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Establishing Empirical Period Formula for RC Buildings in Lima, Peru: Evidence for the Impact of Both the 1974 Lima Earthquake and the Application of the Peruvian Seismic Code on High-Rise Buildings

by Bertrand Guillier, Jean-Luc Chatelain, Hernando Tavera, Hugo Perfettini, Angel Ochoa, and Bilha Herrera

Online Material: Table describing reinforced concrete buildings measured in Lima, Peru.

INTRODUCTION

The easiest building parameter to determine is the elastic fundamental resonance period, or its inverse, the fundamental frequency, preferentially used in seismological studies. This period/frequency is directly related to the building stiffness and can be linked to external inputs (acceleration, soil response, etc.), internal history (construction material and quality, structural design, seismic history, etc.), and more complicated factors such as soil–structure interaction. This frequency is generally obtained through building modeling for the most recent structures but is much more complicated or even impossible to determine for old buildings, the blueprints of which are generally not available.

This crucial parameter can be directly assessed *in situ* using (1) dynamic methods, such as unbinding, harmonic excitation, or percussion (e.g., Trifunac, 1972; Boutin *et al.*, 2001; Crowley and Pinho, 2004) that are expensive, tedious to install, and generally disturbing, (2) traditional earthquake records (e.g., Dunand *et al.*, 2006; Todorovska, 2009), or (3) passive ambient vibration recordings (e.g., Carder, 1936; Trifunac, 1972; Trifunac *et al.*, 2001a,b; Farsi and Bard, 2004; Michel *et al.*, 2008; Farsi *et al.*, 2009; Michel, Guéguen, El Arem, *et al.*, 2010) or other passive method such as coherent Light Detection and Ranging measurement (Guéguen *et al.*, 2010). The most reliable building dynamic parameter estimates are obtained from earthquake records, but this type of data is quite difficult to obtain, very expensive because of the seismic network deployment and maintenance, and heavily dependent on earthquake occurrence, which may be quite a problem in low-to-moderate seismic regions.

Ambient vibration recordings performed on building are recognized to provide larger fundamental frequency than those used for earthquake engineering purposes. In spite of this, ambient vibration studies allow to collect numerous data, allowing statistical processing, which is crucial, especially in the case of existing buildings. When it is needed to define a building typology based on building frequencies using statistics on large data set, the most useful method is the ambient vibration method, as it is less time consuming and easier to set up.

In this paper, we use ambient vibration recordings to study the fundamental building frequency behavior over the cities of Lima and Callao (Peru), to determine a local empirical relationship between this parameter and the building number of floors to be used as a rough frequency estimate (or proxy) in the Peruvian seismic code. An ambient vibration survey has been carried out in 23 hospitals in Lima (Peru), complemented by recordings on nonmedical buildings. A total of 536 recordings have been performed in 344 reinforced concrete (RC) buildings with masonry infill, used to get building fundamental frequencies. Building number of floors, building sizes (length and width, from Google Earth), and year of construction were also collected. A fundamental frequency statistical analysis reveals that the most important factor controlling RC building fundamental period in Lima is the building height (or number of floors), whereas horizontal dimensions are not strongly involved. Moreover, the relationship between the building number of floors and the period is found to be significantly depending on the age of the structures with respect to the year 1974.

1974 is a key year in Lima history, corresponding to (1) the occurrence of the major M_w 8.1 earthquake, about 90 km from Lima, that significantly impacted the pre-1974 high-rise building structures in the city (e.g., Dorbath *et al.*, 1990), with intensities way above any felt earthquake since

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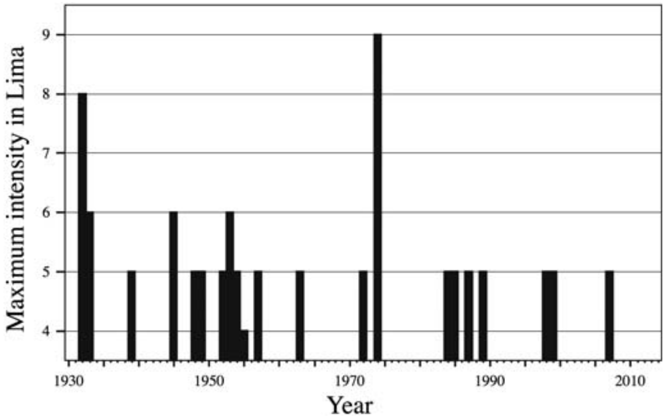


▲ **Figure 1.** Maximum seismic intensities in Lima from 1930 to actual time. The minimum retained intensity has been fixed to 4.

1930 (Fig. 1) and (2) the implementation of the first Peruvian seismic code leading to a significant increase of the post-1974 high-rise building stiffness. We show that different formulas should be used according to the building construction year, as well as the height of the buildings, leading for the first time to an indication that both the 1974 Lima earthquake and the application of the Peruvian seismic code significantly affected the building behavior in the whole city.

PERUVIAN SEISMIC CODE FORMULAS

Seismic codes aim to define the fundamental period for different building types, and, usually, this typology is locally defined. The main factors that can affect this parameter are (1) the nonlinearity phenomena (because building response is generally assumed to be in the elastic domain, Michel, Guéguen, Lestuzzi, *et al.*, 2010), which can increase the period by as much as 35%–40% (Dunand *et al.*, 2006) and (2) the building damage rate, which forces the building period to increase proportionally to the damage rate with a variation from 30% as found with *in situ* measurements by Dunand *et al.* (2004) and Calvi *et al.* (2006) to as high as 50% as found by Masi and Vona (2010) in a laboratory experiment.

To help the building designer, seismic codes are providing formulas to roughly estimate the period based on simple building structural characteristics that can be used when no better estimate is available. This kind of formula may also be used in large-scale seismic vulnerability assessment (e.g., Lagomarsino and Giovinazzi, 2006).

After the 1974 M_w 8.1 Lima earthquake that strongly shook Lima (Dorbath *et al.*, 1990) and damaged numerous buildings in the city, it has been decided to apply the first Peruvian seismic code (E.030, 2007) in which building fundamental periods are determined with the formulas:

$$T_0 = \frac{H}{C_H}, \tag{1}$$

in which H is the building height, and C_H a constant, with $C_H = 35$ when the resistant elements are only frames, $C_H = 45$ when the resistant elements are stairwell and/or elevator shaft, and $C_H = 60$, when the resistant elements are shear walls. Or its alternate expression:

$$T_0 = \frac{N}{C_N}, \tag{2}$$

in which N is the number of floors, and C_N a constant, with $C_N = 12$ when the resistant elements are only frames, $C_N = 15$ when the resistant elements are stairwell and/or elevator shaft, and $C_N = 20$, when the resistant elements are shear walls.

DATA ACQUISITION

In May 2010, a survey of the main hospitals in Lima and Callao (Peru) has been launched in the framework of a United Nations Development Program (UNDP) study (D'Ercole *et al.*, 2011) for risk assessment in Lima, using nondestructive methods within a 1-month work, at 23 state hospitals identified by D'Ercole *et al.* (2011) as being of fundamental interest in case of a crisis.

The ambient vibration survey has been conducted using two CityShark II recorders (Chatelain *et al.* 2000, 2012) connected to Lennartz LE3D-5-second sensors, which has been proven to be a good combination for ambient vibration studies (Guillier *et al.*, 2008). The seismometers have been installed using the same protocol in each building, as done, for example, by Dunand *et al.* (2004) and Farsi *et al.* (2009): the north–south component of the sensor was oriented along the main axis of the building (hereinafter the longitudinal direction) leading to redirect the east–west component of the sensor in the shorter length of the building (hereinafter the transverse direction). Recordings have been performed at the top of the buildings, that is, in most cases the roof (in Lima all roofs are flat due to the absence of rain), and if not accessible at the highest level. Generally, the sensor was installed at the center of the roof.

Recordings were performed over a 15-min period to get enough stable signal windows and to ensure a safe determination of the main frequency peak using a 200 samples/s sampling rate, and following the data collection recommendations of Chatelain *et al.* (2008).

In the 23 selected hospitals, 231 buildings were surveyed among which 196 were RC buildings with masonry fill walls (brick walls). The survey also included a full description of each building, including (1) number of floors, (2) length and width, and (3) year of construction (1937–2010), the latter being available for 191 of the 196 surveyed buildings. Unfortunately, due to time considerations, we have been unable to evaluate the percentage of infilling that is generally assumed to have a strong importance in the final elastic fundamental resonance period (Oliveira and Navarro, 2010).

As the data set from the hospital survey revealed a lack of data in the floor number distribution, a second survey has been carried out to improve the representativeness of floor numbers. Thus, data from 148 other buildings constructed between 1950 and 2011 have been added, raising the total data set to 344 buildings.

Some buildings have been instrumented more than once, either because they were composed of blocks separated by seismic joints or because they were too large to be represented by a single recording (the smallest building surface is 34 m^2, and the largest one over 10,000 m^2). Thus, 213 buildings have been instrumented once, 99 buildings twice, 14 buildings three times, 12 buildings four times, 1 building five times, and 5 buildings six times, leading to a total set of 536 recordings.

The resulting database is composed of 536 recordings in both the longitudinal and transverse directions, giving a total set of 1072 fundamental frequencies/periods (Ⓔ see electronic supplement, Table S1). The numbers of floors of all the 344 buildings, together with the length and width of 320 buildings, have been determined, although the year of construction of only 339 buildings could be retrieved. Unfortunately, due to the limited amount of time to execute the field survey the direction of the building resistant elements has not been checked.

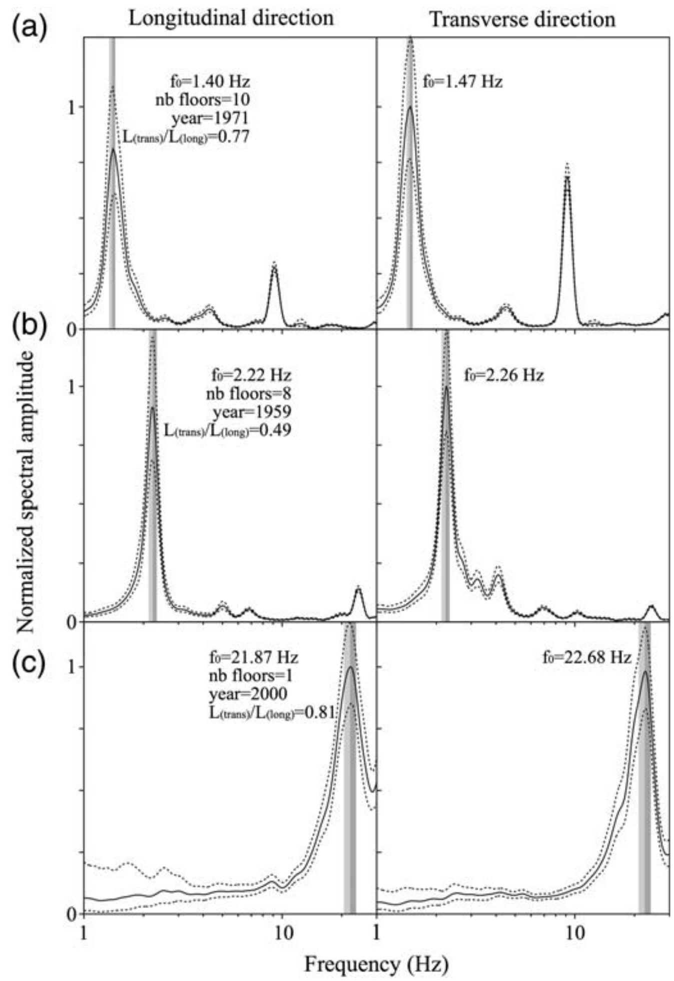
DATA PROCESSING

Fundamental frequencies (f_0) were obtained with the open source geopsy software (www.geopsy.org, last accessed September 2014). Fast Fourier amplitude spectra have been computed in the 1–30 Hz range, a suitable range for the surveyed buildings. Each spectrum curve is obtained from the following way: (1) selection of 25-s stable signal windows, using an anti-trigger (short-term average (STA) = 1 s, short-term average (LTA) = 30 s, with low and high thresholds of 0.2 and 2.5, respectively) to reject strong transients, (2) a 5% cosine taper is applied on both ends of the selected windows to minimize the distortion of the fast Fourier transform (FFT) of the signal, (3) calculation of the Fourier amplitude velocity spectra for each selected window, (4) smoothing of each individual window spectrum with the Konno and Ohmachi (1998) method, using a constant of 40, and (5) the average Fourier amplitude velocity spectra curve is obtained by averaging all individual window spectral curves. The fundamental frequencies, in both the longitudinal (f_{0long}) and transverse (f_{0trans}) directions, have been obtained with geopsy by automatic identification of the peak with the highest amplitude on the FFT curve, together with their standard deviations (Fig. 2).

EXPERIMENTAL FUNDAMENTAL FREQUENCIES

All buildings have a width/length ratio in the range between 1:1 and 1:8 (Fig. 3a). If the building horizontal dimensions were involved in determining building fundamental frequencies, they should be somewhat different in the longitudinal and transverse directions. Both longitudinal and transverse frequencies are actually very close (Fig. 3b), a strong indication that the horizontal structural dimensions only marginally affect building fundamental frequencies/periods, whatever the building height, width/length ratio, and year of construction as illustrated by some examples (Fig. 2).

However, in some buildings a strong difference is observed between the longitudinal and the transverse frequencies (Fig. 4). We thus checked how often this phenomenon occurred in the database. A difference (f_{0long}–f_{0trans}) between the longitudinal and transverse fundamental frequencies less than 10% is observed in 60% of the buildings, and less than 20% in about 90% of the buildings.

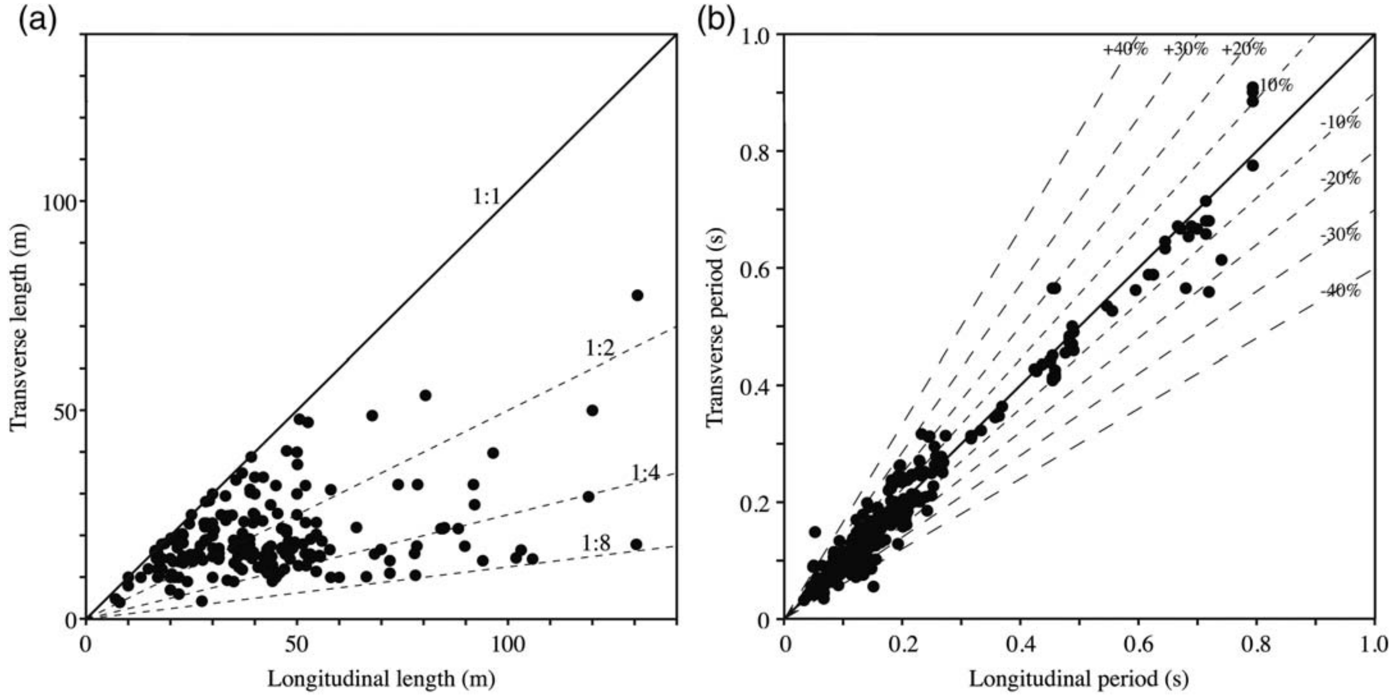


▲ **Figure 2.** Frequency peak-picking examples, for different buildings (lines a–c) in the (left) longitudinal and (right) transverse directions, displaying a strong homogeneity in between both directions. (a) Ten-floor building displaying a 5% difference between the longitudinal and transverse fundamental frequencies. (b) Eight-floor building displaying a 2% difference between the longitudinal and transverse fundamental frequencies. (c) One-floor building displaying a 3% difference between longitudinal and transverse fundamentals. The gray zones indicate the ranges of the peak frequency standard deviations.

COMPARISON WITH SOME SEISMIC CODE FORMULAS

The seismic code formulas used to compute the fundamental period of a building can be divided into three main groups based on the horizontal structure dimensions (L), the building height (H in meters or N in floor number), and locally determined constants (C_t, C_N, C_H, and β):

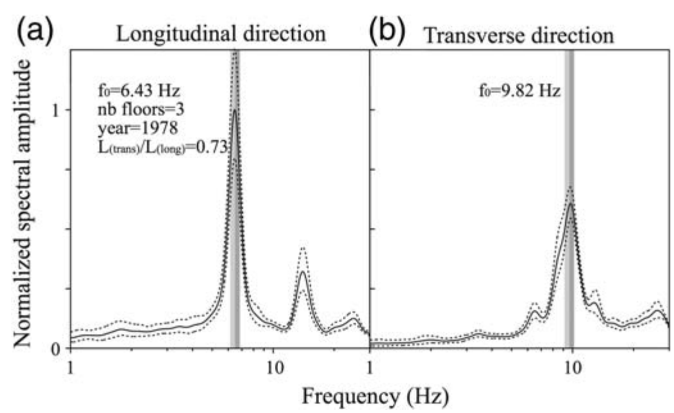
1. formulas using the horizontal structure dimensions (L) initially developed by Housner and Brady (1963), used in the Algerian code (RPA88, 1988) $T = \frac{C_t \times H}{\sqrt{L}}$,



▲ **Figure 3.** Building data showing that horizontal structure dimensions only marginally affect building fundamental frequencies/periods. (a) Transverse length as a function of the longitudinal length (different slopes indicate the different ratios between transverse and longitudinal lengths). (b) Transverse fundamental periods versus longitudinal fundamental periods (dashed black lines indicate the deviations to the 1:1 slope).

with $C_t = 0.09$, or in the Association Française du Génie Parasismique (AFPS, 1990) formula $T = \frac{0.08 \times H^{15}}{\sqrt{H+L\times\sqrt{L}}}$;

2. formulas calculating the building period as a power-law function of the building height, $T = C_t H^{\beta}$, as used in the Uniform Building Code (UBC; 1997) ($C_t = 0.049$; $\beta = 0.75$), the Risk-UE works (Lagomarsino and Giovinazzi, 2006) ($C_t = 0.065$; $\beta = 0.9$), the European code (Eurocode 8, 2004) ($C_t = 0.05$; $\beta = 0.75$), or the Swiss code (SIA, 2003) ($C_t = 0.052$; $\beta = 0.75$); and



▲ **Figure 4.** Frequency peak picking for a three-floor building in the (a) longitudinal and (b) transverse directions, displaying a strong heterogeneity (50%) in between both directions.

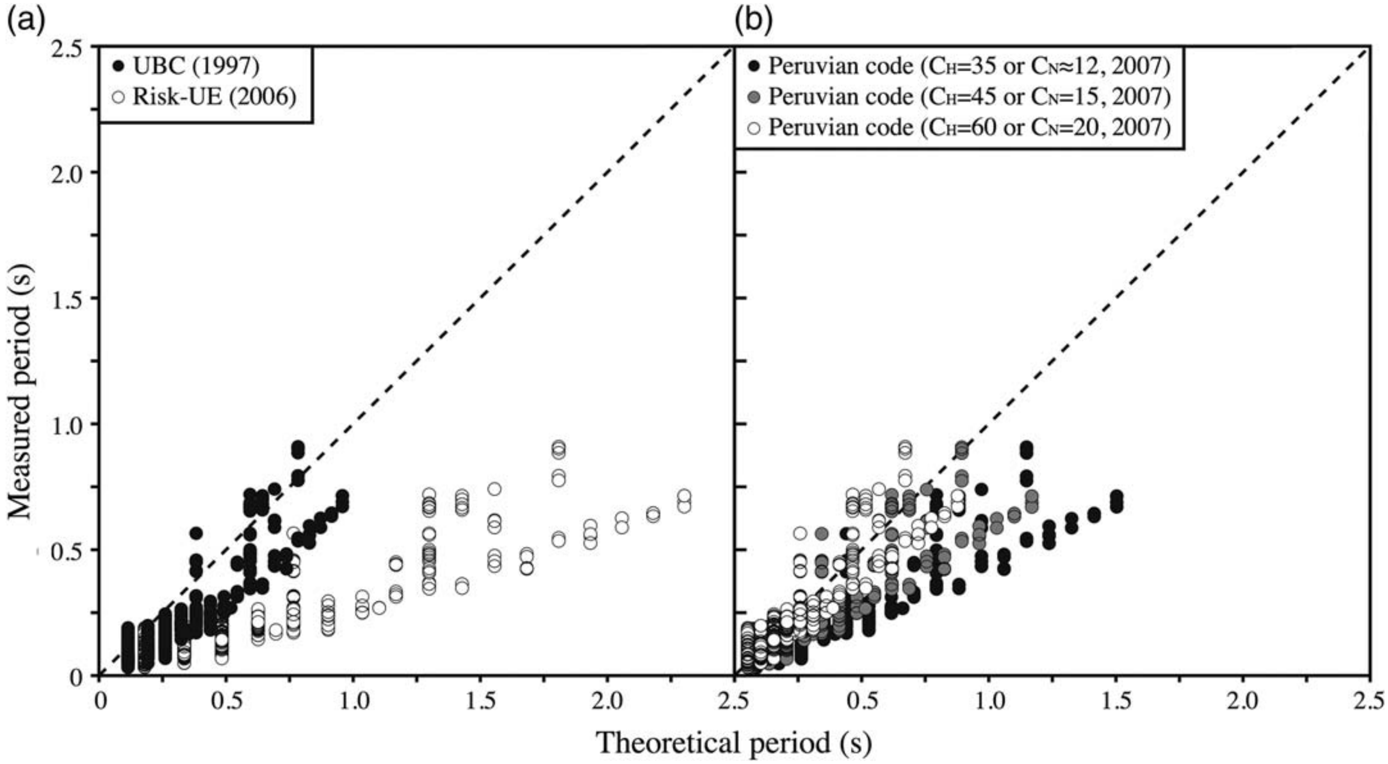
3. linear formulas, such formulas (1) and (2), promoted worldwide by Clive (1990) and Day (2001), used in the standard law in Japan (Building Standard Law of Japan [BSLJ], 2011; Ishikawa and Bradley 2012, with $C_N \approx 17$) or the Peruvian seismic code (E.030, 2007, with $C_N \approx 12$, 15, or 20, depending on the construction system).

Building periods calculated with UBC (Fig. 5a, filled circles) and Risk-UE (Fig. 5a, open circles) formulas do not fit the experimental data because (1) their period ranges are too small and (2) they systematically overestimate the experimental periods.

Good fits are obtained with the linear formula from the Peruvian code, with either of the constants: $C_N \approx 12$ (Fig. 5b, black filled circles), 15 (Fig. 5b, gray filled circles), or 20 (Fig. 5b, open circles), the best fit being obtained with $C_N = 20$.

EMPIRICAL FREQUENCY FORMULAS FROM MULTIPLE LINEAR REGRESSIONS

The five buildings for which the year of construction is unknown (representing 11 measurements) have been rejected from the data set leading to keep only 525 measurements. The data set is large enough to be statistically significant and be used to determine a simple linear relationship between the building periods and the number of floors by computing multiple regressions of the building periods as a function of the floor number using formula (2), as in Michel, Guéguen, Lestuzzi, *et al.* (2010).



▲ **Figure 5.** Building periods plotted as a function of (a) the theoretical periods modeled using formulas that take into account only the height of the building in a power-law function (UBC, Risk-UE) and (b) the Peruvian code. The dashed black lines indicate the 1:1 slopes.

When all buildings are taken into consideration (1050 T_0–N pairs), the following relationship is obtained (Table 1; Fig. 6a):

$$T_0 \approx \frac{N}{21}.$$

However, two crucial events occurred in 1974 that may have changed the behavior of Lima buildings: (1) the occurrence of the M_w 8.1 Lima earthquake and (2) the implementation of the first Peruvian seismic code, following this earthquake. It is therefore possible that the constant C_N is significantly influenced by the building construction year.

To test such a possibility, regressions between T_0 and N have been computed starting with 1–3 floor buildings, by increasing the number of floors by step of 1, on three data sets such as buildings of all ages, pre-1974 buildings, and post-1974 buildings.

Up to four floors, C_N is close to 24, for the three data sets, although it is changing when including buildings with five floors or more (Table 1; Fig. 6b,c).

For buildings with five floors or over, two formulas are obtained, with quite different C_N:

- for pre-1974 building (Fig. 6b), $T_0 = 0.0652N \approx N/15$ ($r^2 = 0.74$, r^2 is the coefficient of determination);
- for post-1974 buildings (Fig. 6c), $T_0 = 0.0412N \approx N/24$ ($r^2 = 0.99$, r^2 is the coefficient of determination).

DISCUSSION

When considering all buildings together (Fig. 6a), a value of $C_N = 21$ is obtained, close to the values found in Portugal ($C_N \approx 24$) by Oliveira (2004); in France ($C_N \approx 25$) by Michel, Guéguen, Lestuzzi, *et al.* (2010); and in Lebanon ($C_N \approx 25$) by Salameh *et al.* (2014).

Table 1
Values of C_N and r^2 (Coefficient of Determination) from Regression Analysis, for Different Heights of Buildings (Using the Formula $T_0 = N/C_N$) for All Buildings and Those Constructed Before and After 1974

	1–3 floors		1–4 floors		1–5 floors		1–6 floors		1–7 floors		1–8 floors		1–9 floors		All Data	
	C_N	r^2	C_N	r^2	C_N	r^2	C_N	r^2	C_N	r^2	C_N	r^2	C_N	r^2	C_N	r^2
All ages	23.8	0.466	23.5	0.596	19.8	0.630	21.6	0.621	23.1	0.625	22.6	0.669	20.0	0.763	20.6	0.840
Pre-1974	23.7	0.456	23.2	0.600	18.5	0.647	20.1	0.632	20.8	0.626	20.2	0.677	18.0	0.793	16.7	0.879
Post-1974	23.9	0.474	23.9	0.589	25.6	0.576	27.7	0.616	29.2	0.702	29.1	0.736	29.0	0.772	27.1	0.940

In the Lima case, when considering only low-rise buildings, $C_N = 24$ for both pre- and post-1974 structures, whereas for high-rise buildings C_N increases from 15 for pre-1974 structures (Fig. 6b) to 24 for post-1974 structures (Fig. 6c). Such a feature is not observed in the above-mentioned studies, in which no difference is made between low-rise and high-rise buildings as all data fit to a single curve.

In Lima, the low-rise buildings, whatever their age, fit to a unique curve with $C_N = 24$. It implies that pre-1974 low-rise buildings not only were not affected by the implementation of the seismic code but also were not impacted by the 1974 earthquake. The 1974 earthquake occurred about 90 km from Lima, far enough for the predominant periods of the radiated waves to be higher than that of the low-rise buildings (Seed *et al.*, 1969; Akkar *et al.*, 2011).

For high-rise buildings, the significant change of C_N from 15 for pre-1974 structures to 24 for post-1974 structures, indicating a stiffness increase, may be explained in two ways:

1. Pre-1974 high-rise buildings were constructed with $C_N = 15$ and low-rise buildings with $C_N = 24$. In such a case, (1) this is inconsistent with the single C_N value found by Oliveira (2004), Michel, Guéguen, Lestuzzi, *et al.* (2010), and Salameh *et al.* (2014) for both types of buildings, (2) the difference cannot be explained, as at the time there was no building code, and thus the constructive system was identical for both types of buildings. Moreover, it would imply that the buildings have not been affected, neither by aging nor by earthquakes, including the 1974 event, and thus they would still be able to sustain a 30%–35% loss of frequency before entering into a hazardous frequency domain (Dunand *et al.*, 2004, 2006).
2. The pre-1974 high-rise buildings have been impacted by the 1974 Lima earthquake, which caused sufficient internal damages to induce an increase of their fundamental period (Dunand *et al.*, 2004, 2006), thus explaining the decrease of C_N from an unknown value down to 15. As mentioned in the previous section, all pre-1974 buildings would fit on a line with $C_N = 24$, leading to evaluate the frequency loss due to the 1974 earthquake to about 35%–40%, thus ranking most pre-1974 high-rise building in a hazardous frequency domain.

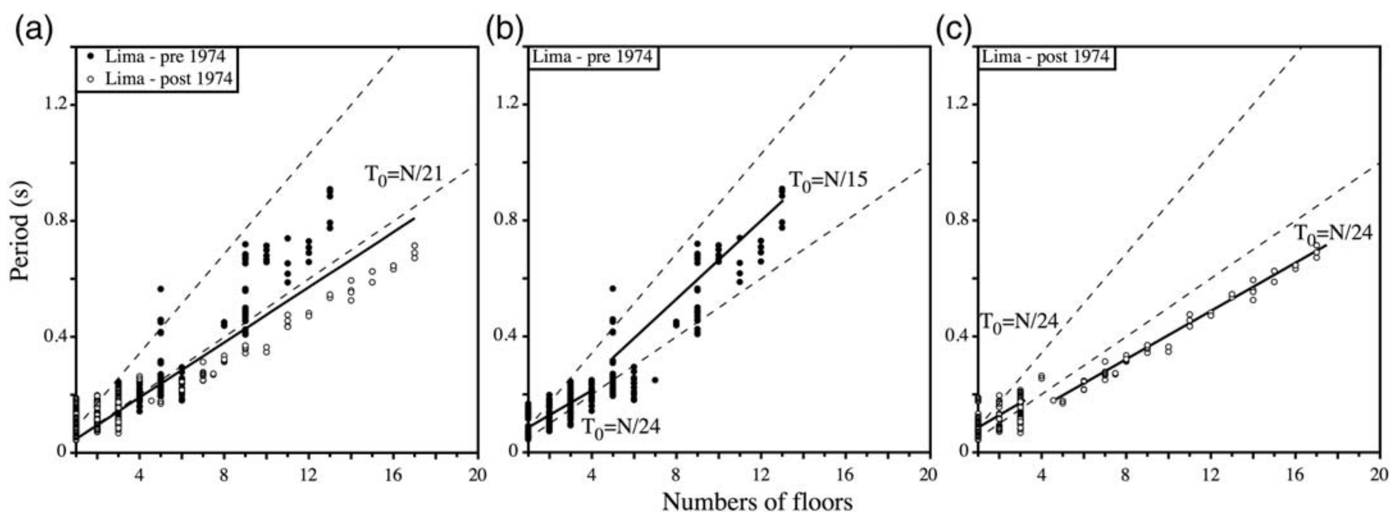
For the post-1974 buildings, two parallel lines are obtained with $C_N = 24$ (Fig. 6c), the high-rise building curve being located underneath the low-rise building curve. This can be explained by the implementation of the Peruvian seismic code, ruling only buildings over 15 m (i.e., five floors), which application had the effect of stiffening the high-rise buildings.

CONCLUSION

The study of 344 Lima RC in-filled framed buildings using ambient vibrations, with a total set of 1072 fundamental periods, allowed us to point out that, statistically, the elastic fundamental resonance period is only dependent on building height, and the horizontal dimensions (length and width) are not playing any significant role.

Three relationships have been defined associating the Lima building periods (T_0) to the number of floors (N), depending both on the construction date and the height of the buildings:

- $T_0 \approx N/24$, for buildings less than five floors whatever the year of construction.
- $T_0 \approx N/15$, for buildings with five floors or more built before 1974.
- $T_0 \approx N/24$, for buildings with five floors or more built after 1974.



▲ **Figure 6.** Lima reinforced concrete (RC) filled frame building fundamental periods versus the number of floors (N). (a) Pre-1974 (filled circles) and post-1974 (open circles) buildings taken as a whole. (b) Pre-1974 buildings. (c) Post-1974 buildings. The solid lines represent the linear regressions. The dashed curves show the periods obtained using the actual Peruvian seismic code (E.030, 2007) when applying formula (2), with $C_N = 12$ (upper curve), and $C_N = 20$ (lower curve).

Even if this type of relationship gives only a rough estimate of the building fundamental periods, they may be the only available estimation for vulnerability assessment, especially in large urban areas such as Lima. The homogeneity of the formula for low-rise buildings whatever their age ($C_N = 24$) suggests (1) a continuity in the construction methods used before and after the application of the Peruvian code for buildings lower than five floors and (2) that the initial relationship between period and number of floors was about $T_0 \approx N/24$. We also show that those low-rise buildings have not been significantly affected by the 1974 earthquake. For buildings higher than four floors, two different formulas are obtained depending on the building year of construction, namely before and after 1974. That very year, two crucial events occurred that could be incriminated to have somewhat changed the Lima building behavior: (1) the M_w 8.1 Lima earthquake and (2) the implementation of the first Peruvian seismic code. The 1974 earthquake probably caused a 35%–40% decrease in the building stiffness for buildings higher than four floors, bringing those buildings into a hazardous period range. When the Peruvian seismic code was applied, it resulted in an increase in stiffness of the high-rise buildings.

More buildings should be surveyed outside of the zone impacted by the 1974 earthquake to determine precisely the origin of the difference between the pre-1974 and post-1974 building behavior. Depending on the origin of this difference, some very important Lima buildings can actually be damaged and reach critical operation conditions in term of safety, and thus, some very important hospitals could be subject to early collapse in case of a significant earthquake occurring close to Lima. Moreover, this study underlines the importance of establishing, in seismic zones, a reference state of the urban built to assess the impact of an earthquake on the whole city (Heaton, 2014) and especially for buildings of strategic importance such as the hospitals studied here.

To check the state of pre-1974 buildings, studies should be carried out in areas that have not been impacted by the 1974 Lima earthquake to evaluate the initial C_N constant. Such studies should also be launched in northern and eastern Peru, which have not been impacted by any significant earthquake, to check if no changes are observed in the building periods over time. Also, as the center-south of Peru has been impacted both by the 1996 M_w 7.7 Nazca earthquake (e.g., Chatelain *et al.*, 1997) and by the 2007 M_w 8.0 Pisco earthquake (e.g., Perfettini *et al.*, 2010), whereas southern Peru has been impacted by the 2001 M_w 8.4 Arequipa earthquake (e.g., Tavera *et al.*, 2006), a study should be conducted to evaluate the pre- and postevent building behaviors in each of these zones.

This is the first time that the impact of both an earthquake on the frequency behavior of a building population and the establishment of a seismic code is demonstrated.

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Bertrand Guillier
Jean-Luc Chatelain
Hugo Perfettini
Institut de Recherche pour le Développement ISTerre
BP 53
38041 Grenoble, France
bertrand.guillier@ird.fr

Hernando Tavera
Angel Ochoa
Bilha Herrera
Instituto Geofísico del Perú
Calle Badajoz #169
Ate Vitarte, Lima 3, Peru

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