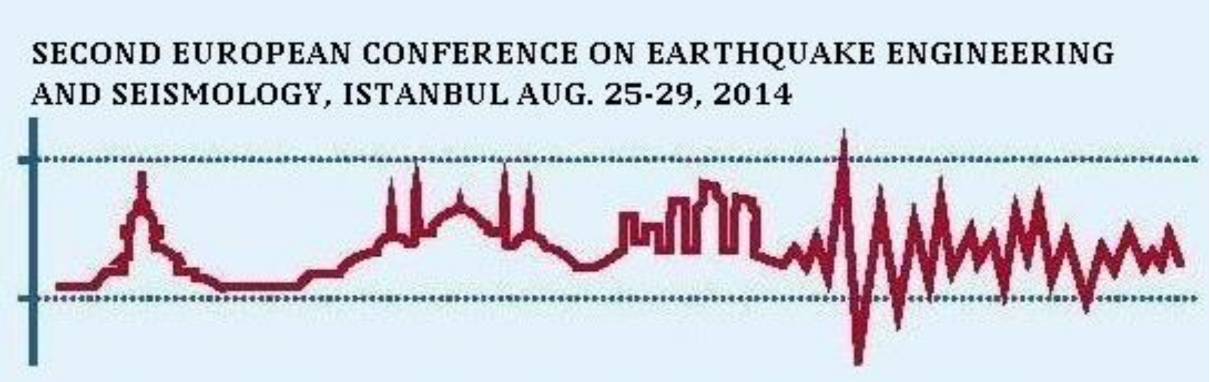

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DYNAMIC PROPERTIES OF BEIRUT BUILDINGS: INSTRUMENTAL RESULTS FROM AMBIENT VIBRATIONS

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ABSTRACT

The Beirut (Lebanon) area is exposed to a high seismic hazard because of its location close to major faults (Yammouneh, Roum, Hasbaya, Rachaya and Serghaya). The lack, until very recently, of enforcement of a building code together with the concentration of population, politic and economic activities, and the consequences of the civil war on buildings, transform this high hazard into a very high risk. It is therefore mandatory to assess the level of hazard and vulnerability, in view of shaping a policy to stabilize and eventually reduce the risk. Besides investigations to identify the local hazard (Brax, 2013), and considering the peculiarities of the Beirut building stock weakened by a long civil war, it has been decided to investigate whether the dynamic properties of Beirut buildings exhibit special characteristics as compared to other cities of the Mediterranean area.

An ambient vibration measurement campaign has been carried out for a set of 303 buildings ranging from 2 to 33 stories. Most of them are reinforced concrete frames, 182 are located on rock and 121 on soft soils. The recordings are basically 15 minutes long and have been processed using the Geopsy software, to extract the natural frequencies and the corresponding damping values. A statistical analysis was then performed to identify correlations between these dynamic parameters and the geometrical characteristics of the buildings, and to compare them with existing relations. The results show that the key parameter controlling the fundamental frequency is the building height (or number of floors), while horizontal dimensions of the building have an only marginal influence. A comparison between the two groups of measurements in rocky and soft soil highlights slightly different, but statistically meaningful, correlations between the natural period T and number of floors N (T=N/23 for rock sites and N/18 for soft sites).

A comparison between the measured frequencies and those computed from conventional formulas recommended in classical building codes exhibits very significant differences: the latter lead to an about 80% overestimation of the actually measured periods, while the measured damping exhibits a striking correlation with the frequency (the higher the building the lower the damping, with typical values around 1% for 2 Hz / 12 story buildings and around 5% for 6-8 Hz / 3-4 story buildings). These results are very consistent with conclusions drawn from similar measurements in other areas. Part of the large differences with building code recommendations may be due to the very

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low level of excitation; they seem too large however to be consistent with the (limited) frequency shifts for severely damaged buildings.

Keywords: Ambient vibration, Dynamic parameters, Seismic code, Beirut buildings, Period, Risk, Hazard

INTRODUCTION

The main objective of seismic regulations is to prevent loss of life and reduce property damage due to earthquakes. Generally, in most seismic codes, the assessment of design seismic forces is the result of identifying dynamic parameters, such as the natural period of structure, damping and mode shapes: frequencies and damping of a structure will indeed control the amplitude, phase, and the duration of its response to an earthquake, as pointed out by Housner and Brady (1963): "The natural period of vibration is the single most informative fact about the internal structure of buildings." As outlined by Michel (2007), these parameters are directly related to its internal structure. The mode shapes indicate the distribution of deformation in the structure during the earthquake. "Two structures having the same distribution of mass and the same fundamental period may experience shear forces of appreciably different magnitudes if the internal structures (mode shapes) are different". (Housner and Brady, 1963).

It is hard to predict exactly the natural frequency of an existing structure: the lack of structural details often prevents from correctly estimating the actual stiffness of old buildings. Therefore it is important to develop reliable empirical formulae in order to estimate this natural frequency for an assessment of their vulnerability. However, the construction type and traditions may significantly vary from one region to another, and importing empirical relationships from other parts of the world may be misleading, especially as they may have been established on insufficient or unrepresentative samples. In-situ tests are thus very useful in estimating the dynamic properties of a building. The application of this method on a representative number of structures can lead to an empirical relationship between structural parameters (such as number of floors, dimensions, age, material and type of construction, etc.) and the dynamic characteristics (frequency, damping, mode shapes). These tests have long been based on forced excitations of the structure either from a natural source such as earthquake or from artificial sources such as explosion, impact of a large mass, rotating oscillator generating forced vibrations. For instance, as early as 1935, Blume imagined a rotating machine whose function was to generate forced vibration. Indeed, the forced vibrations in structures facilitate registration, and control signal so it can represent strong movement, even if the solicitation takes place from above and not from below. Their significant cost however, and the increasing sensitivity of seismic sensors favoured the use of ambient vibrations due to the natural activity (wind, ocean, etc) or anthropogenic activity (traffic, machines, etc.), which prove to be easy, fast, inexpensive, and reliable. Udwadia and Trifunac (1974) confirmed that the results under ambient vibrations are as relevant and the measurements are much faster to perform than under forced vibration. Comparative studies between ambient vibrations and forced vibrations show that the resonance frequencies under high motion are slightly to moderately lower (10 to 30% as long as the building is not seriously damaged). (McVerry and Beck, 1983; Bard et al., 1992; Ulm et al., 1993, Celebi, 1996; Satake, 1996; Meli et al., 1998; Irie and Nakamura, 2000; Mucciarelli et al., 2004; Dunand et al., 2006). As well known, the frequency is given by Eq.(1):

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \tag{1}$$

The decrease of frequency under stronger motion may be explained by a decrease in stiffness, the mass remaining constant. According to Dunand (2005), pre-existing cracks in concrete widen as solicitation increases, especially at assembling nodes, as well as at soil-structure interface. It can generate large strains at the soil-foundation interface and reversible localized non-linearities. Since cracks affect the inertia of cracked section, which is lower than the inertia of the uncracked section, the rigidity decreases, leading to a reduction in fundamental frequency.

Despite these drawbacks, the overall consistency between forced and ambient vibration measurements and the simplicity of the latter favour their development as a practical and reliable tool for determining the dynamic parameters needed for modeling the behaviour of the structure under earthquake. It has indeed been applied in many regions in the world, and has been applied for the first time in Beirut.

Lebanon has been severely affected by earthquakes over centuries. The most recent one occurred on March 16, 1956, in southern Lebanon, and caused a lot of damage resulting in a large number of casualties. Beirut city has faced destruction and reconstruction multiple times, and moreover suffered from a long civil war in the period 1975-1990, which may have significantly weakened a number of existing buildings, and altered the quality of the (few) newly built ones.

This paper highlights the application of ambient vibration on structures in Beirut. The primary goal of this study is to derive Beirut-specific empirical relations between dynamic parameters and building attributes (size, age, material, structural type, …), and to compare their values with those recommended in the recently enforced (2005) building code. A secondary goal is to investigate a) whether the war has weakened structures and thus affected their dynamic properties, and b) whether the recent evolutions of building codes can be seen in building dynamic parameters.

ESTIMATING THE NATURAL FREQUENCY OF BUILDINGS

Usual formulae as recommendend in building codes or common practice

The most common empirical relationship Eq.(2) relating the natural period to the number of floors of a building:

$$T = \frac{N}{10} \tag{2}$$

This formula has been recommended by the U.S. building code and applied on metal and reinforced concrete frames, but cannot be applied on buildings with reinforced concrete walls (Housner and Brady 1963).

Concerning buildings with reinforced concrete walls, the U.S. building code proposes the relation based on a cantilever model (Crowley and Pinho 2010) as in Eq.(3):

$$T = C\frac{H}{\sqrt{L}} \tag{3}$$

with H: height of the building, L: length in the direction of considered movement, and C is a constant that was estimated by Carder (1936) using the ambient vibration method following the earthquake in Long Beach in 1933 and completed by Housner and Brady (1963) based on Japanese data. This relationship has also been adopted by the Algerian code (RPA88, 1988), Korean code (Lee et al. 2000) and partially in the French code (PS92, 1995).

Another empirical relationship applied on frames is proposed in ATC3-06 form (ATC 1978) as reported by Crowley and Pinho (2010) (Eq.(4)):

$$T_1 = C_t H^{\beta} \tag{4}$$

It is used in Eurocode 8 (CEN 2004) and the SIA,Swiss Code (2003). UBC (1997), EC8 and SIA use $\beta = 0.75$ for any type of structure, though based on a study concerning frames (Crowley and Pinho 2010). In EC8 this formula applies only to buildings whose height is less than 40 m. As for the coefficient C_t, it was determined by Crowley and Pinho (2010), based on records of the San Fernando earthquake; unlike the β coefficient, it depends on the type of structure. For example in EC8, $C_t = 0.05$

for reinforced concrete walls, while in UBC 97 C_t = 0.085 for metal frames, 0.073 for reinforced concrete frames, and 0.049 for reinforced concrete walls.

The old French Code (PS92, sometimes used in Lebanon), proposes to estimate the natural period through the following relations Eq.(5) which differ from one type of construction to another:

$$T_0 = 0.09\frac{H}{\sqrt{L}}\text{, for all type of frames}$$

$$T_0 = 0.08\frac{H}{\sqrt{L}}\sqrt{\frac{H}{H+L}}\text{, for reinforced concrete walls} \qquad (5)$$

The recent Lebanese code that was introduced in Lebanon in 2005 specifies the design guidelines and regulations applied to the general seismic structural design. Due to the absence of experimental or theoretical methods, and based on valid assumptions, the fundamental period of vibration of the structure T shall be calculated using the following equation Eq.(6) (Lebanese seismic code):

$$T_1 = \alpha H^{\frac{3}{4}} \qquad (6)$$

where α=0.085 for steel moment-resisting frames, 0.07 for reinforced concrete moment-resisting frames, 0.05 for other buildings, H= total height of structures (in meters).

It is important to realize that all these empirical formulae were established on the basis of a limited number of measurements performed on buildings using the method of forced vibrations. Nowadays, with the development of the ambient vibration technique that allows the records of a large number of measurements in a quick and inexpensive way, it is possible to verify these expressions and even establish new ones that represent more reality.

EXPERIMENTAL ESTIMATION - AMBIENT VIBRATION METHOD

The concept of ambient vibration method was introduced in the 30s by the U.S. Coast and Geodetic Survey (Carder 1936) and became increasingly adopted with the development of technology.

A number of measurements have been performed in France since the mid-nineties. Farsi (1996) established a relation (Eq. (7)) between the natural period and the height of the building, based on measurements on 26 buildings within Grenoble city:

$$T = H^{\frac{1.1}{100}} \qquad (7)$$

Michel et al. (2010) used a larger set of recordings from 60 buildings in the city of Grenoble in addition to the 26 previously performed by Farsi and Bard (2004) in Grenoble, and 28 buildings in Nice done by Dunand (2005), to update the empirical relation between the period and number of floors then eventually the height: considering that the height of a floor is equivalent to 3 m (Eq. (8))

$$T_0 = 0.013H = \frac{H}{75} = 0.039N = \frac{N}{25} \qquad (8)$$

On the other hand, Guillier et al. (2014), based on a set of 344 buildings in Lima- Peru, found a similar relationship for buildings built after 1974 (i.e., after a strong earthquake in Lima). Dunand (2006) developed a similar relationship based on 54 in-situ recordings obtained in Nice.

Oliveira (2004) conducted similar studies by recording ambient vibrations on 235 buildings in Portugal and derived the following empirical relationship (Eq. (9)):

$$T = 0.045N \qquad (9)$$

Moreover Oliveira and Navarro (2010) have compiled all the empirical relationships linking the period and damping to the geometrical characteristics, obtained in different regions in the world. The result of this compilation is listed in Table 1.

Table 1: Summary of existing relationships in all regions of the world

Authors	**City (Country)**	**No. buildings**	**T (N)**	**T (H)**	**ξ (T)**
Kobayashi et al. (1987)	Mexico City (Mexico)	20 RC	T = 0.105 N		ξ T = 4.0%
Midorikawa(1990)	Santiago de Chile (Chile)	107 RC	T = 0.049 N		ξ T = 0.8%
Midorikawa(1990)	Villa del Mar (Chile)	21 RC	T = 0.049 N		ξ T = 1.2%
Lagomarsino(1993)		182 RC + SF			$\xi = 0.0073+ 0.007T^{-1}$
Kobayashi et al. (1996)	Granada (Spain)	21 RC	T = 0.051 N		ξ T = 2.0%
Enomoto et al. (1999)	Almeria (Spain)	34 RC	T = 0.05 N		ξ T = 0.8%
Espinoza (1999)	Barcelona (Spain)	25 RC	T = 0.089 N + 0.032		
Enomoto et al. (2000)	Caracas (Venezuela)	57 RC	T = 0.06 N		
Sánchez et al. (2002)	Adra (Spain)	39 RC	T = 0.049 N		
Navarro et al. (2002)	Granada (Spain)	89 RC	T = 0.049 N		ξ T = 2.1%
Messele and Tadese (2002)	Addis Ababa (Ethiopia)	28 RC	T = 0.057 N	T = 0.018 H	
Satake et al. (2003)	(Japan)	205 RC + SF		T = 0.015 H	ξ T = 1.4%
Dunand et al. (2002)	Grenoble (France)	26 RC		T = 0.015 H	$\xi = 0.7 \times T^{-0.25}$
Oliveira (2004)	Lisbon (Portugal)	193 RC	T = 0.042 N		
Navarro and Oliveira (2004)	Lisbon (Portugal)	37 RC	T = 0.045 N		ξ T = 1.1%
Gallipoli et al. (2009)	Potenza, Senigallia (Italy)	65 RC		T = 0.016 H	

BEIRUT: SEISMIC RISK, GEOLOGY AND RECENT CONSTRUCTION HISTORY

Seismic hazard in Beirut

Lebanon, and especially its capital the city of Beirut, faces several major natural hazards, the most important of which is seismic hazard. Due to its geographic position between the Arabian, African and Eurasia Plates, the country is crossed by five main fault branches: the Roum, Yammouneh, Serghaya, Rachaiya and Hasbaya faults (Khair, 2001). In the past, these faults have generated earthquakes of magnitude exceeding 7, leading to massive destruction in Beirut and Tripoli. In 551, 1202, 1759 and 1837, violent earthquakes devastated the Middle East. The most devastating earthquake occurred in 551 AD: it was accompanied by a tsunami that affected the whole coast from Tripoli (Northern Lebanon) to Tyre (Southern Lebanon) and wiped out the city, killing thousands of people, and turning off the economic activity in the Beirut area for about 1000 years.

The geology of Beirut

The Lebanese geological context is very complex, presenting a very large spatial variability of soils within a very small area. The geology of Beirut and its suburbs (Dubertret 1944) shows that the subsoil can be classified in two main categories: sandy areas and limestones or marly-limestones outcropts. The former can be subdivided into 6 categories: Dune Ramleh, shifting sand dunes, Red Sand, Alluvial Sand, Yellowish sandy soils and Embankments on the maritime border area. The limestones or marly-limestones layers are from the Cretaceous period. The Ashrafieh hill and the eastern part of the peninsula of Beirut, on the west side of Nahr Beirut consist of Helvetian marls. The hills surrounding North of Beirut (Metn) are formed by red sand overlying a clay layer. There are also some cases where the limestone-marl alternations appear on the surface. This heterogeneity and variability of soil in Beirut results in a significant variability of the seismic response (Brax, 2013), and emphasizes the need for detailed geotechnical investigations for any project. Some areas of Greater Beirut present a high potential for liquefaction in case of an earthquake (Harb, 2003). Despite such a large variability within a big hazard area, the urban expansion is not currently subjected to strict construction standards.

Beirut : A short construction history

Beirut was subjected to a dramatic urban evolution over recent decades, resulting in an expansion of the city from the coast to Mount Lebanon, wiping out natural areas at the expense of construction and urban development. It was the French mandate, which succeeded the Ottoman period from 1921 to 1940, that marked the first signs of development of the city of Beirut in transport, infrastructure and sanitation. Table 2 highlights the classification of structures from that period until recently with respect to construction material, water/cement ratio, height for different age range.

Although this city is in the middle of a region of an alerting seismic risk, no seismic codes and provisions were enforced until 2005 when the Order of Engineers has imposed seismic rules especially for high-rise buildings. However, their actual enforcement in practice may be questioned. Consequently this leads to a very significant vulnerability level for the vast majority of buildings in Beirut.

Table 2: Quality of construction material and building practice throughout the urban evolution of Beirut (adapted from Ruppert, 1969)

		Construction Material					**Height**	
Construction Period	**"Type of houses" according to H. Ruppert (1969)**	**Type construction material**	**Assumed quality of cement**	**Assumed quality of Sand**	**Assumed quality of Steel**	**Water/Cement dosage**	**Height limitation**	**Average Height per floor**
Prior 1950	Lebanese House, from the french mandate	Sandstone or Mixed : Sandstone/ Reif. Concrete	Good	Good		Manual	26 m	Approx. 5 m for ground floor, 4 m per floor
1950-1970	Houses from after the WWII	Reinforced Concrete	Good	Good		Manual	1954: Suppression in certain cases of height limitation. Beginning of column floor	Approx. 3m25
1970-1975	Undefined by Ruppert	Reinforced Concrete	Good	Good		Automatic	1970: Exemption of limitation for "big group structures"	Approx. 3m25
1975-1980	Undefined by Ruppert	Reinforced Concrete	Probably Bad	Probably Bad		Automatic		Approx. 3m25
1980-1990	Undefined by Ruppert	Reinforced Concrete	Probably Bad	Probably Bad	Often Bad, Problems at import	Automatic	1990-1997 : Possibility of increasing one floor ("Floor el-Murr")	Approx. 3m25
1990-2002	Undefined by Ruppert	Reinforced Concrete	Good	Medium	Good	Automatic		Approx. 3m25

DETERMINATION OF EMPIRICAL FORMULAE SPECIFIC TO BEIRUT

In the framework of the ANR Libris project (isterre.fr/annuaire/pages-web-du-personnel/christophe-voisin/article/projet-libris), ambient vibrations recordings have been performed on Beirut buildings with a CityShark acquisition station (a dedicated, 24 bit data logger: Chatelain et al., 2000), connected to a 3 component Lennartz velocimeter (LE3D-5s) with a flat response between 0.2 and 50 Hz, in order to identify their natural frequencies and associated damping. The adjustable recording time was set at 15 min, and it was systematically obtained on the highest point of the building, since the vibration amplitude is the highest at this level.

This campaign aims at testing the empirical formulae presently recommended in the design codes, and if needed proposing Beirut-specific relationships considering the local construction typology. It was carried out on 303 buildings located as displayed in Fig.1, out of which:

- 182 are built on rocky sites, the majority of them being in: Sassine (S) Sioufi (Si), Geitawi (G) and the rest scattered in: Rmeil (R), Minet El Hosn (MH), Furn El Hayek (FH).
- 121 are located on soft ground in the regions of Bourj Hammoud, Badaro and Jdeideh.

The type of building is essentially reinforced concrete structures.(Fig. 1)

Each signal was then processed as illustrated in Fig.2 using the Geopsy Software to extract the fundamental frequencies and the associated damping using Fourier Transform and Random Decrement technique (Dunand, 2005). For each building i, the available information are its fundamental frequencies in each horizontal direction (longitudinal f_{Li} and transverse f_{Ti}), the corresponding damping values (ς_{Li} and ς_{Ti}), the horizontal dimensions (length L_i and width W_i), the height H_i, and the number of floors N_i.

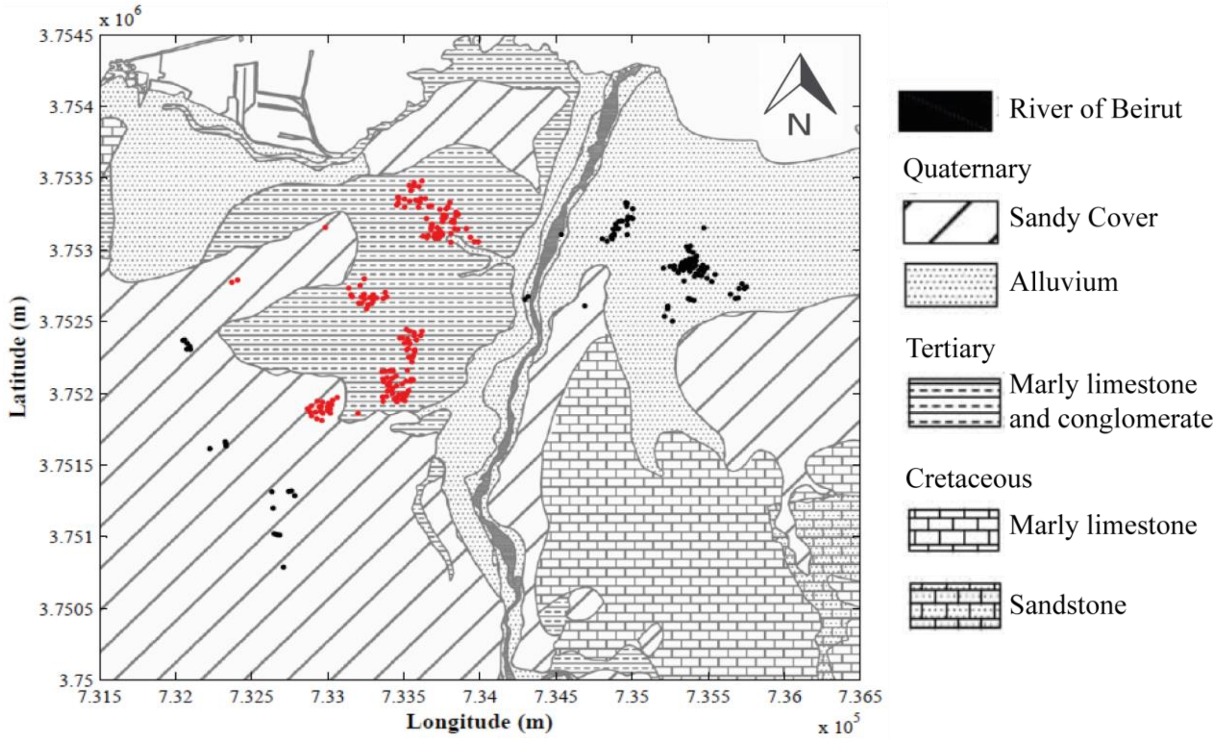

Figure 1: Geological map of Beirut and location of 303 buildings measured in Beirut: red on rock soil, black on soft soil (Dubertret, (1944) simplified by Salloum et al. (2012)). Mapping using the UTM (Universal Transverse Mercator) coordinate system (Zone: 36)

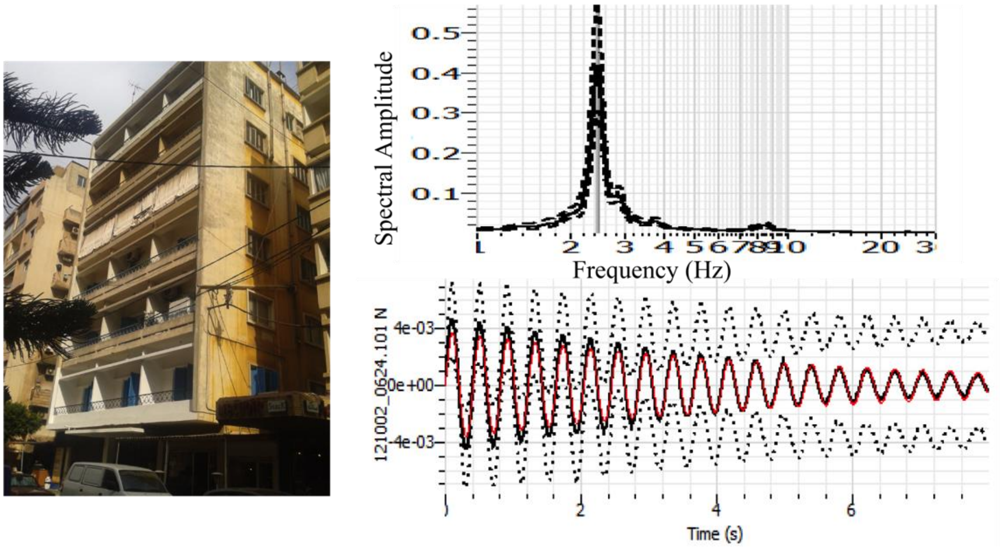

Figure 2: Photo of an RC building measured in Beyrouth, with the spectral curve showing the fundamental frequency and the damping curve using Random Decrement technique by Geopsy Software (www.geopsy.org)

A statistical analysis was established on the database in order to find correlations between the dynamic and geometrical parameters of the buildings in Beirut. Some of the results are displayed in Figures 3 (effect of horizontal size), 4 (effect of height or number of floors) and 5 (comparison with "theoretical" periods as predicted with code formula).

The statistics on horizontal dimensions displayed on Fig.3 left indicates that only very few buildings have a square shape, which allows to investigate the sensitivity of the fundamental frequency in each direction (longitudinal and transverse) on the corresponding horizontal dimension.

The right part of Fig.3, displaying the transverse frequency as a function of the longitudinal frequency, indicates that both frequencies are very close to one another, and thus the absence of any clear effect of the horizontal size of the building.

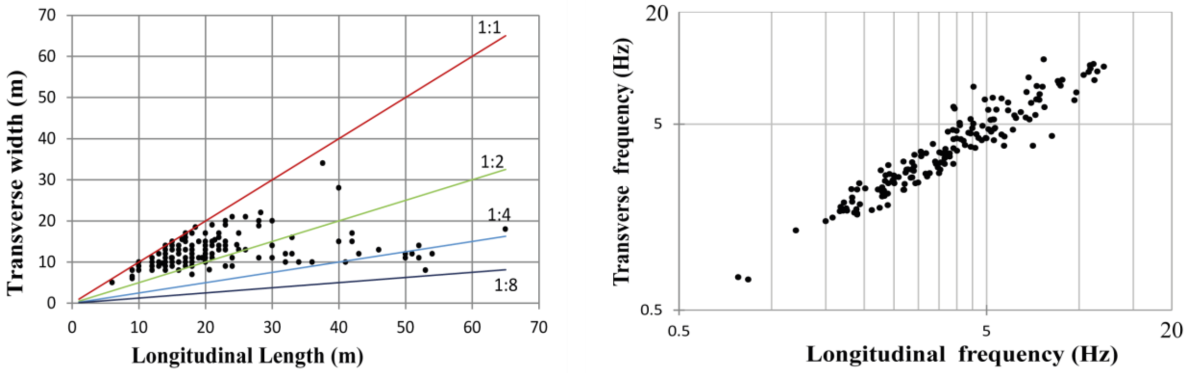

Figure 3: Geometrical distribution of the measured buildings: transverse width versus longitudinal length (left), transverse frequency versus longitudinal frequency (right)

The key parameter controlling building frequencies is therefore its height (or alternatively its number of floors). A linear regression between the natural period and the number of stories resulted (Fig.4) in relations T≈N/23 for buildings on rock, and T≈N/18 for those on soft soils, with correlation coefficients of 0.889 and 0.900, respectively. These high correlations between the period and the number of floors, and between the longitudinal and transverse frequencies, allow to conclude that the horizontal building size has an only negligible effect on the natural frequency, and the dominant parameters are the building height or number of floors, with a slight influence of the foundation soil.

The differences between the soil and rock data sets raise the question of their actual statistical meaning; statistical tests were thus performed to compare residual variances (Fisher-Snedecor Test) and the slopes of the two regressions (Student Test). The slightly longer period on soft soils is fully consistent with the observed larger damping on soft soils as illustrated on Fig.4 right: soil-structure interaction is a likely candidate to explain such differences, with both slightly lengthened periods and increased damping due to radiation from the foundation.

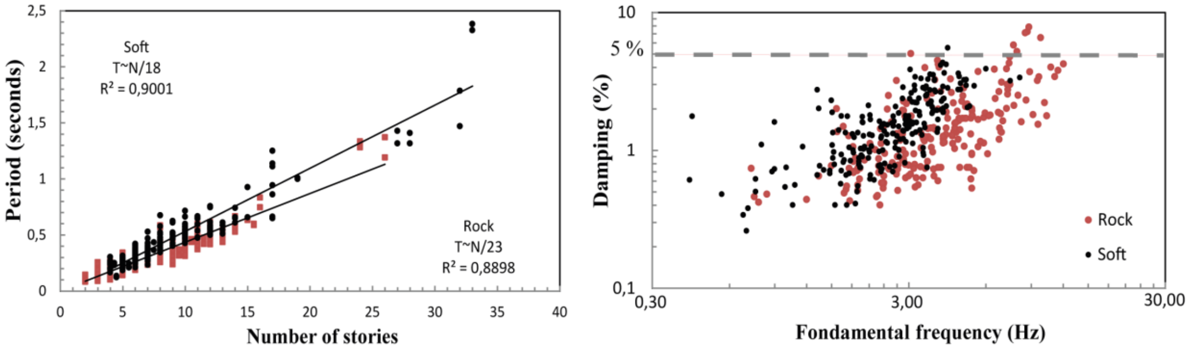

Figure 4: Correlation of fundamental periods (T) with number of floors (N) (left), and damping with natural frequency (right)

In both cases, the damping values do exhibit a clear trend to increase with frequency, from values around 1% around 1 Hz, up to around 5% around 5-7 Hz. This trend is consistent with previous observations as shown in the last column of Table 1. Measured values rarely exceed the conventional value of 5% recommended in most seismic codes, which do not consider any correlation with the natural frequency of the structure. It must be emphasized however that damping values are obtained here under very weak motion, and caution must be taken to extrapolate these values to higher ground motion levels. Such results underline the need for a better in-depth understanding of the origin of damping, and its sensitivity to material, structural type, building size and ground motion level.

Relations with respect to height in the form ($T = C H^{\alpha}$ result in values C = 0.0187 and α = 0.9123 with a high correlation coefficient, while relations involving the horizontal dimension of the structure have a lower coefficient of correlation. A comparison with UBC97 and PS92 (Fig.5) depicts a significant difference between the actually measured periods and those estimated according to the formulae proposed in building codes: the latter significantly overestimate the experimental period derived from ambient vibrations ($T_{theoretical}/T_{measured} \approx 2$ with standard deviation 0.65 on rock sites and $T_{theoretical}/T_{measured} \approx 1.7$ with standard deviation 0.5 on soft sites). As seismic actions are generally inversely proportional to the period for high-rise buildings in the classical force design approach, this period overestimation results in an underestimation of the design actions; this unconservative conclusion would be reversed when considering a displacement based design.

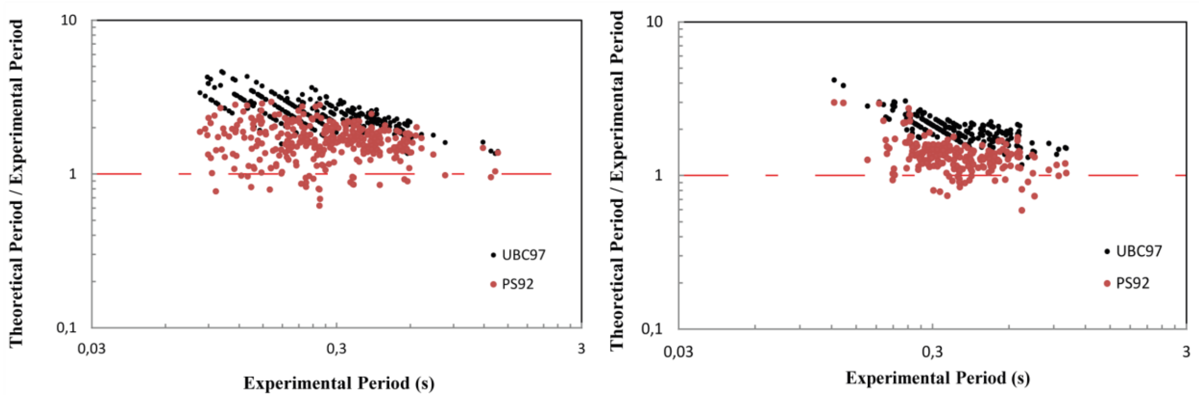

Figure 5: Comparison between experimental period obtained with ambient vibration method and theoretical period in seismic design code: rock sites (left), soft sites (right)

CONCLUSIONS

A comprehensive set of dynamic parameters (frequency and damping) has been acquired in Beirut for more than 300 buildings on the basis of ambient vibration measurements. The results show once more that periods are primarily controlled by building height or number of floors in the form $T = N/N_{ref}$, with $N_{ref} = 23$ for rock sites (correlation coefficient 0.889), and $N_{ref} = 18$ for soft soil sites (correlation coefficient 0.900).The differences between rock and soft soils are statistically meaningful and consistent with the effects of soil-structure interaction. Other geometrical parameters do not contribute statistically to the relationship.

The results derived from ambient vibrations indicate two significant differences with building code recommendations. The measured periods are much lower than the values provided by the American and French seismic code (PS92 and UBC97) ($T_{code}/T_{measured} \approx 2$). In addition, structural damping increases with increasing fundamental frequency whereas it is considered as a constant usually equal to 5% in most seismic codes. The codes thus seem not to be on the conservative side in the force-based design approach.

These relationships are important for the city of Beirut. Event though they are derived for very weak motion, they should be taken into account in the discussion of new Beirut specific period estimates.

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