Estimate of fundamental period of reinforced concrete buildings: code provisions vs. experimental measures in Victoria and Vancouver (BC, Canada)

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ABSTRACT

The fundamental period of a group of reinforced concrete (RC) buildings located in the cities of Victoria and Vancouver (British Columbia, Canada) has been estimated using ambient vibration data. As result a preliminary height-dependent relationship has been derived for a fully elastic condition. The regression returns very similar values respect to those obtained in other countries using the system identification technique based on ambient vibrations. As expected, the results show that building periods estimated based on simple equations provided by earthquake design codes in Europe (EC8) and North America (UBC97 and NBCC-2005) are significantly greater than the periods computed using ambient vibration records on the monitored buildings.

Keywords: fundamental period, reinforced concrete buildings, ambient vibration, Canadian buildings, code

1. INTRODUCTION

In the framework of seismic risk assessment and mitigation the estimation of fundamental period of buildings is an important issue both for design of new buildings and performance assessment of existing ones.
Depending on mass and stiffness, the fundamental period is a global characteristic describing the behaviour of building under seismic loads. For this reason, it is easily and directly usable to determinate the global demands on a structure due to a given seismic input. Moreover, the estimation of fundamental period of buildings is useful to identify possible resonance phenomena between buildings and soil vibration.
The vibration period of reinforced concrete (RC) buildings is affected by many factors such as structural regularity, number of storeys and bays, dimensions of member sections, infill panel properties and position, load levels, etc. For these reasons, a reliable estimation of the fundamental period of buildings is not easy to carry out and, both in the design of new buildings or in the assessment of existing ones, it is not a priori known (i.e. before analysing the structural model at hand).
To address this issue, several earthquake design codes provide formula in order to estimate the fundamental period of buildings starting from their typological characteristics such as height, framing system and material type. Traditionally the expressions provided worldwide by seismic codes have been obtained by regression analysis of values estimated using both numerical and empirical approaches. The most common expressions available worldwide have been obtained on the basis of vibration data recorded during past earthquakes. Usually, they are height-depend relationships setting up considering the total height of buildings or their number of storeys. Furthermore, other studies have been recently carried out on the basis both of numerical approaches particularly with respect to existing RC buildings.
At this point, the available code, experimental and numerical expressions, for the same structural system and building height, return different results for the vibration period of studied buildings. This discrepancy increases especially when values from code relationships are compared with those obtained by numerical analyses and, even more, when they are compared with those provided by in-situ experimental measurements. The reasons for these differences have been investigated by many researchers in the past.

2. STATEMENT OF THE PROBLEM

During the past years, empirical, semi-empirical and numerical relationships have been proposed in order to estimate the fundamental period of RC buildings starting from their height and structural type. In the Applied Technological Council of 1978 (ATC3-06, 1978) a semi-empirical expression was employed to estimate the fundamental period of RC buildings based on their height. The expression had the form $T = C_t\, H^{0.75}$ where C_t is taken to be 0.03 for RC moment-resisting frames and H represents the building height measured in feet. The mathematical functional ($T=\alpha H^{\beta}$) of this formulation was theoretically derived using the Rayleigh's method considering the horizontal forces linearly distributed along the height, the mass distribution constant along the height, the linearity of deformed shape and the base shear proportional to $1/T^{2/3}$. This expression, or slight variations of it, was been subsequently adopted by the Uniform Building Code (UBC, 1997), the European seismic design regulation, Eurocode 8 (CEN, 2004), and the National Building Code of Canada (NBCC, 2005) for moment resisting frames. The difference is about the coefficient C_t that has been conveniently adapted from feet to meters ($C_t \approx 0.075$) in the European and Canadian versions.

The formulation adopted by the main building regulations is a semi-empirical expression because the numerical value of constant C_t has been obtained through the regression of vibration data measured on a set of buildings during the 1971 San Fernando earthquake. Starting from this expression, Goel & Chopra (1997) obtained equal results collecting earthquake recording data measured from eight Californian earthquakes (e.g., 1971 San Fernando earthquake, 1994 Northridge earthquake, etc.). Specifically, 37 RC Californian buildings, having height between 10 and 100 meters, were monitored during the eight earthquakes. Of those, 22 buildings experienced peak ground accelerations (PGA) up to 0.15g while 15 buildings experienced values of PGA>0.15g. The estimated values of fundamental periods of monitored buildings are comparable with those provided by the UBC97 formulation. This is not a surprise because the sample used to set up the height-based relationship provided in the UBC-97 (1971 San Fernando earthquake) is a subsample of Goel & Chopra (1997) dataset. The formulation adopted in the UBC-97 code takes into account only the material (i.e., RC buildings), the structural type (i.e., buildings with RC frames) and primarily the height of the buildings.

Furthermore other structural characteristics such as the presence, position and consistence of infill walls that, varying mass and in particular stiffness, could influence the dynamic behaviour of building under seismic loads, are not taken into account.

In order to understand the influence of the other building characteristics on the estimation of fundamental period, Kose (2009) has shown that, in case of RC frame buildings, height takes into account the most part of variance with respect to in-plan regularity, infills and shear walls distribution. Moreover, on the bases of several numerical analyses of typical RC buildings, the author has demonstrated also that the current code equations under-predict the fundamental period values with respect to those provided by the numerical models with differences depending upon the model parameters. Before the work of Kose (2009), other studies have been carried out using numerical approaches in order to achieve simple and reliable expressions to estimate the fundamental period of RC frame buildings both with (Infilled Frame, IF) and without (Bare Frame, BF) the contributions of infill walls. Figure 1 illustrates the results obtained by two different research groups (Crowley and Pinho 2004, Masi and Vona 2008) using the best-fit regression of vibration data numerically provided for existing typical RC buildings under seismic loads. Figure 1 shows that the values provided using code provisions are lower than those obtained by numerical simulations - especially when RC building with bare frames (i.e. without effective infills) are considered. In fact, there are several differences when, for the buildings with same height, the influence of infilled walls is, or is not, considered.

In the structural analysis of RC buildings not all the components able to influence mass and stiffness are generally considered in the model as, for example the stiffness of non-structural elements.. Then, a relationship based on in-situ experimental measurements could be a good alternative approach to estimate the fundamental vibration frequency of buildings on the basis of a single measure suitable to include the contributions of all the structural characteristics on the shaking of RC buildings. For this reason, some authors are collecting building vibration data, both due to earthquake and ambient shaking, in order to set up empirical formula to estimate the fundamental period of RC buildings. For example, Hong & Hwang (2000), analyzing vibration data collected on 21 RC buildings, obtained values of fundamental periods lower than those provided by codes and/or Goel & Chopra (1997) provisions (Figure 2). The buildings studied by Hong & Hwang (2000), designed using the UBC-97 code, experienced shaking during four moderate earthquakes and then the expected behaviour in term of fundamental periods should be similar to that proposed by the code ($T=0.075*H^{0.75}$, H in meters). Despite this, the height-dependent shape of fundamental period respect to building height, as shown in Figure 2, returns values significantly lower respect to expected ones.

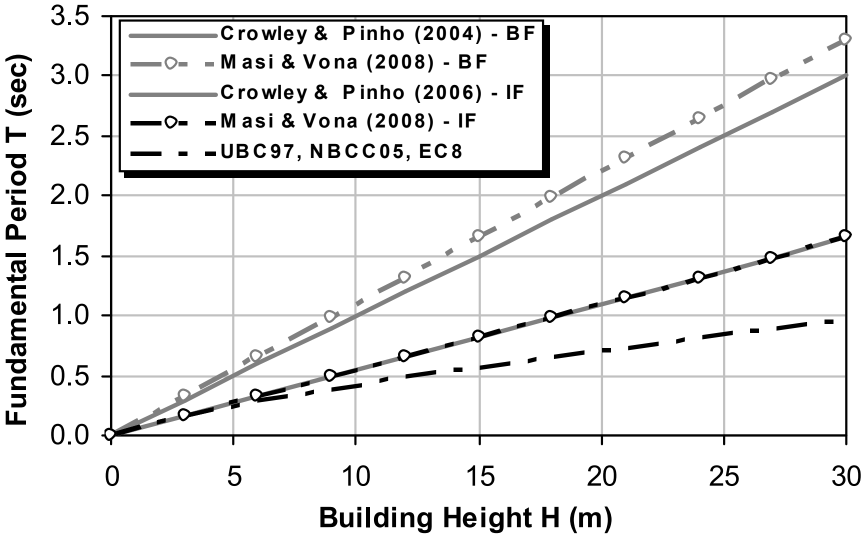

Figure 1 Estimation of fundamental period of RC buildings having frames with (IF, Infilled Frame) and without (BF, Bare Frame) infills walls. Comparison with Code (UBC97, NBCC05, EC8) previsions.

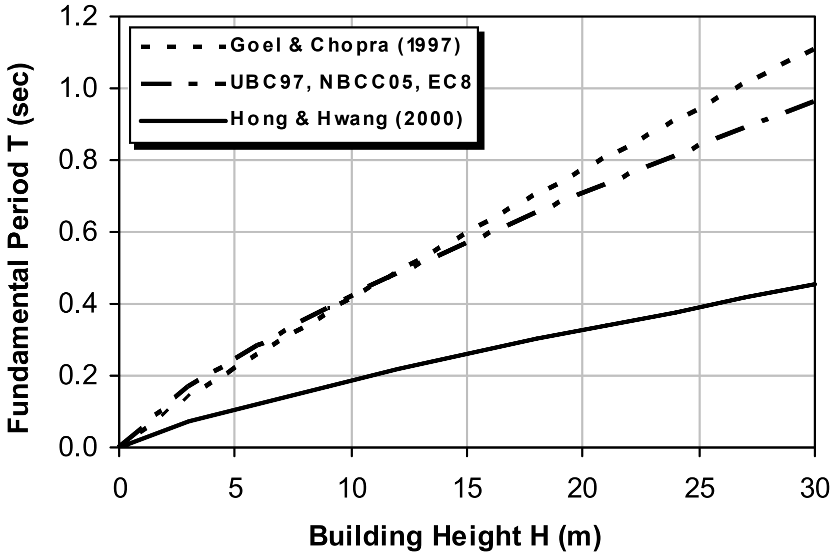

Figure 2. Comparison between Code, Goel & Chopra (1997) and Hong & Hwang (2000) formulations of fundamental period of RC buildings.

Starting from these considerations, many authors, prevalently in the European countries, monitored RC buildings using ambient vibrations. On the basis of recorded data they concluded that the obtained results appear in strong contrast with those provided by numerical and code formulations. On the contrary, the obtained results are close to those provided by Hong & Hwang's (2000) formulation. For example, Gallipoli *et al.* (2010), estimating the fundamental period of about 250 RC buildings with frame structure located in Italy, Slovenia, Croatia and the Republic of Macedonia found values smaller than those provided using code equations (i.e., $T=0.075*H^{0.75}$) and/or numerical simulations (e.g., T=0.055H for cracked infilled RC buildings, Crowley & Pihno, 2006). The comparison of these results with other studies (e.g., Olivera & Navarro, 2009; Hong & Hwang, 2000) shows that the agreement among empirical estimations using ambient noise data is very good (Figure 3) and it is different to both code and Goel & Chopra (1997) previsions.

In this paper a preliminary study to determine the results obtained by in-situ ambient vibration measurements carried out on typical RC buildings located in the west coast of Canada has been reported. The code equation to estimate fundamental periods of the monitored RC buildings in Canada is given by $T=0.075*H^{0.75}$ (NBCC-2005), that is the same equation provided in the United States and in European codes.

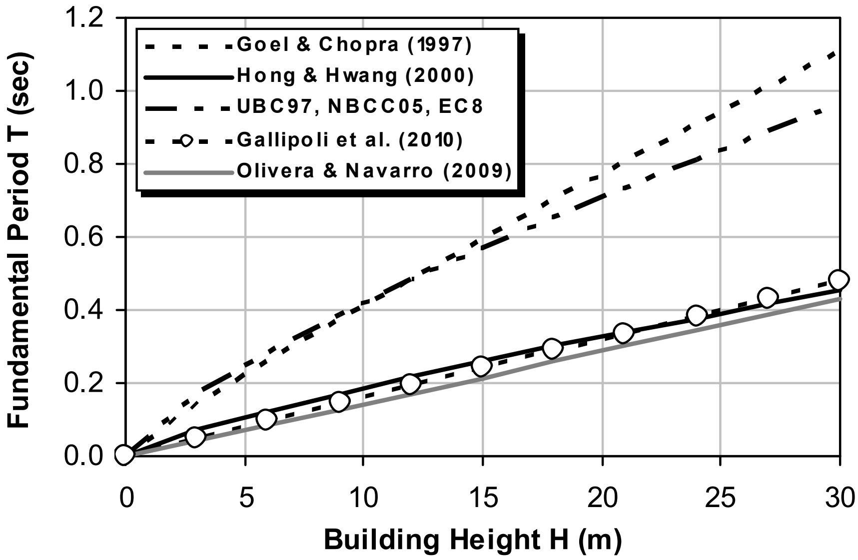

Figure 3. Comparison between Code, Goel & Chopra (1997) and the results of empirical studies based on ambient vibration measurements.

3. MEASUREMENTS ON CANADIAN REINFORCED CONCRETE BUILDINGS

The measurement of ambient vibrations has been carried out on twelve RC buildings on the west coast of Canada. Nine of them are located in Victoria and three in Vancouver (both major cities in British Columbia). These buildings range from four to nineteen storeys, and considering the respective interstorey height, the range of building height is between 12 and 70 meters (Table 1).

Table 1. Measured RC frame buildings in Victoria and Vancouver (BC, Canada). The superscript 1 indicates the buildings located in the city of Victoria while the superscript 2 indicates the buildings in Vancouver. ERD = earthquake resistant design as per building codes.

Name of Building	Age of Building	N. of Storeys	Height (m)	Seismic Design
BC Geological Survey[1]	1992-1994	10	34	ERD
Victoria Public Library[1]	1975-1977	8	28	ERD
Law Courts[1]	1990-1997	7	25	ERD
Pacific Forestry Centre[1]	1964-1965	4	14	NO ERD
Reef Hotel[1]	2004	8	24	ERD
Executive House Hotel[1]	1970-1975	18	47	ERD
Marriott Hotel[1]	2004	18	52	ERD
Target Self Storage[1]	1950	4	12	NO ERD
University of Victoria[1]	2008	6	20	ERD
Student House[2]	Post-2000	19	50	ERD
Hampton Inn Hotel[2]	Post-2000	19	70	ERD
Holiday Inn & Suite[2]	1998-2000	6	16	ERD

Buildings in British Columbia have typically shear walls in the central core of the building and perimeter gravity load columns, all connected by flat RC slabs. The external cladding consists of glass only or walls with very large windows. Inside the buildings the partitions are made of generally light materials but it is common (especially in the older buildings) to also find strong walls (e.g., reinforced or unreinforced concrete block). As an example of monitored buildings, in Figures 4 and 5 two of them, placed respectively in Victoria and Vancouver, are shown.

For each building, measurements were taken at three points: 1) near the top of building with a location more possible near the external beams and/or structural elements, 2) on the basement of building considering the vertical projection of the measurement point on the roof and 3) in the free field around the building. The measurements have been carried out between the 30th of July and the 4th of August, 2010. All measurements have been performed with the same equipment (Micromed Tromino, http://www.tromino.eu/index.asp?lng=1), a digital tri-directional tromometer, which is a high-resolution seismometer whose 24-bit dynamic is aimed at the very low amplitude range. Seismic noise was sampled for 12 minutes at each site using a survey frequency of 128 Hz. The measurements have been carried out with the instrumental axes orientated with the main directions of buildings. Particularly, the North-South direction has been placed accordingly with the longest in-plan dimension of buildings (named longitudinal direction), while the East-West direction has been placed along the orthogonal side (named the transversal direction).

4. DATA ANALYSIS AND RESULTS

Using ambient vibration signals recorded near the highest level of buildings, fundamental period values have been estimated applying the Horizontal to Vertical Spectral Ratio (HVSR) technique. In fact, according to Castro *et al.* (1998), HVSR technique can provide an estimate of the fundamental frequency of a structure using the ratio between the amplitude of the Fourier spectra of horizontal and vertical components recorded on the highest level of structures. Using this technique, the vibration frequency of fundamental mode of monitored buildings corresponds to the frequency at the maximum amplitude of HVSR shape. The HVSR values have been calculated by averaging the H on V obtained by dividing the signal into non-overlapping windows of 30 seconds. Each window was de-trended, tapered, padded, FF-Transformed and smoothed with triangular windows with a width equal to 10% of the central frequency. For each HVSR curve the relative average $\pm 1\sigma$ confidence interval is given.

Figures 4 and 5 show, for two typical monitored buildings (located in Victoria and Vancouver, respectively), the HVSR shapes for the two main in-plan directions. Table 2 reports the fundamental period values of the monitored RC buildings estimated with the HVSR technique using the ambient data recorded near the highest level of the structures.

Table 2. Fundamental period of surveyed buildings computed using HVSR method. Longitudinal direction (Long.) is the longest in-plan dimension of the building, while transversal (Trans.) is perpendicular to that. The superscript 1 indicates the buildings located in the city of Victoria while the superscript 2 indicates the buildings in Vancouver.

Buildings					Period (sec) – HVSR	
#	**Name**	**Age**	**# of Storeys**	**Height (m)**	**Long.**	**Trans.**
N.1	BC Geological Survey[1]	1992-1994	10	34	0.49	0.48
N.2	Victoria Public Library[1]	1975-1977	8	28	0.42	0.28
N.3	Law Courts[1]	1990-1997	7	25	0.41	0.32
N.4	Pacific Forestry Centre[1]	1964-1965	4	14	0.23	0.28
N.5	Reef Hotel[1]	2004	8	24	0.28	0.23
N.6	Executive House Hotel[1]	1970-1975	18	47	0.92	1.14
N.7	Marriott Hotel[1]	2004	18	52	0.59	0.59
N.8	Target Self Storage[1]	1950	4	12	0.18	0.27
N.9	University of Victoria[1]	2008	6	20	0.32	0.28
N.10	Student House[2]	Post-2000	19	50	0.86	0.86
N.11	Hampton Inn Hotel[2]	Post-2000	19	70	0.80	0.60
N.12	Holiday Inn & Suite[2]	1998-2000	6	16	0.35	0.30

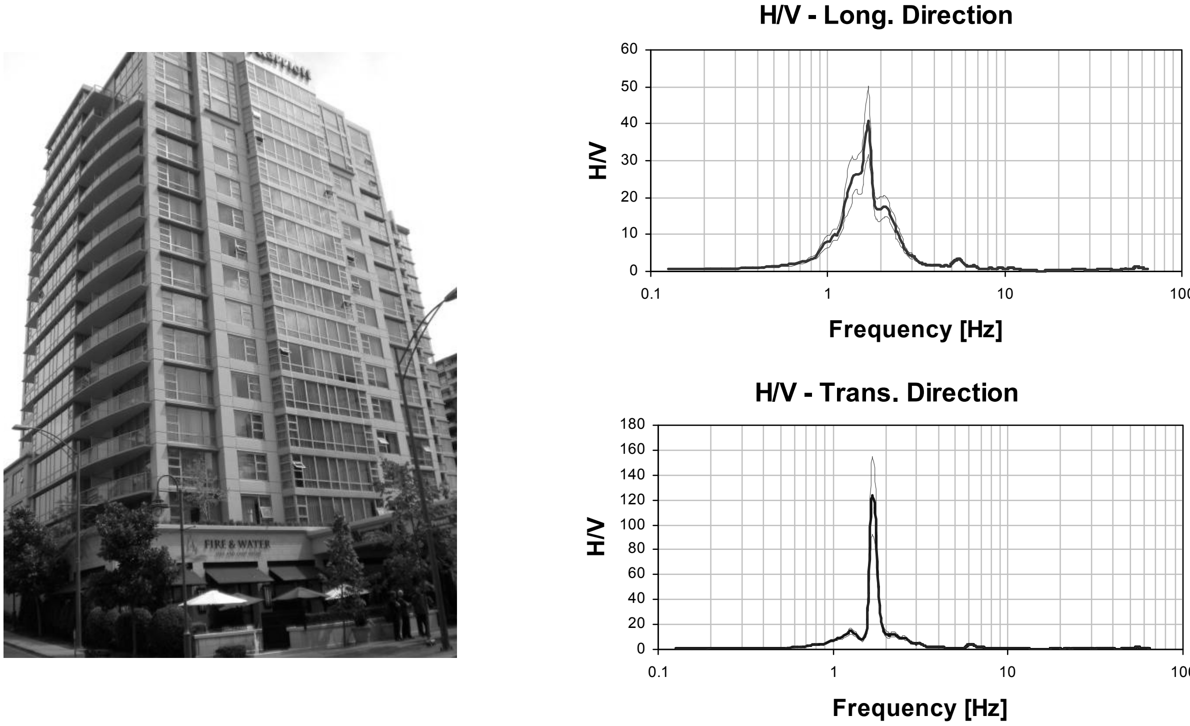

Figure 4. On the left: Marriott Hotel in Victoria. On the right: HVSR curves for the ambient vibration signals recorded on the longitudinal (Long) and transversal (Trans) direction of monitored building as a function of the vibration frequency. The mean value of H/V has been reported with ± 1σ (standard deviation).

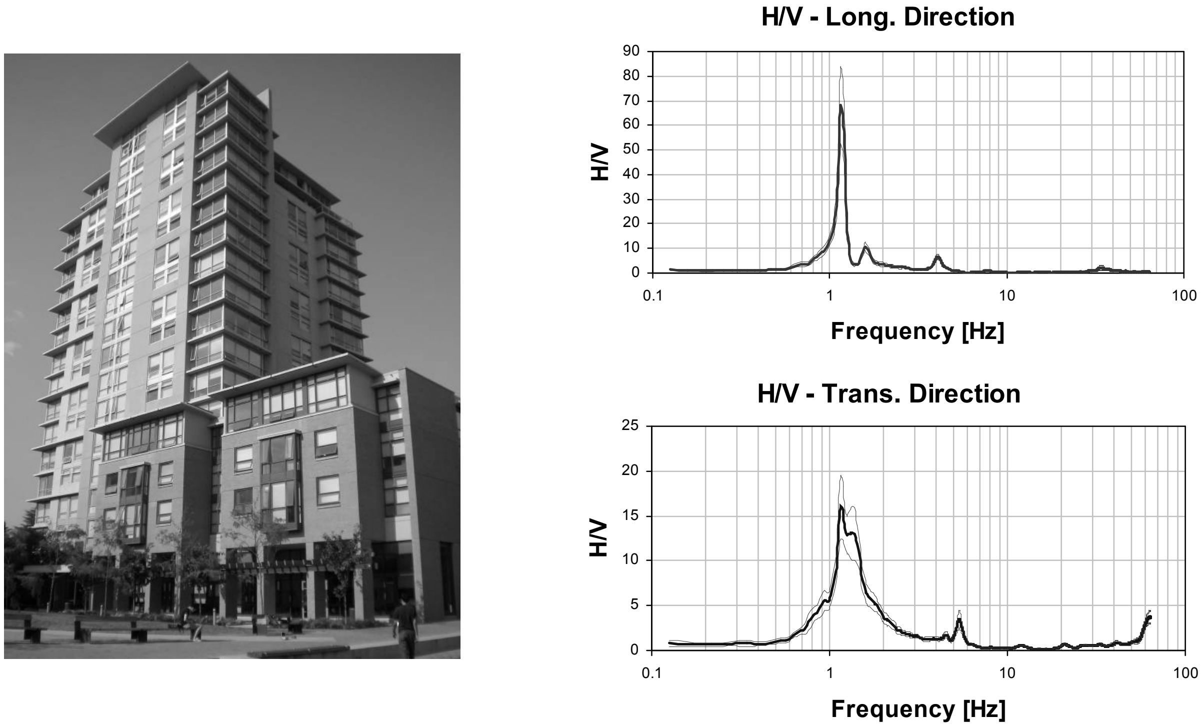

Figure 5. On the left: Student House in Vancouver. On the right: HVSR curves for the ambient vibration signals recorded on the longitudinal (Long) and transversal (Trans) direction of monitored building as a function of the vibration frequency. The mean value of H/V has been reported with ± 1σ (standard deviation).

Comparing HVSR values with results provided applying other techniques Gallipoli *et al.* (2009) found a good agreement among them. Following this approach, we also consider the Horizontal to Horizontal Spectral Ratio (HHSR) technique, using both the ambient vibration signals recorded near the highest level and on the basement of buildings, to estimate the fundamental period.

Where available, we have also computed ratios using the ambient vibrations recorded in the free-field of monitored buildings. In Figure 6 the results provided by HVSR technique have been compared with those obtained using the HHSR technique applied both using basement (on the left) and free-field (on the right) ambient vibration signals.

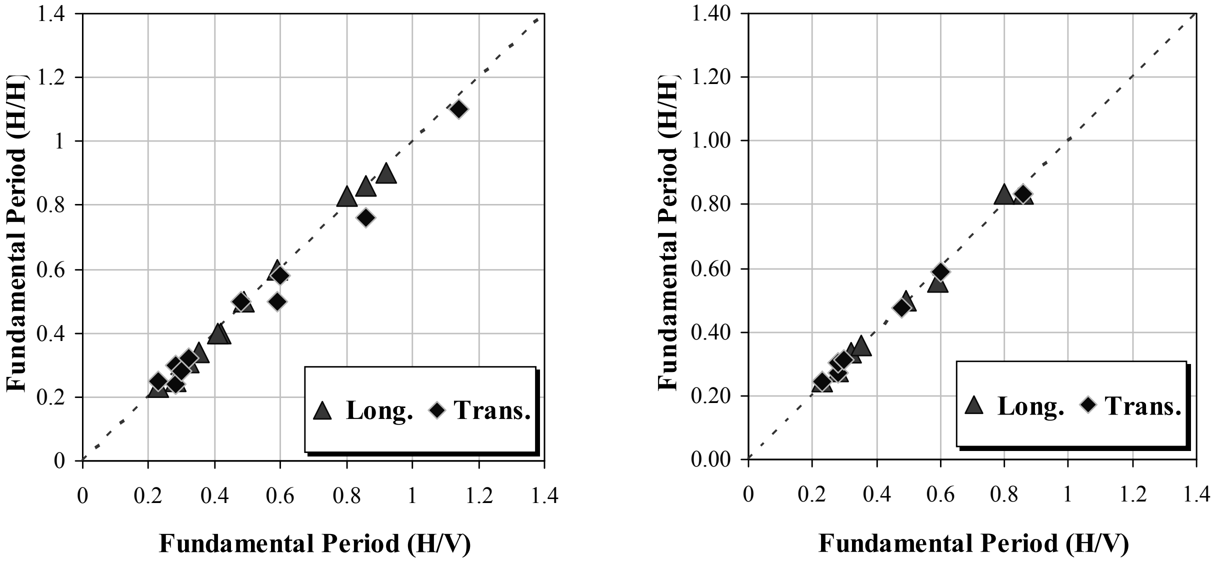

Figure 6. On the left: comparison between the fundamental periods estimated from HVSR and HHSR (measure on the basement) techniques for the two orthogonal directions (see text for details). On the right: comparison between the fundamental periods estimated from HVSR and HHSR (measure on free-field) techniques for the two orthogonal directions (see text for details).

As can be seen, the estimation of fundamental periods using the different techniques returns substantially coincident results. Further, using the higher of the two period values evaluated on the orthogonal components (computed using HVSR method) a preliminary height-dependent relationship for Canadian RC buildings has been set up for a fully elastic condition: $T=0.037*H^{0.76}$, with a regression coefficient R=0.88 (see Figure 7).

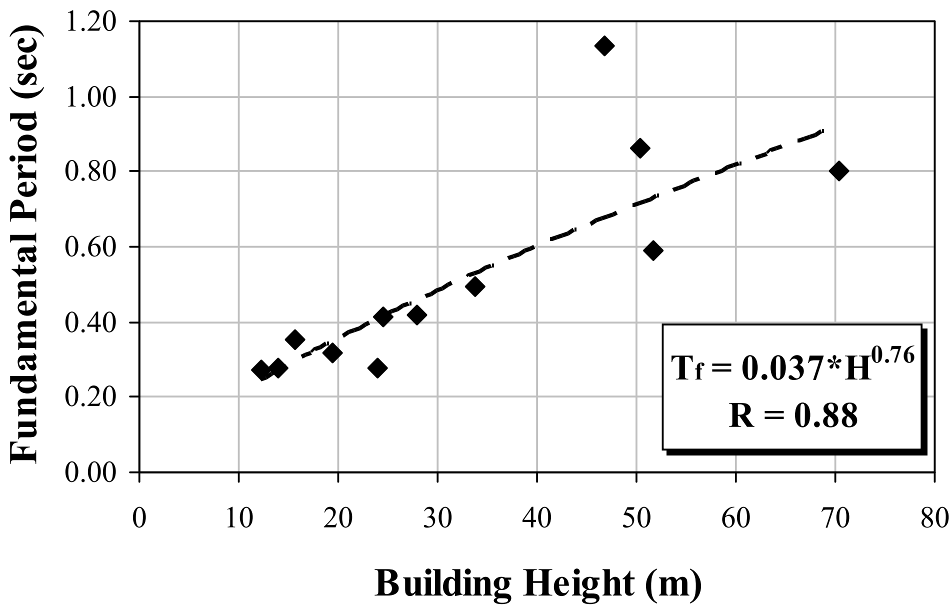

Figure 7. Fundamental period of monitored buildings as a function of their height (single values and their regression).

5. COMPARISONS WITH LITERATURE STUDIES AND CODE PROVISIONS

Figure 8 shows the comparison between the building vibration data recorded on the monitored RC Canadian buildings with those provided by Goel & Chopra (1997), code provisions (EC8, UBC97 and NBCC2005) and Hong & Hwang (2000).

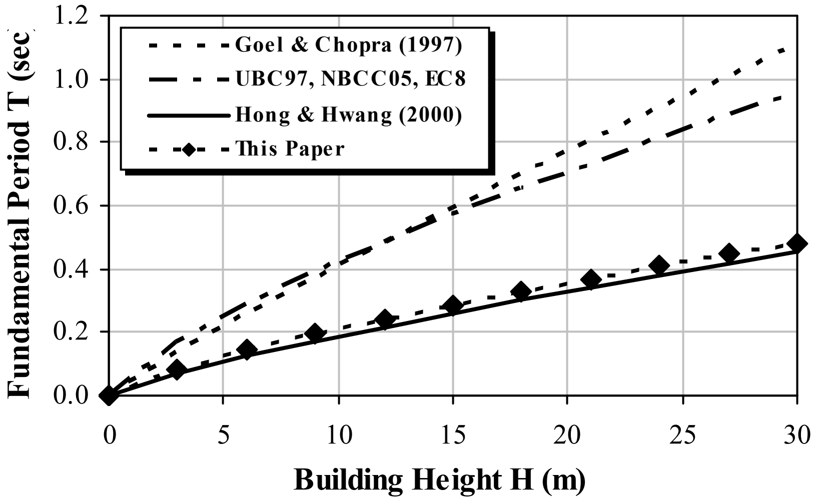

Figure 8. Comparison between Code, Goel & Chopra (1997), Hong and Hwang (2000) formulations with the regression obtained from the analysis of Canadian data (this paper).

The comparison shows a very good agreement between the fundamental periods measured on the Canadian buildings and the expression proposed by Hong & Hwang (2000). Similarly, in Figure 9 the regression obtained analyzing the Canadian data and the experimental estimations for RC buildings reported in Gallipoli *et al.* (2010) have been compared. Agreement among the empirical estimates (including the new results from Canada) is very good. However, if these results are compared with those obtained using code equations ($T=0.075*H^{0.75}$ - the same in Europe, US and Canada) or numerical formulations, it can be clearly observed that the code-based periods, and even more the numerical ones, are higher than the values obtained by ambient vibration data. At least a part of this difference can be attributed to the comparison of results obtained from weak shaking levels (ambient noise) and those obtained using stronger earthquake shaking (code values).

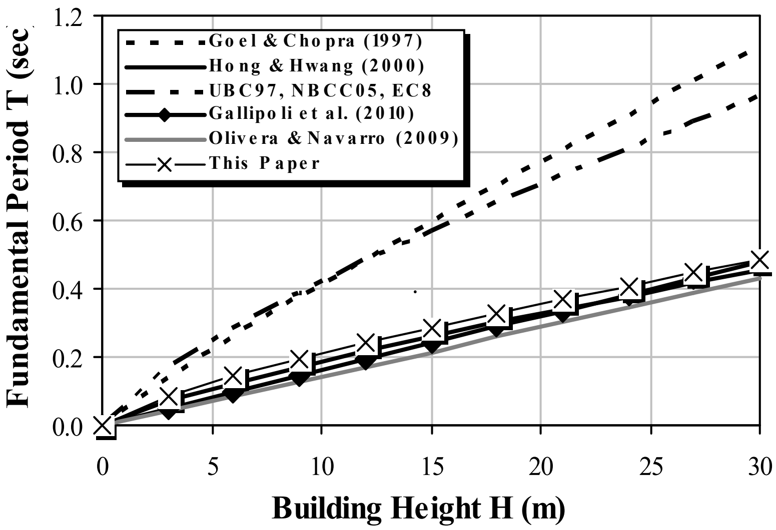

Figure 9. Comparison among period-height relationships. The empirical values based on ambient noise vibration are selected from Gallipoli *et al.* (2010), Oliveira & Navarro (2009) and BC Canada (this paper). The empirical values based on earthquake vibration are derived from Goel & Chopra (1997) and Hong & Hwang (2000). The theoretical relationships are the provision from EuroCode 8 (equal to UBC and NBCC2005).

6. CONCLUDING REMARKS

Worldwide, several design codes provide simple formulations to estimate the fundamental period of buildings starting from their main characteristics, such us material type, structural system and building height. Particularly for reinforced concrete (RC) frame buildings, previous studies demonstrated as code values are frequently in strong contrast with those estimated through in-situ ambient noise measurements. Because many of these studies are based on data collected on RC buildings placed in the European countries, this paper focuses on twelve RC buildings, located in the cities of Victoria and Vancouver (British Columbia, Canada), carrying out a field campaign to estimate their fundamental periods using in-situ ambient vibration measurements.

Results show that empirical measures are very similar to those obtained from RC structures located in other countries confirming that the fundamental periods obtained from weak-motion ambient noise data are substantially lower than those achieved using building-code expressions or numerical estimations. On one side, such differences can be partially explained considering that building code values are based on stronger shaking levels thus larger values of fundamental building periods can be expected (Celebi, 2009). On the other hand, such differences confirms that not all the components able to influence mass and stiffness are generally considered in the numerical models as, for example, the role of non-structural elements. This article, as those already published by other authors, suggest that further efforts are still required to better understand amount and causes of the large differences found between fundamental periods estimated at low shaking levels and stronger shaking levels. To this end, a more accurate and comprehensive consideration of the contribution of all building characteristics is needed.

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