km radio from the stadium. Then, the planned and obtained measurements during the concerts are shown and evaluated. Finally the conclusions and recommendations in relation with the effects of the coordinate jump of the public on the field, the properties of the affected buildings, their distance to the stadium and the effects on the structures, contents and inhabitants are presented. It is shown that for buildings in resonance with the spectator jumps (2 Hz of natural frequency, i.e. buildings around 10 to 12 stories at Buenos Aires), the acceleration level at the upper stories is sever to persons (even is not high enough to produce structural and non structural damage) to distances of more than 3 km from the stadium.*

## 1. INTRODUCTION

This paper summarize the studies carried out at University of Buenos Aires (UBA) to establish the causes and effects of building vibrations generated by rock concerts at River Plate stadium at Buenos Aires city.

The research activities were developed in the framework of a Cooperation Agreement between the UBA College of Engineering and the Enviromental Protection Agency (APRA) of Buenos Aires City due to vibration claims from owners of multistory buildings during rock concert events in the River Plate Stadium. The buildings (in general, 10 and 11 levels) were 600 to 2000m away from the Stadium  (Fig. 1).


Fig. 1. Vibrations claims during rock concert events at River Plate Stadium in Buenos Aires

Due to the lack of an analytical model generally accepted and a systematic and planned set of acceleration records, there is a broad controversy regarding the causes, the intensity and the effects of stadium field crowd-induced vibrations during rock concerts on neighborhood buildings.

In order to have a correct diagnosis about the level of annoyance and the possible solutions to the problem is needed a physical model capable of predict the building vibrations due to the actions generated by the spectacle. To satisfy this objective it was necessary to develop: a) an analytical model capable of representing the building responses, b) a planned set of acceleration records at soil and building floors at different distances of stadium during the rock concerts and c) the adjustment of the model according to the experimental results.

In this paper, are first summarized the limits of the vibrations human sensitivity. Then, the dynamic loads generated by the public during a rock concert, and in particular, the action on the environmental generated by the coordinated crowd jumping at the rhythm of the music at the field of the stadium are presented.

After that, it is developed an acceleration wave propagation model with origin at the periodic type of loading generated by the coordinated crowd jumping. The soil is represented by a semi-infinite isotropic elastic solid where the energy is propagated through volumetric waves (compression waves P and shear waves S) and surface Rayleigh waves R as shown in Fig. 2.

On turn, the acceleration waves reach the building foundations so that the accelerations at the different levels of the buildings can increase or decrease according to the dynamical structural properties. In particular, if the natural frequency of the building coincides with the excitation frequency, the resonance effect produces a large amplification of accelerations at uppers floors.

Finally, from the equations describing the above behavior and the results obtained in the planned measurements, conclusions regarding the effects on the structural, non-structural components and inhabitants of buildings are presented.

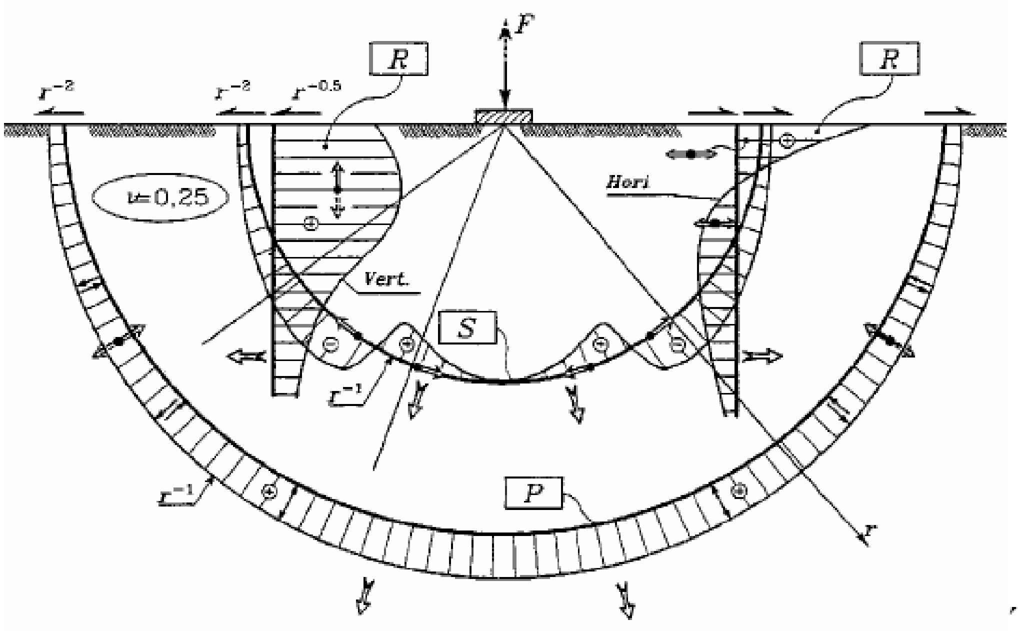


Fig. 2. Wave propagations in a semi-infinite isotropic elastic solid

## 2. HUMAN SENSIVITY TO VIBRATIONS

In Argentina, the human exposure to vibrations in buildings (frequency between 1 Hz to 80 Hz) is regulated by the norm IRAM 4078 Parte II (December 1990) based on the ISO Standard 2631/1985 "Evaluation of Human Exposure to whole-body Vibration".

According to that norm, the experience in several countries has shown that it is usual that the vibration claims in dwelling buildings start as soon as the vibrations reach the perception threshold. Therefore the allowable levels of vibrations are established in the norm mainly to minimize inhabitant complains than to other factors like health risk or work difficulties.

The norm defines basic curves representing constant levels of human response to vibrations considering the human perceptions or complaints. These curves are acceleration levels as a function of the excitation frequency. The allowable acceleration levels for different building uses and event hours are established as a multiple of these basic curves. For acceleration of velocity levels below these basic curves it is expected no comments or complain due to vibrations.

The primary magnitude used in the norm to describe the vibration intensity is the root mean square (RMS) of the accelerations. Given an acceleration history $a(t)$, the acceleration RMS ($\sigma_a$) for a period of time $T$ is computed as

$$\sigma_a = \sqrt{\frac{1}{T} \cdot \left( \int_0^T a(t)^2 \, dt \right)} \tag{1}$$

Thus, in the particular case of an harmonic excitation, $a(t) = A \sin\left(\frac{2\pi t}{T}\right)$, the amplitude $A$, satisfy the following equation

$$\sigma_a = \frac{A}{\sqrt{2}} \tag{2}$$

Fig. 3 shows the basic curves defined by the norm for accelerations $a_x(f)$ and $a_z(f)$ (m/s$^2$) as a function of frequency $f$ in the directions of the axis x (horizontal accelerations) and z (vertical accelerations).

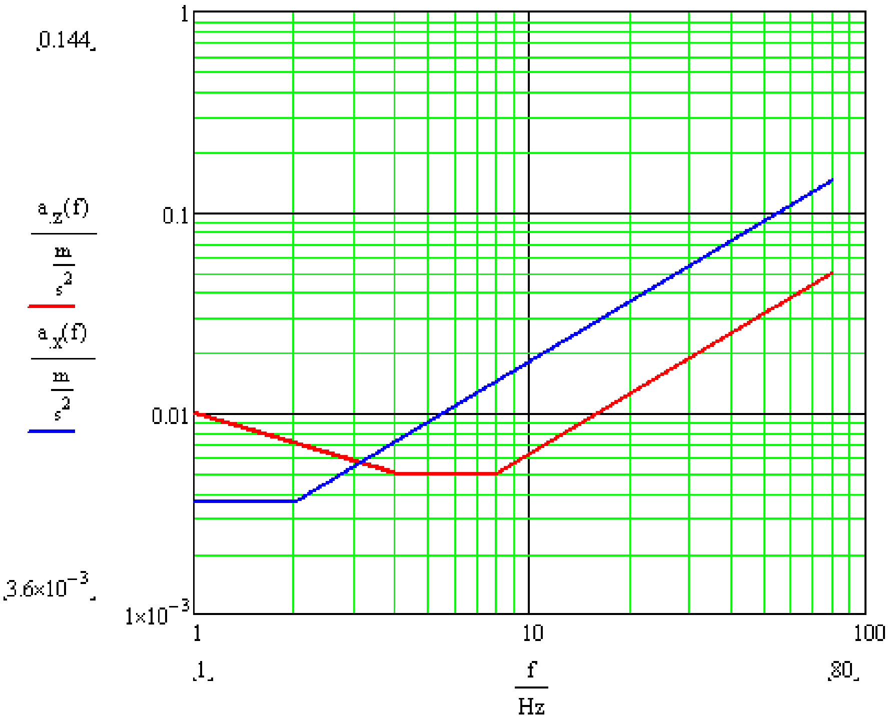


Fig. 3. Curvas básicas de respuesta humana constante a las vibraciones en las direcciones X y Z

For dwellings, the norm establishes the following multiplication factors for the allowable levels of vibration: a) During day hours: (2.0 to 4.0) and b) at night: (1.40). Since most of the musical events are at night, the last factor is used in this paper as a multiplication factor of the basic curves of Fig. 3 to obtain the acceleration limits.

If it is considered an excitation frequency of 130 beats/minute, $f_b = 130 . \frac{1}{\min} = 2.167 \frac{1}{s}$ (corresponding to the music rhythm in a rock concert), the allowable continous acceleration RMS in the vertical and horizontal directions are respectively $A_Z(f_b) = 0.097 . \% . g$ and

$A_X(f_b) = 0.056.\%.g$, where $g$ is the gravity acceleration. Note that for the frequency of the music beat in a rock concert, the human body is more sensitive to the horizontal than to the vertical vibrations.

It is important to take into account that in residential areas the tolerable vibrations can vary in a wide range. The specific values depend on cultural and social factors as well as psychological predisposition of building occupants.

Considering the international recommendations and the observations obtained in this study, it is assumed in this paper that the level of the acceleration RMS above what intermittent vibrations are clearly noticed for most of the people at buildings away of the stadium - where the vibrations are generated by the coordinate crowd jumping on the field following the rhythm of the music of a rock concert - is $A_1 = 0.1\%g$ $(0.01 m/s^2)$.

On the other hand, for ten times larger values, about $1\%g$ $(0.10 m/s^2)$, the accelerations are molest for persons, the hanging objects (lamps, flower-pots) can oscillate few millimeters and persons can feel alarmed by the movement.

## 3. DYNAMIC LOADS GENERATED BY THE CROWD DURING A ROCK CONCERT

### 3.1. Experimental studies and analytical representation of loads

During a rock concert, the music has the effect of synchronizing the movement of the spectators. Thousands of people, particularly, on the field jump exactly at the same time due to auditive and, specially, visual impact. For people on the stadium tribunes' exact synchronization for so many people is much more difficult.

In this paper the action of the crowd is modeled following the experimental studies carried out in the University of Surrey, UK [1]. In these studies it was examined thoroughly the statistical nature of crowd loading by measuring the individual performance of 100 people jumping and bobbing (oscillating vertically with feet in permanent contact with the ground) to four different tempos (frequencies of 1.5, 2.0, 2.67 y 3.5 Hz) in such a way as to allow the loading from very large crowds to be estimated by summing the individual force histories of the participants. They were encouraged to move as if they were enjoying a lively rock concert (Fig. 4).

From the studies of the University of Surrey it was recommended a synchronized load representing the crowd action given by eq.(3), where $W$ is the weight of the crowd, $f$ is the frequency of the beat, $DLF_n$ is the dynamic load factor for each harmonic $n$ y $\varphi_n$ is the phase lag of each harmonic.

$$P(t) = W.\left[1 + \sum_{n=1}^{\infty}\left(DLF_n.\cos(2.\pi.n.f.t - \varphi_n)\right)\right] \tag{3}$$


Fig. 4. Studies of Crowd-induced rhythmic loading at University of Surrey [1]

In **Fig. 5** it is shown the normalized force of people jumping following a beat of 2 Hz [1].

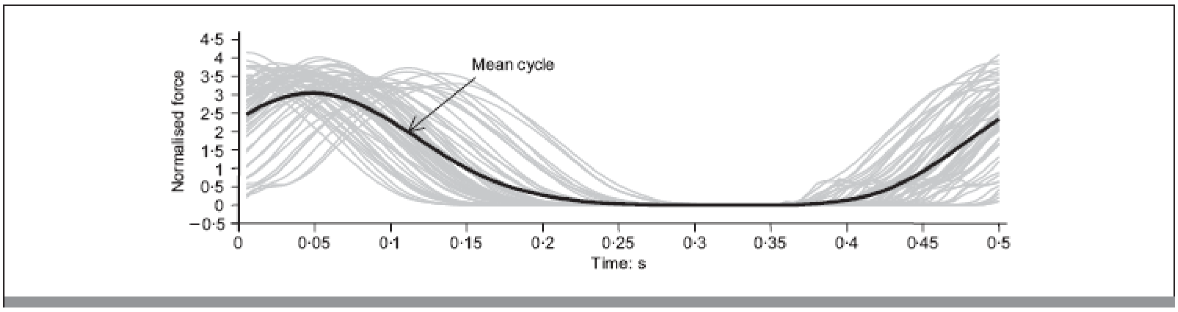


Fig. 5. Segment superposition of 29 s of force history and their mean [1]

In Fig. 6 it is shown the variation of dynamic load factors with crowd size for the first three harmonics.

The loads in the study of the University of Surrey have been measured on a rigid base. Considering that the crowd jumping on grass maintains the feet in permanent contact with the ground, the bobbing values have been used in this paper.

Therefore, from the values recommended in the study of the University of Surry and considering a frequency of 120 beats/minute (2 Hz) coincident with the experimental values obtained around the River Plate Stadium, the following dynamic loads factors were used in this paper for the first three harmonics $DLF = \begin{pmatrix} 0.321 \\ 0.080 \\ 0.010 \end{pmatrix}$, with a beat frequency, $f_b = 120.\frac{1}{\min} = 2.\frac{1}{s}$

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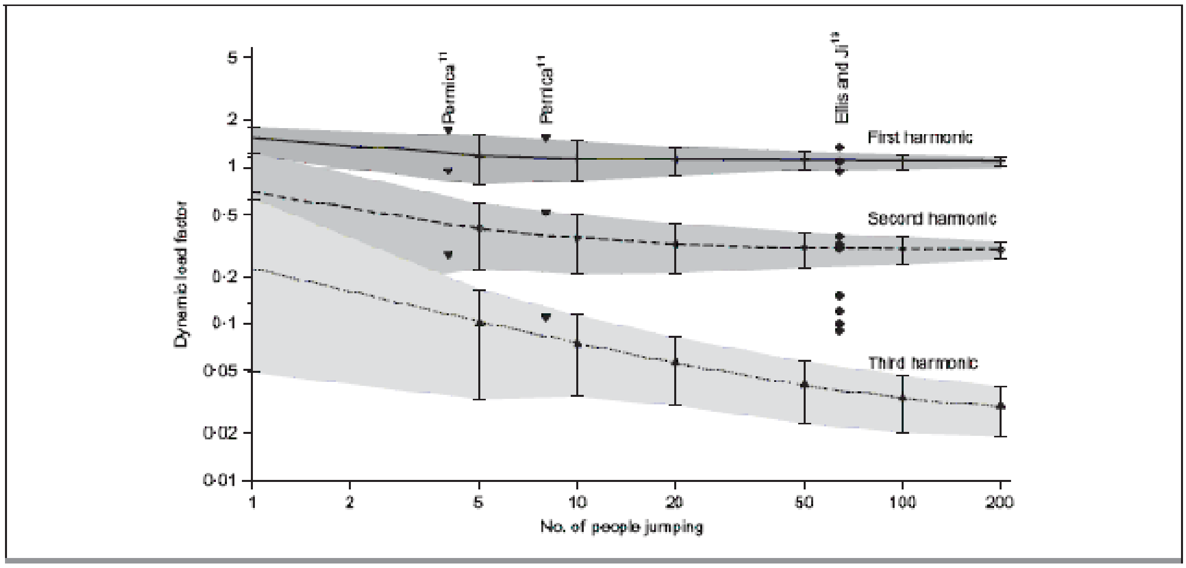

Fig. 6. Variation of dynamic load factors with crowd size [1]

### 3.2. Crowd-induced rhythmic loading on the stadium field

Assuming the synchronized jumping of 35,000 people on the field and an average weight of 62.4 kgf for the assistants to a rock concert a total weight of $W_t = W_0 . N_{esp} = 2.204.10^4 .kN$ is obtained. Considering eq. (3), it is possible to compute the power spectral density for the first three harmonics of the crowd-induced rhythmic loading as

$$S_{esp_i} = \frac{1}{2} . \left[ (DLF_i . W_t)^2 \right] = \begin{pmatrix} 2.502.10^7 \\ 1.554.10^6 \\ 2.428.10^4 \end{pmatrix} .kN^2 \quad (4)$$

with the following frequencies for each harmonic:

$$F_{b_i} = f_b . i = \begin{pmatrix} 2 \\ 4 \\ 6 \end{pmatrix} .Hz \quad (5)$$

$$\omega_b = 2 . \pi . F_b = \begin{pmatrix} 12.566 \\ 25.133 \\ 37.699 \end{pmatrix} \frac{1}{s} \quad (6)$$

## 4. WAVE PROPAGATION FROM THE STADIUM TO THE NEIGHBORHOOD

### 4.1. Dynamic soil properties at the stadium neighborhood

Considering the average soil properties in a depth according to the length of the Rayleigh waves corresponding to the 2 Hz frequency of the crowd jumping, the following values are obtained from soils studies around the stadium:: shear modulus $G = 60.3 MPa$ , soil density, $\rho = 1900 . \frac{kg}{m^3}$ , Poisson modulus $\nu = 0.35$ , soil damping factor $\varsigma = 0.005$, elasticity modulus,

$\mathrm{E}=2.(1+\nu).G=162.795.MPa$, Lamé constant $\lambda=\dfrac{\nu.\mathrm{E}}{(1+\nu).(1-2.\nu)}=140.687.MPa$, P wave propagation velocity P, $Cp=\sqrt{\dfrac{\lambda+2.G}{\rho}}=370.828\dfrac{m}{s}$, S wave propagation velocity $C_S=\sqrt{\dfrac{G}{\rho}}=178.14\dfrac{m}{s}$, R wave propagation velocity for $\nu=0.35$, $C_R=\sqrt{c_{R_1}}.C_S=166.563\dfrac{m}{s}$, with a wave propagation velocity ratio, $\dfrac{C_R}{C_S}=0.935$.

### 4.2. Wave propagation on the surface of a semi-infinite isotropic elastic solid

In 1904, assuming that most of the vibration energy is transported by the Rayleigh waves, Lamb [2] obtained analytically the displacements $u(t)$ at any point of a semi-infinite isotropic elastic solid located at a distance $r$ from an harmonic load $Pe^{i\omega t}$ of frequency $\omega$. The Lamb solution can be written as [3]:

$$u(t)=U(\omega,\varsigma,r)e^{i\omega t}=-\frac{\omega H}{2\rho C_R^{\ 3}}e^{-\frac{\varsigma\omega r}{2C_R}}H1^{(2)}\left(\frac{\omega\, r}{C_R}\right)Pe^{i\omega t}=H_u(\omega,\varsigma,r)Pe^{i\omega t} \tag{7}$$

where $H1^{(2)}(\cdot)$ is the Hankel function of second kind and first order . $H$ is a constant that depends on the Poisson modulus only ($H=0.095$ for $\nu=0.35$). Therefore, $H_u(\omega,\varsigma,r)$ is the transfer function representing the displacement soil response.

By double differentiation of eq. (7) respect of time, the acceleration response $\ddot{u}(t)$ in any point of the semi-infinite space can be computed as

$$\ddot{u}(t)=\ddot{U}(\omega,\varsigma,r)e^{i\omega t}=-\omega^2 H_u(\omega,\varsigma,r)Pe^{i\omega t}=H_{\ddot{u}}(\omega,\varsigma,r)Pe^{i\omega t} \tag{8}$$

### 4.3. Soil accelerations away the stadium due to crowd-induced rhythmic loading on the field

Using the random vibrations theory [4], the transfer function of eq.(8) $H_{\ddot{u}}(\omega,\varsigma,r)$ and the power spectral density of the crowd-induced rhythmic loading $S_{esp_i}$ [eq.(4)] it is possible to obtain the power spectral density of the horizontal acceleration at different distances from the stadium $r$ for each harmonic $i$ as

$$S_{\ddot{u}}(i,\zeta,r)=S_{esp_i}.\left(\left|H_{\ddot{u}}(2\pi f_b i,\zeta,r)\right|\right)^2 \tag{9}$$

Thus, the RMS horizontal accelerations can be computed as

$$\sigma_{\ddot{u}}(\zeta,r)=\left(\sum_{i=1}^{3}S_{\ddot{u}}\left(i,\zeta,r\right)\right)^{\frac{1}{2}} \tag{10}$$

In Fig. 7 are shown the RMS horizontal accelerations obtained on soil at 500, 1000 and 1500 m distance from the River Plate stadium (0.081 %g, 0.042 %g and 0.026 %g respectively) using eq. (10).

These small values explain why the vibrations are practically no felt at the one or two story dwellings, even at those located closest to the River Plate stadium. In Section 2, it was shown that the limit above what intermittent vibrations are clearly noticed for most of the people is around 0.1 %g.


Fig. 7. RMS horizontal acceleration on soil at 500, 1000 y 1500 m from River Plate stadium

### 4.4. Building accelerations away the stadium due to crowd-induced rhythmic loading on the field

As shown in Fig. 7, the accelerations on soil and at rigid dwellings (no amplification) are just perceptible, even for those in the closest zone near the River Plate stadium.

However, when the low frequency horizontal accelerations reach the foundations of multi-story buildings the accelerations can be amplified or reduced at the different floors depending on the dynamic building properties. In particular, when the excitation frequency coincides with the building natural frequency, a large amplification is obtained at the upper stories due to the resonance condition.

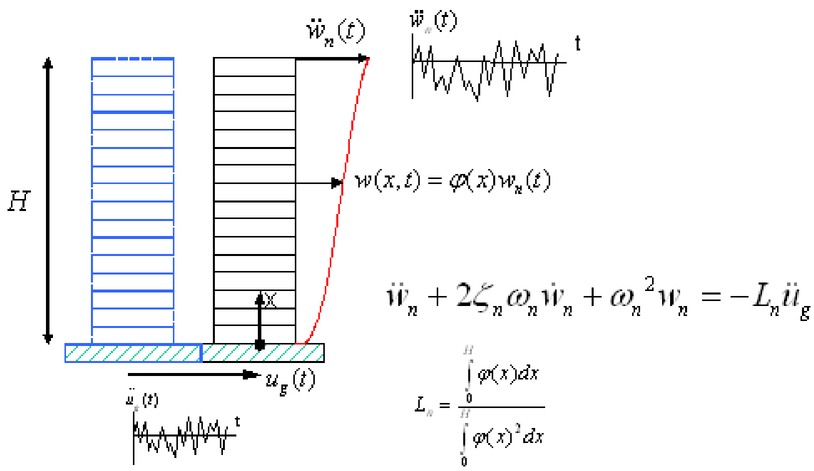


Fig. 8. Building vibrations due to base accelerations. Generalized single degree of freedom system model.

Fig. 8 shows the response to base accelerations of a multi-story building using a generalized single degree of freedom system [5]. The equation of motion is

$$\ddot{w}_n(t) + 2\xi_n\omega_n\dot{w}_n(t) + \omega_n^2 w_n(t) = -L_n\ddot{u}(t) \tag{11}$$

where $w_n$ is the displacement of the top of the building, $\xi_n$ is the building damping factor, $\omega_n$ is the building natural vibration frequency, $L_n = \dfrac{\int_0^H m(x)\varphi(x)dx}{\int_0^H m(x)\varphi(x)^2\,dx} = 1.50 \; for \; \varphi(x) = \dfrac{x}{H}$ is the generalized participation factor, $m(x)$ is the mass along the building height assumed constant in this paper, $H$ is the building height, $\varphi(x)$ is the shape function that define the form of deflections (assumed linear in this paper) and $\ddot{u}(t)$ is the soil acceleration as described in the previous section.

By applying the Fourier transform to eq.(11), the response in the frequency domain is obtained as

$$W_n(\omega,\omega_n,\xi) = -\frac{L_n}{\omega_n^2 - \omega^2 + 2\xi_n\omega_n\omega\, i}\ddot{U}(\omega) = H_n(\omega,\omega_n,\xi_n)\ddot{U}(\omega) \tag{12}$$

where $H_n(\omega,\omega_n,\xi_n)$ is the transfer function representing the building top displacement response for a building of frequency $\omega_n$ and damping factor $\xi_n$, $\ddot{U}(\omega)$ is the Fourier transform of $\ddot{u}(t)$ and $W_n(\omega,\omega_n,\xi)$ is the Fourier transform of the top building displacement $w(t)$.

Using eq. (12), the Fourier transform of the top building acceleration $\ddot{w}(t)$ can be computed as

$$\ddot{W}_n(\omega,\omega_n,\xi) = \frac{\omega^2\, L_n}{\omega_n^2 - \omega^2 + 2\xi_n\omega_n\omega\, i}\ddot{U}(\omega) = \omega^2 H_n(\omega,\omega_n,\xi_n)\ddot{U}(\omega) = H_{\ddot{w}}(\omega,\omega_n,\xi_n)\ddot{U}(\omega) \tag{13}$$

Therefore, the power spectral density of top building accelerations for each excitation frequency $\omega_i$ can be computed as

$$S_{\ddot{w}_n}(\omega_n,\xi_n,\omega_i,\zeta,r) = \left(\left|H_{\ddot{w}}(\omega_i,\omega_n,\xi_n)\right|\right)^2 S_{\ddot{u}}(\omega_i,\zeta,r) \tag{14}$$

Thus, the RMS top building acceleration can be computed for the first three harmonics as

$$\sigma_{\ddot{w}_n}(\omega_n,\xi_n,\zeta,r) = \left(\sum_{i=1}^{3} S_{\ddot{w}_n}\left(\omega_n,\xi_n,\omega_i,\zeta,r\right)\right)^{\frac{1}{2}} \tag{15}$$

Fig. 9 shows the RMS top building accelerations (building damping factor $\xi_n = 0.02$) as a function of the period of the first vibration mode $T_n = \dfrac{2\pi}{\omega_n}$ obtained using eq.(15) at distances of 1000, 1500 and 2000 m away of River Plate stadium.

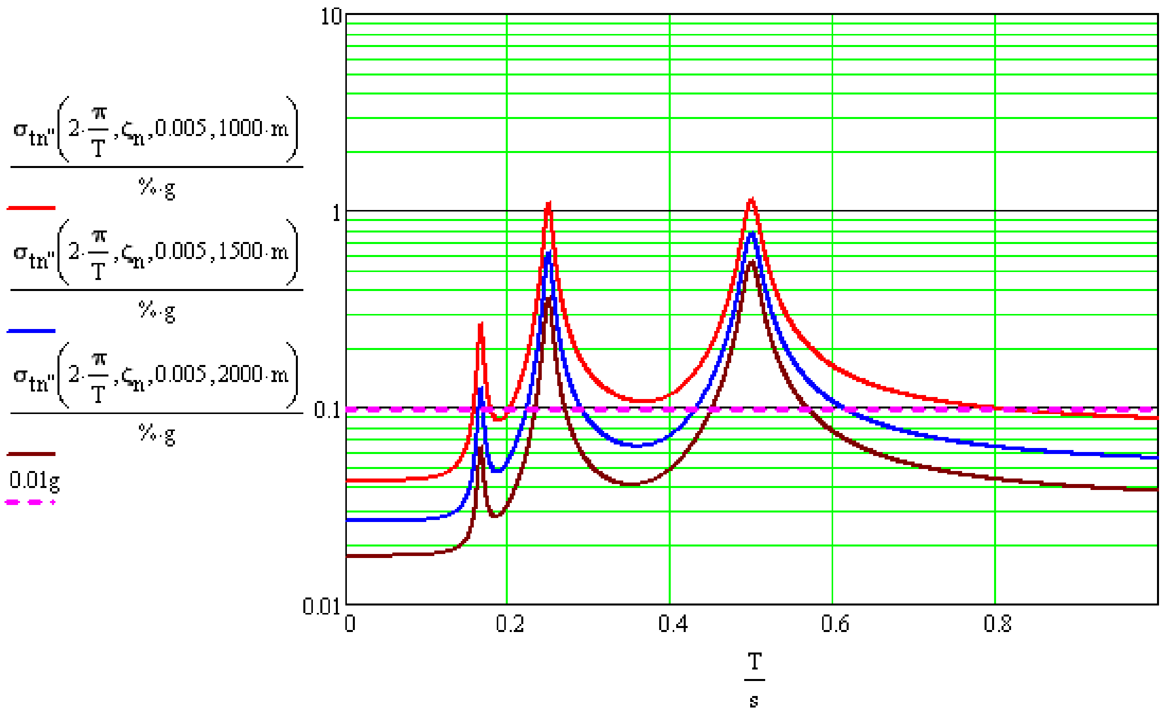


Fig. 9 RMS building top accelerations [%g] for natural periods between 0 to 1 sec

Fig. 9 clearly shows the resonance with the first and second harmonic of the crowd-induced rhythmic loading [eq. (5)] at frequency of 2 and 4 Hz (Periods of 0.5 and 0.25 s respectively).

Although in most of the cases, the building top accelerations are below the perception threshold of 0.1%g, they reach values near 1% g, even for distances larger than 1500m from the stadium, for buildings whose natural frequencies coincide with the crowd jumping frequencies.

In Fig. 10 are shown the RMS building top accelerations for buildings with 2 Hz of natural frequency obtained at 500, 1000, 1500 and 2000 m distance from the River Plate stadium (1.93 %g, 1.13 %g, 0.76 %g and 0.55 %g respectively) using eq.(15).

The period of the building first mode of vibration is strongly correlated to the building height. From experimental data on reinforced concrete shear wall buildings (the usual structural construction for multi-story buildings in Buenos Aires), Satake et al [6] proposed in 2003 the following relationship,

$$T_n = 0.015 \frac{H}{m} \tag{16}$$

Considering an average inter-story height of 3 m and using eq.(16), the resonance frequencies of 2 and 4 Hz would correspond to buildings between 11 and 12 stories and 6 stories respectively, depending on the specific values of the dynamic building parameters (stiffness, mass and damping).

The analytical results clearly explain why the vibrations are mostly felt at buildings of that number of stories, even to long distances away the stadium (3000 m), meanwhile the inhabitants of lower and taller buildings do not feel vibrations even if they are located closer the River Plate stadium.


Fig. 10. RMS building top accelerations for buildings with 2 Hz of natural frequency computed at 500, 1000, 1500 and 2000 m distance from the River Plate stadium

## 5. STRUCTURAL AND NON-STRUCTURAL DAMAGE RISK

For accelerations smaller than 2% g at the building top, the influence of the acceleration on damage is neglectful. The structural and non-structural building damage is more related with the level of displacements, particularly the inter-story relative displacements as considered for wind and earthquake building codes.

Considering that the maximum building horizontal acceleration, $A$, happens at resonance with the first harmonic of the spectators jumping ( $f_b = 2Hz$ ), it is possible to compute the maximum displacement at the building top, $X$ , as

$$X(A) = \frac{A}{\left(2\pi f_b\right)^2} \tag{17}$$

The buildings closest to the River Plate stadium with a height susceptible of reaching the resonance condition are located about 800 m away from the stadium. Using the RMS building top acceleration $\sigma_{\ddot{w}_n}$ [eq. (15)] and eq. (2), the acceleration amplitude can be computed as

$$A = \sqrt{2}\,.\sigma_{\ddot{w}_n}\left(2\pi f_b, \zeta_n, 0.005, 800\,m\right) = 1.927\ \%\ g \tag{18}$$

Although this acceleration level is very molest for building inhabitants, the corresponding maximum displacement is only

$$X(A) = 1.2\ mm \tag{19}$$

Considering that the approximate height of a building in resonance with the crowd jumping is [eq.(16)], $H = \frac{T_b}{0.015} m = \frac{0.5}{0.015} m = 33.33 m$ , the ratio displacement/height can be computed as

$$\frac{X(A)}{H} = \frac{1.2\,10^{-3}\,m}{33.33m} = \frac{1}{1000}\frac{1}{28} \tag{20}$$

That means that the maximum displacement of the closest buildings near the River Plate stadium due to the crowd-induced rhythmic loading on the stadium field is about 30 times smaller than the serviceability allowable displacement for wind action established by most of the structural codes (H/1000).

Therefore, this level of relative displacement is much smaller than the required to produce damage to structural and non-structural elements.

## 6. ACCELERATION RECORDS OBTAINED DURING THE CONCERTS

In order to validate the analytical model a measurement plan was developed. The ground accelerations and the building responses were measured during the concerts of ACDC (4th and 6th of December, 2009), Metallica (21st and 22nd of January, 2010) and Cold Play (26th of February, 2010) at the River Plate Stadium. Measures were also taken during the Gustavo Cerati concert (20th of December, 2009) at Club Ciudad. In Fig. 11 it is shown where the measures were obtained during the concerts. The coordinate jump of the spectators was caught on video during the Metallica and Cold Play concerts.


Fig. 11. Locations were the ground accelerations and the building response were obtained

The ground accelerations obtained at 450 m away from the stadium show that the frequency content matches the spectator's movement during rock concerts (Fig. 12). The acceleration levels measured at the ground were below the human perception threshold (0.06% g).

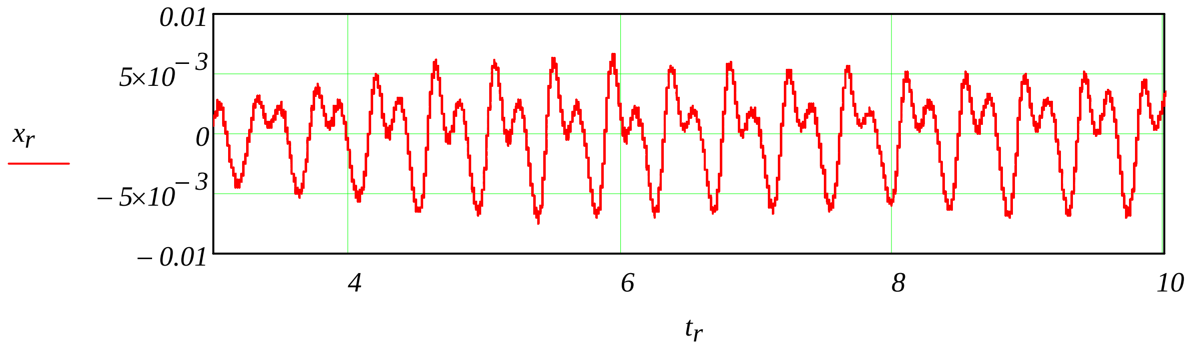


Fig. 12. Acceleration record obtained on ground 450m away from the stadium during the coordinate crowd jumping at stadium field – Metallica concert (sample duration 7sec)

On the other hand, during the concerts, the recorded accelerations at buildings inside a 1000m radius were well above the comfort limits. The buildings having natural frequencies around 2-2.5 Hz were the most affected by the Rayleigh wave's transmitted trough the foundations. The maximum measured accelerations reached up to 1.5% g (RMS 1.1% g) at the top of an 11-story building located 850m away from the stadium (Fig. 13).

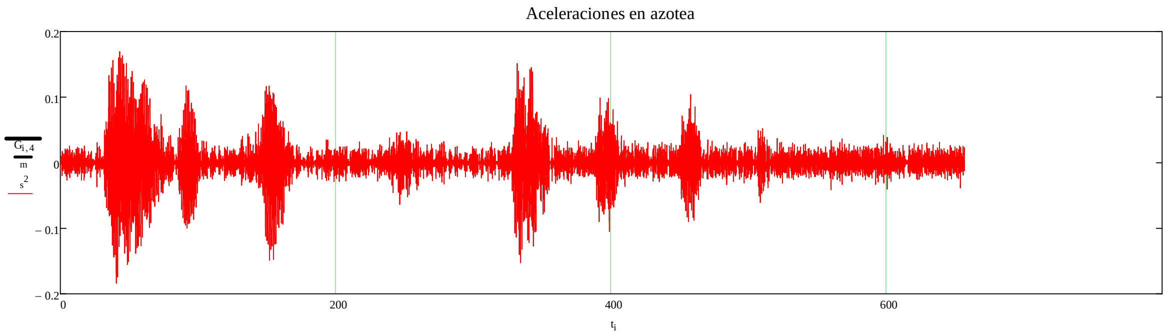


Fig. 13. Accelerations recorded at the top of an 11-story building located 850m away from the stadium during the ACDC concert (sample duration 20 minutes)

## 7. CONCLUSIONS

### 7.1. Conclusions from the obtained measures

As a result of the obtained measured the following conclusions were reached:

- From the acceleration records and the simultaneous crowd jumps caught on video, it was established that the Rayleigh waves were the result of the coordinate jump of the spectators during some segments of the rock concerts. The obtained accelerations and the radius where the vibrations are felt by the building inhabitants are related to the number of spectators coordinately jumping following the rhythm of the music.

- The recorded ground and building accelerations matched reasonably with the results of the analytical model of wave propagation and building response.

- The recorded accelerations and displacements are below the levels required to produce structural and/or non-structural damage on buildings. However the accelerations on 10 to 12 story buildings located about1000m away the stadium produced alarm in the inhabitants of the upper floors.

### 7.2. Conclusions from the analytical model

This paper studies the vibration transmitted from the ground to the buildings (and the people living in them) due to the coordinated jump of 35,000 spectators during rock concerts developed at River Plate Stadium, in Buenos Aires. The main conclusions are:

- The coordinated movement of the spectators jumping to rhythm of the music generates acceleration waves with a frequency of 2 and 4 Hz. These waves (mainly Rayleigh waves) are propagated over the ground reaching the buildings foundations in the surrounding area of the stadium.

- At the ground level of dwellings some occupant could perceive the vibrations inside approximately 380m radius from the stadium (Fig. 14).


Fig. 14.Area where some people could feel vibrations on ground level

- The horizontal vibrations are magnified by buildings whose natural frequency matches the frequency of the spectator’s movement.

- The RMS accelerations could reach values between 0.6% g and 1.1% g at the top level of buildings about 10-12 stories (at resonance with the first harmonic of the spectators movement) and at the top level of buildings about 6 stories (at resonance with the second harmonic of the spectators movement) inside a 3000m radius away from the stadium (Fig. 15). The number of stories to get resonance can slightly change as a function of the characteristics of the structural system, the foundation type, the quantity of the non-structural walls and the spectator’s movement.

- For RMS values larger than 0.6% g, the accelerations are very molesting for persons. The hanging objects (lamps, flower-pots) can oscillate few millimeters, the water in fishbowls can move clearly and inhabitants can alarm by the movement.

- The calculated drifts and accelerations on buildings in the surrounding areas of the stadium are not high enough to produce structural and/or non-structural damage.

- This study was conducted assuming the simultaneous jump of 35,000 spectators at the stadium field. The ground and building accelerations are directly proportional to the number of spectators jumping in a coordinated manner with the music.

- As a result of the low frequency of the vibration it is not possible to use the traditional vibration control methods such as digging a shallow trench around the source (because of the depth of the Raleigh waves).


Fig. 15. Area where people at the upper floors could feel vibrations on buildings at resonance with the spectators movement

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