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ORIGINAL RESEARCH PAPER

Seismic response of Beirut (Lebanon) buildings: instrumental results from ambient vibrations

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Abstract Resonance period is a key parameter in the seismic design of a structure, thus dynamic parameters of buildings in Beirut (Lebanon) were investigated based on ambient vibration method for risk and vulnerability assessment. Lebanon is facing high seismic hazard due to its major faults, combined to a high seismic risk caused by dense urbanization in addition to the lack of a seismic design code implementation. For this study, ambient vibration recordings have been performed on 330 RC buildings, period parameters extracted and statistically analyzed to identify correlations with physical building parameters (height, horizontal dimensions, age) and site characteristics (rock sites or soft sites). The study shows that (1) the building height or number of floors (N) is the primary statistically robust parameter for the estimation of the fundamental period T; (2) the correlation between T and N is linear and site dependent: $T \approx N/23$ for rock sites and $N/18$ for soft sites; (3) the measured damping is inversely proportional to the period: the taller the building the lower is the damping; (4) a significant overestimation of the period exists in current building codes. However part of the large discrepancy with building code recommendations may be due to the very low level of loading.

Keywords Lebanon · Beirut · RC buildings · Ambient vibration · Dynamic parameters · Soil type · Fundamental period/frequency · Damping · Seismic code

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1 Introduction

The principal goals of seismic provisions are to protect human lives by limiting damages and structural failures, to maintain the function of structures when an earthquake occurs. Seismic actions to design a structure against earthquakes are estimated based on its dynamic parameters, such as the fundamental period, damping and mode shapes. The fundamental period is critical to assess the seismic response of the structure that can be further used in building codes and modeling. Periods and damping of a structure control the amplitude and the duration of its response to an earthquake. "The natural period of vibration is the single most informative fact about the internal structure of buildings. 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", as reported by Housner and Brady (1963). The period T in seconds is linked to the mass M and rigidity K of the structure through Eq. (1):

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

This fundamental period can be computed based on modeling, structural drawings and material characteristics being not easy to retrieve however, especially for old buildings; or using empirical relationships from seismic codes. To overcome these difficulties, experimental techniques can be used to estimate the dynamic properties of a building, leading to a more accurate empirical relationship between major characteristics of a building (number of floors, size, age, type of construction, material) and its dynamic behavior. These methods consist of inducing excitation in the structure in order to generate vibrations: this excitation can be produced from a natural source such as an earthquake (Celebi 1996; Michel 2007; Todorovska 2009a, b) or more frequently from artificial sources generating forced vibrations such as explosion, large mass impact, running oscillator (Trifunac 1972; Boutin et al. 2001; Crowley and Pinho 2004). Since these methods are citizen perturbing and/or time consuming and/or expensive, the U.S. Coast and Geodetic Survey (Carder 1937) first introduced the concept of ambient vibration method when measuring buildings in California and Montana. Since then, this method has been progressively developed over the years and has been adopted increasingly worldwide because it is easy, fast, inexpensive, reliable, and based on the use of low excitation generated by ambient sources like wind or anthropic activity such as traffic, machinery, etc. (Gutenberg 1958; Asten 1978; Asten and Henstridge 1984; Bonnefoy-Claudet et al. 2006) and applicable on soil (Nakamura 1989; Lachet and Bard 1994; Haghshenas et al. 2008) and on buildings (Trifunac 1972; Farsi and Bard 2004; Dunand 2005; Mikael et al. 2013). Trifunac (1972) confirmed that the fundamental frequency and damping under ambient vibrations are consistent with those obtained by forced vibrations for low input motion but much faster to perform. For larger seismic input motion, comparative studies between ambient vibrations and forced vibrations show that the resonance frequencies under high motion are slightly to moderately lower by 10–30 % as long as the building is not seriously damaged (McVerry and Beck 1983; Bard et al. 1992; Ulm et al. 1993; Celebi 1996; Satake and Yokota 1996; Meli et al. 1998; Irie and Nakamura 2000; Mucciarelli et al. 2004; Michel 2007). The decrease in frequency (or the increase in period) under strong excitation may be explained by a decrease in rigidity (Farrar et al. 2001), the mass remaining constant [Eq. (1)]. According to various authors (Luco et al. 1987; Meli et al. 1998; Dunand 2005; Clinton et al. 2006; Michel and Guéguen 2010) pre-existing cracks in concrete widen as loading

increases, especially at assembling nodes and soil-structure interface. It can generate large strains at the soil-foundation interface and reversible localized non-linearities. Since the opening of cracks decreases the area of the available resisting section, it lowers the rigidity with respect to the case of an uncracked section, which in turn results in a reduction in fundamental frequency. However as recordings under ambient vibration are inexpensive and easier to obtain than forced vibrations data, it is obvious that ambient vibration is a practical and reliable tool for determining the dynamic parameters needed for modeling the behavior of the structure under weak motion.

The goal of this paper is to find empirical relationships between the dynamic parameters (period, damping) obtained from ambient vibration and geometrical/geotechnical characteristics specific to Beirut housing (Lebanon). Many Lebanese cities have been severely affected and even destroyed by earthquakes over the last centuries. In addition Beirut is a city that has faced destruction and reconstruction multiple times. The 1975–1990 period has marked Beirut with a civil war leading to a complete loss on the quality building control. Furthermore, no seismic code was applied before 2005. The first Lebanese seismic code was recently introduced and applied on buildings above 3 floors. Moreover it is based on American and European provisions without taking into account the Lebanese peculiarities. This paper thus studies coherence between seismic codes and the actual behavior of the Lebanese buildings, contributing to a safer design when a strong earthquake occurs. Comparisons are established between experimental measurements in Lebanon and those recorded in multiple countries in the world. Both period and damping obtained are considered according to the soil types underlying the buildings to evaluate this parameter impact. It has been also compared to the theoretical values computed from the seismic codes used in Lebanon, and to the elastic part of the capacity curves of RC buildings developed in large-scale vulnerability assessment. This is the first time ambient vibration on buildings is introduced in Lebanon.

2 Period estimation in seismic design codes

Some seismic codes use equations that include the geometrical dimensions of the building: the building height, H (in meters) and the length, L (in meters), in the direction of considered movement. For buildings having shear walls, the U.S. building code proposed a relationship calibrated using a cantilever model to compute the fundamental period T (Crowley and Pinho 2010):

$$T = C \frac{H}{\sqrt{L}} \tag{2}$$

with C, a constant estimated by Carder (1937) using the ambient vibration method following the earthquake in Long Beach in 1933 and completed by Housner and Brady (1963) based on Japanese data.

According to Crowley and Pinho (2010) the above mentioned formula comes from the equation of the period of vibration of a cantilever (considering shear deformations only), with the thickness of the wall considered to be more or less constant and thus only the ratio between width and length of the building is an input parameter, as demonstrated in the following Eq. (3):

$$T = 4\sqrt{\frac{m}{\kappa G}}\frac{H}{\sqrt{A}} = \frac{\alpha H}{\sqrt{A}} = \frac{\alpha H}{\sqrt{Dt_w}} = \frac{\alpha_1 H}{\sqrt{D}} \tag{3}$$

where m is the mass per unit length, G is the shear modulus, A is the area of the cantilever, κ is the shape factor to account for non-uniform distribution of shear stresses, D is the length of the cantilever and t_w is the thickness.

The Algerian code (RPA88 1988), the Korean code (Lee et al. 2000) and partially the French code (PS92 1995) also adopted this equation to determine the fundamental period. Moreover the French Code (PS92) proposes to estimate the fundamental period depending on the type of construction through the following relations:

$$T = 0.09\frac{H}{\sqrt{L}}, \quad \text{for metallic frames and reinforced concrete frames} \tag{4}$$

$$T = 0.09\frac{H}{\sqrt{L}}\sqrt{\frac{H}{H+L}}, \quad \text{for shear walls} \tag{5}$$

However other seismic codes do not incorporate the structural dimension in the fundamental period relationships. Indeed Crowley and Pinho (2010) reported another empirical relationship with power-law form applied on frames, initially proposed in ATC3-06 (ATC 1978) and then adopted by EC8 (Fardis et al. 2009), the Swiss Code (SIA 2003) and the Canadian code (NBCC 2005):

$$T = C_t H^\beta \tag{6}$$

where C_t and β are locally determined parameters that depend on the type of the structure.

UBC (1997), EC8 (2004) and SIA (2003) use $\beta = 0.75$ for any type of structure (Crowley and Pinho 2010) whereas the Risk-UE project (Lagomarsino and Giovinazzi 2006) uses $\beta = 0.9$. In EC8 this formula applies only on buildings whose height is less than 40 m. The coefficient C_t was determined by Gates and Foth (1978), by using records of the earthquake of San Fernando and depends on the type of structure, unlike the β coefficient. For example in EC8, $C_t = 0.05$ for reinforced concrete walls, while in UBC97 $C_t = 0.085$ for metallic frames, 0.073 for reinforced concrete frames and 0.049 for reinforced concrete walls.

Linear correlations between fundamental period and number of stories of a building (N) exist in some seismic codes. The most common and simplest empirical relation which is a quick estimation proposed by the U.S. building code for metallic frames and reinforced concrete frames only, i.e. not including buildings having shear wall characteristics (Housner and Brady 1963):

$$T = \frac{N}{10} \tag{7}$$

Japanese standard law (BSLJ 2011) also adopts linear relationships such as:

$$T \approx \frac{N}{27} \tag{8}$$

The recent Lebanese code specifies the design guidelines and regulations applied to the general seismic structural design (refer to Sect. 4.3 for more details on the Lebanese building code). Due to the absence of experimental data or specific modeling, the

fundamental period of vibration of the structure T is defined by using the following power function equation:

$$T = \alpha H^{\frac{3}{4}} \tag{9}$$

where $\alpha = 0.085$ for metallic moment-resisting frames, 0.07 for reinforced concrete moment-resisting frames, 0.05 for other buildings, H is the structures height (in meters).

3 Experimental estimation of dynamic parameters using ambient vibration method

Ambient vibration measurements were performed in various regions in the world and some linear and power-laws empirical relationships between dynamic parameters (period, damping) and geometrical characteristics of buildings are compiled in Table 1 and displayed in Fig. 1. Several recordings have been performed in France since the mid-nineties. Farsi (1996) and Farsi and Bard (2004) have first established a relation between the fundamental period T and the height H of the building by using measurements on 26 buildings within Grenoble city:

$$T = \frac{H^{1.1}}{100} \tag{10}$$

Next, 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), and 28 buildings measured in Nice by Dunand (2005), to update the empirical relation between the period and number of floors (N), considering the height of a floor is about 3 m:

$$T = 0.013H \approx \frac{H}{75} = 0.039N \approx \frac{N}{25} \tag{11}$$

Guillier et al. (2014) measured 344 RC buildings in Lima (Peru), and derived three linear relationships between number of floors and fundamental periods by considering 2 categories of buildings: 0–4 floors and $\geq$5 floors built before and after 1974, 1974 being the year the first Peruvian code was introduced after a strong earthquake occurred the same year:

$$
\begin{aligned}
T &= \frac{N}{24} \quad \text{for buildings less than five floors whatever the year of construction} \\
T &= \frac{N}{15} \quad \text{for buildings with five floors or more built before 1974} \\
T &= \frac{N}{24} \quad \text{for buildings with five floors or more built after 1974}
\end{aligned}
\tag{12}
$$

Oliveira (2004) conducted similar studies by recording ambient vibrations on 235 buildings in Portugal and derived the following empirical relationship [Eq. (13)]:

$$T = 0.045N \approx \frac{N}{22} \tag{13}$$

Table 1 Summary of existing linear relationships and power-laws between dynamic and geometric characteristics in all regions of the world based on ambient vibrations method

Authors	City (country)	No. buildings	T (N)	T (H)	ξ (T)
(a) Linear correlation between fundamental period and height of the building (or equivalent number of storeys)					
Kobayashi et al. (1987)	Mexico City (Mexico)	20 RC	T = 0.105 N		ξ T = 4.0 %
Midorikawa and Jigyodan (1990)	Santiago (Chile)	107 RC	T = 0.049 N		ξ T = 0.8 %
	Viñã del Mar (Chile)	21 RC	T = 0.049 N		ξ T = 1.2 %
Lagomarsino (1993)	Mixed origin	182 RC + SF			$\xi = 0.72 + 0.7T^{-1}$
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		
Sanchez 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	$\xi = 1.4/T - 0.18$
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		
Wamitchai (2004)	Bangkok (Thailand)	50 RC		T = 0.019H	ξ T = 1.1 %
Navarro et al. (2007)	Adra (Spain)	38 RC	T = 0.049 N ± 0.001		
Herak and Herak (2009)	Zaghreb (Croatia)	100 RC		T = 0.013H	
Gallipoli et al. (2009)	Potenza, Senigallia (Italy)	65 RC		T = 0.016 H	
Gallipoli et al. (2010)	Slovenia	47 RC		T = 0.016 H	
	Croatia	62 RC			
	Republic of Macedonia	70 RC			
Oliveira and Navarro (2010)	Portugal	130 RC	T = 0.039 N	T = 0.013H	
Michel et al. (2010)	Grenoble, Nice (France)	114 RC	T = 0.039 N	T = 0.013 H	

Table 1 continued

| Authors	City (country)	No. buildings	T (N)	T (H)	ξ (T)
Ditommaso et al. (2013)	L'Aquila (Italy)	68 RC		$T = 0.026\ H$	$\xi\ T = 0.75 \pm 0.04$
Guillier et al. (2014)	Lima (Peru)	344 RC	$T = 0.042\ N$		
Vidal et al. (2014)	Lorca (Spain)	59 RC	$T = (0.054 \pm 0.002)\ N$		
(b) Power-form correlation between fundamental period and height of the building (or equivalent number of storeys)					
Hong and Hwang (2000)	Taiwan	21 RC		$T = 0.0294\ H^{0.804}$	
Guler et al. (2008)	Turkey	6 RC		$T = 0.026\ H^{0.9}$	
Gilles and McClure (2008)	Montreal (Canada)	8 RC SW		$T = 0.018\ H^{1.007}$	
Chiauzzi et al. (2012)	Victoria, Vancouver (Canada)	12 RC		$T = 0.037\ H^{0.76}$	
Hatzigeorgiou and Kanapitsas (2013)	Greece	20 RC		$T = 0.073\ H^{0.745}$	
Pan et al. (2014)	Singapore: soft soil	116 RC	$T = 0.0927\ N^{0.8183}$	$T = 0.0372\ H^{0.8325}$	
	Singapore: firm soil		$T = 0.0657\ N^{0.8607}$	$T = 0.0244\ H^{0.8840}$	
Al-Nimry et al. (2014)	Jordan	29 RC		$T = 0.0291\ H^{0.71}$	
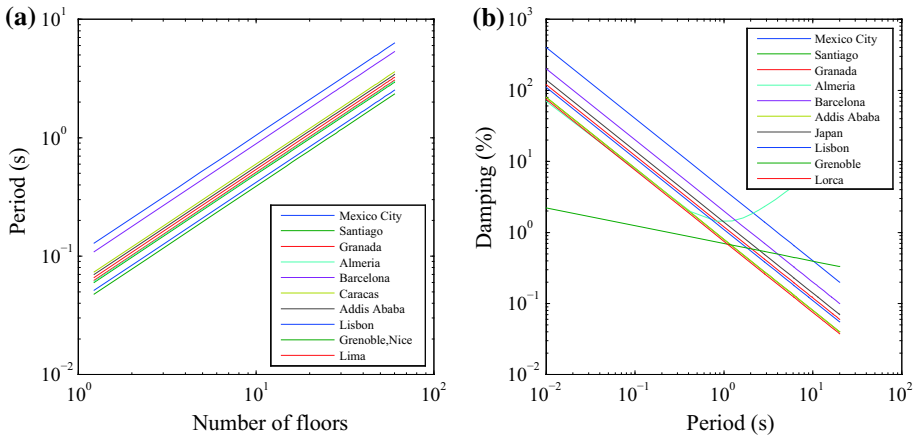
Fig. 1 Correlations between **a** fundamental period (s) and number of floors, **b** damping (%) and fundamental period (s). These correlations are obtained in many regions in the world based on the ambient vibration method

4 Beirut: seismic risk, geology and recent construction history

4.1 Seismic hazard assessment of Beirut

Lebanon is a small Middle East country crossed by the 1200 km long Levant Fault System (LFS). In Lebanon, the LFS split into three main branches, on land and offshore as well: the left lateral strike-slip Yammouneh Fault (last known rupture: 1202, M7.5), the Beirut-Tripoli Thrust (551, M7+), and the Rachaya–Serghaya Fault (1759, M6.5) (Fig. 2). The 551 event was accompanied by a tsunami hitting the whole eastern Mediterranean coast, destroying several cities including Beirut, Tripoli, Saida and Tyre. The most recent large earthquake is the double shock of 16 March 1956 which killed 136 people, destroyed 6000 houses and damaged 17,000 (Brazee and Cloud 1984; Khair et al. 2000). Seismological trenches have shown that the return period of devastating earthquakes is ∼1100 years along the Yammouneh Fault (Daëron et al. 2007), 1500–1750 years along the Mount Lebanon Thrust (Elias et al. 2007) and ∼1300 years along Serghaya Faults (Gomez et al. 2003). Considering the dates of the last major events that occurred on the Yammouneh Fault (1202), and on the Mount Lebanon thrust (551), together with the slip rate inferred by geodetic measurements (Gomez et al. 2003), geologist estimate that these two faults are now mature enough to produce earthquakes with magnitude >7 at any time because of the accumulation of sufficient deformation combined to a rich collection of previous paleo-seismic and historical data.

4.2 Beirut geology

The city of Beirut is built on 9 by 12 km rocky cape jutting into the Mediterranean Sea. The geological basement, dated from the Cretaceous, is visible in the two hills of Achrafieh to the east, and Tallet el Khayat to the west. They are made of marly limestones, sometimes associated to conglomeratic beds. The dominant feature of the geology is formed by a sandy cover that extends mostly in the south west and upon the low elevation parts of the
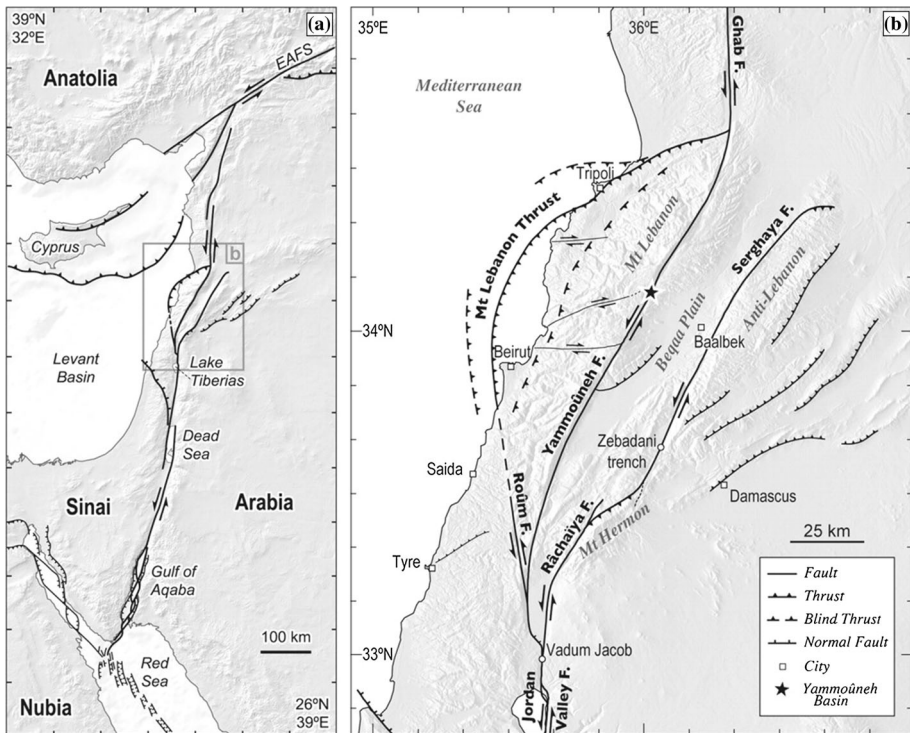
Fig. 2 Tectonic setting of the study: **a** regional sketch map of the Levant fault system, **b** focused map of the main active faults in Lebanon (Daëron et al. 2007)

hills (e.g. Ramlet el Baydah to the west of the city) and along the eastern bank of the River of Beirut. This sandy cover is in turn covered by recent alluvium mostly expressed in Beirut downtown, along the River of Beirut and in the area of Bourj hamoud and Daoura, to the east of Beirut city. More complex quaternary sediments with interbedded alluvial sand and clay layers are located in the River of Beirut (Fig. 3) (Salloum et al. 2014; Cornou et al. 2014).

Previous studies have outlined moderate to large seismic amplification, as a consequence of spatial variable geology (Brax 2013). Several areas are prone to large probability of liquefaction during a seismic event due to the elevated water table and small percentage of fines in sandy areas (Harb 2003). Such geologic hazard did not prevent the city from getting overpopulated, reaching almost full saturation of land occupancy.

4.3 Brief construction history of Beirut

The building stock in Beirut is relatively recent, mostly younger than one century old, except few monuments from the Ottoman Empire period. In the early twentieth century, during the French mandate (1921–1948), the city witnessed a significant growth in infrastructures and constructions. The initial sandstones constructions were rapidly substituted by concrete buildings which continued rising today. With the booming of real estate and scarcity of the land, a vertical expansion of the city is observed with numerous underground and aboveground floors. This boom comes as a result of a slow down during
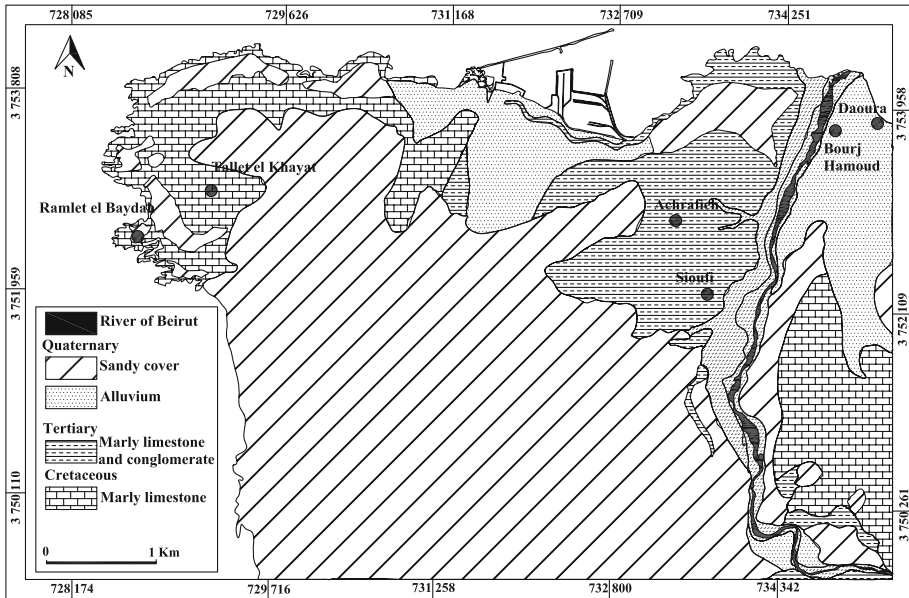
Fig. 3 Geological map of Beirut and location of its major cities (Dubertret 1945 simplified by Salloum et al. 2014)

the civil war of 1975–1991, where the quality controls in construction industry were not enforced. Table 2 displays the evolution of the Lebanese construction from the French mandate period until recently. After 1991, construction practice enhanced significantly with the implementation of standardized quality control. The seismic building code appeared in 2005 with some regulations from the Order of Engineers backed up by governmental decision to enforce building quality. It was introduced through governmental decrees No 646 (2004) and 14293 (2005), exempting constructions up to 10 m (or 3 floors) from any seismic requirements. However, the permit practice still lacks control prior, during and after construction, especially at the municipal level because local authorities are not yet properly qualified to supervise the application of the code and control the quality of the material. This critical urbanization transformed Lebanon into one of the Mediterranean countries with the higher seismic risk, and increased the vulnerability due to the wide heterogeneity in type and quality building at district and city level.

5 Extraction of fundamental period and damping of buildings

Within the framework of the ANR Libris project (2010–2014) an ambient vibration measurement campaign was conducted on buildings and soil. 615 sites were measured (Brax 2013; Salloum et al. 2014) to obtain the soil resonance frequency map of Beirut using HVSR (horizontal to vertical spectral ratio) approach (Nakamura 1989; Mucciarelli and Gallipoli 2001). 330 buildings were investigated from March to July 2012 (Fig. 4) (Salameh et al. 2014): 197 buildings on rock sites and 133 on soft sites. Therefore 660 measurements are considered taking into account the longitudinal and transverse components. Histograms in Fig. 5 show the distribution of the dataset with respect to their

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

| Construction period	Construction material					Height	
	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, French mandate (Ruppert 1969)	Sandstone or mixed: sandstone/reif. concrete	Good	Good		Manual	26 m	Approx. 5 m for ground floor, 4 m per floor
1950–1970, after WWII (Ruppert 1969)	Reinforced concrete	Good	Good		Manual	1954: suppression in certain cases of height limitation. beginning of column floor	Approx. 3m25
1970–1975	Reinforced concrete	Good	Good		Automatic	1970: exemption of limitation for "big group structures"	Approx. 3m25
1975–1980	Reinforced concrete	Probably bad	Probably bad		Automatic		Approx. 3m25
1980–1990	Reinforced concrete	Probably bad	Probably bad	Often bad, problems at import	Automatic	1990–1997: possibility of increasing one floor ("Floor el-Murr")	Approx. 3m25
1990–2005	Reinforced concrete	Good	Medium	Good	Automatic		Approx. 3m25
Post 2005	Reinforced concrete	Good	Medium	Good	Automatic	Lebanese seismic code application	Approx. 3m25
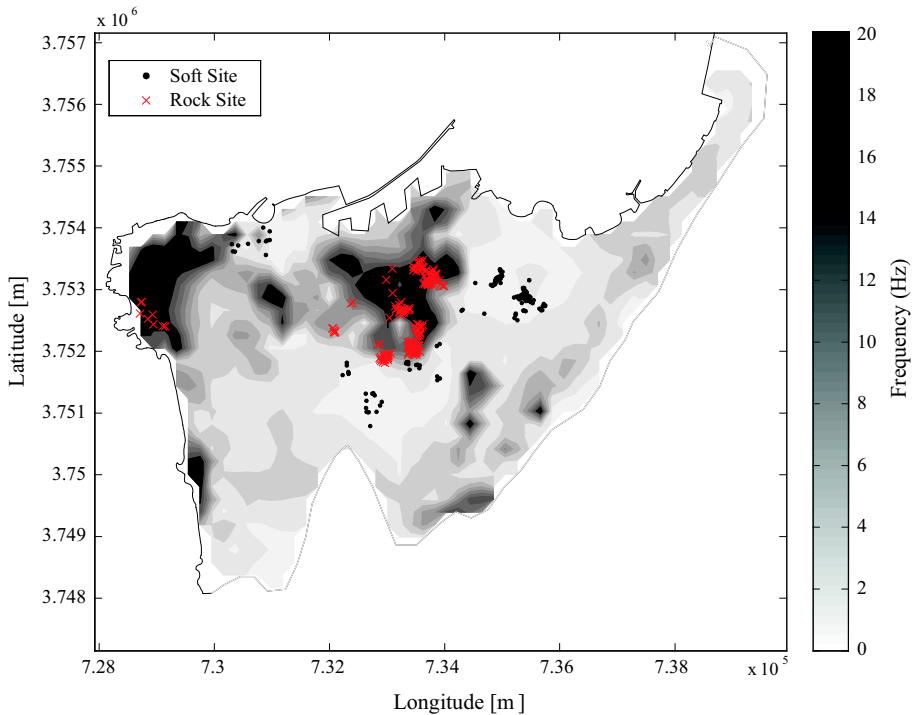
Fig. 4 Location of 330 buildings measured in Beirut on rock and soft sites on an interpolated map of the fundamental soil frequencies (Brax 2013; Salloum et al. 2014). Frequency is given in Hertz. Mapping using the UTM (Universal Transverse Mercator) coordinate system (Zone: 36)

construction date according to Table 2 (Fig. 5a) and the number of floors (Fig. 5b). This ambient vibration survey has been carried out using a Lennartz LE-3D-5 s seismometer connected to a CitySharkII© recorder (Chatelain et al. 2000), assumed to be a performant combination in ambient vibration studies (Guillier et al. 2008). The recordings lasted 15 min at a rate of 200 sps, and were performed on the roof of the building as the higher the location of the measurement the stronger the amplitude of vibration for the fundamental mode. The seismometer was located in the center of the roof and the "North–South" sensor of the seismometer oriented along the main (longitudinal) axis of the building (Dunand et al. 2004; Farsi et al. 2009; Guillier et al. 2014). The number of floors, the year of construction and the dimensions of the buildings (height, length, width) are also collected for statistical analysis. Signal processing is done using the "geopsy" open source software (www.geopsy.org, last accessed February 2016, Wathelet 2008) in the 0.1–50 Hz range.

It is clear that the soil variability can be divided into two distinct types: rock sites with no H/V peak frequencies or frequency >20 Hz, and soft sites having a fundamental frequency less than 20 Hz. Certain areas located on the boundaries between rock and soft sites are considered as transition zones. It is assumed that high rise buildings resting on shallow soft soils, i.e. having a fundamental period much longer than the soil fundamental period, are not affected by the presence of a thin soft layer, and will behave as if resting directly on rock, while a low rise building located on the same place would feel the presence of the soft layer when its natural period is shorter than the soil period. In the former case, the
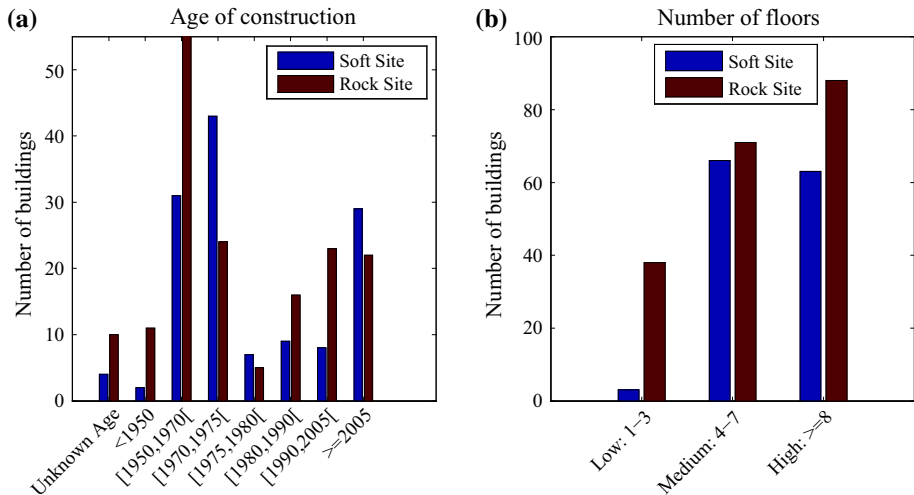
Fig. 5 Distribution of the buildings measured in Beirut on soft and rock sites in function of **a** the age of construction, based on the classification of Table 2, and **b** the number of floors

quarter-wavelength at the building period is much longer than the soil thickness, and the effective foundation impedance is mostly controlled by the (shallow) underlying rock; in the latter case, the quarter-wavelength is comparable to or much smaller than the soil thickness, and the effective foundation impedance is controlled by the mechanical properties of the soft soil. Finally the buildings are distributed with respect to the two soil types following the criteria described above.

5.1 Fundamental period of buildings

The processing procedure is illustrated in Fig. 6 for one particular building on each horizontal component. Individual spectrum is obtained as follow: (1) selection of 25 s duration stable signal windows, using an automatic anti-trigger selection based on STA/LTA with a low and high thresholds of 0.2 and 2.5 respectively (STA = short time average over 1 s, LTA = long time average over 30 s) to avoid strong transients, (2) application of a 5 % cosine taper on both ends of the windows to minimize the distortion of the fast Fourier transform (FFT), (3) computation of the Fourier amplitude spectra for each selected window (4) smoothing of each individual spectrum using the Konno and Ohmachi (1998) method (with a constant b value of 80; this large value being chosen to discriminate two peaks with slightly different periods) and (5) the average Fourier amplitude spectrum is obtained by averaging all individual smoothed spectra. Longitudinal and transverse periods are identified by geopsy automatic picking of the highest period peak from the FFT curves; automatic picking was however systematically checked by visual inspection. In the Fig. 6 example, the 7-story building has a longitudinal period of 0.41 s (Fig. 6b).

The fundamental period identification is not always obvious where coupling between neighboring buildings do exist. In simple cases, where the building is isolated, the spectrum shows usually multiple peaks: the last one corresponds to the fundamental period and the peaks at shorter periods are related to harmonic modes. However in the case of Beirut region, especially in the oldest parts of the city, buildings are constructed with no
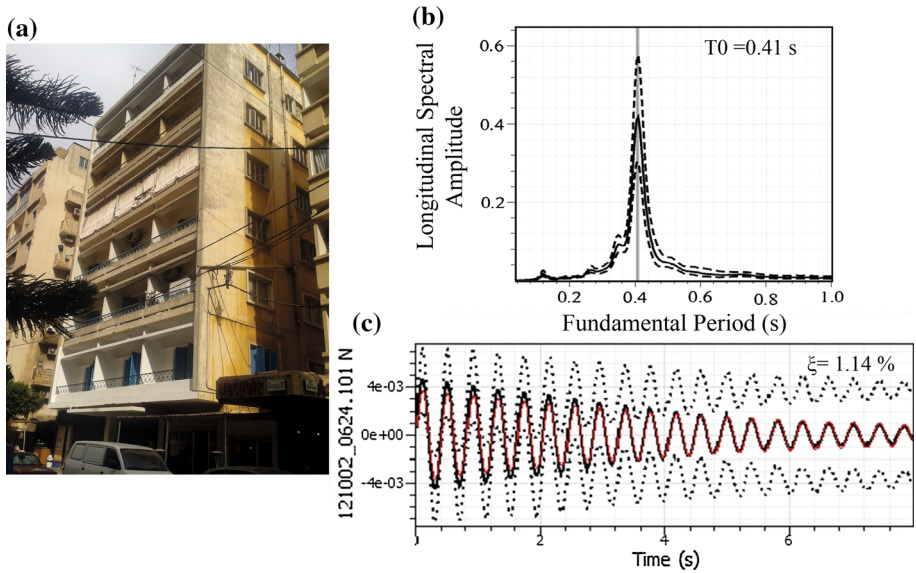
Fig. 6 Example of a 7-story RC building measured in Beirut (Badaro) located on soft soil: **a** Photo of the 7-story RC building, **b** the spectral curve showing the longitudinal fundamental period and **c** the damping curve for $T_0 = 0.41$ s using Random Decrement technique by geopsy software (www.geopsy.org). The continuous *black line* corresponds to the mean of the random decrement and the *dashed lines* correspond to the standard deviation bounds; the *solid red line* corresponds to the fitted exponentially decreasing function

movement joint between them; the interference between structures may mislead the identification of the correct fundamental period. For example Fig. 7 shows the period spectrum of two joined buildings Si1 and Si2 in the Sioufi area (soft soil in Beirut): the spectrum of Si1 (10 floors) displays two pronounced peaks at $T_0 = 0.53$ s and
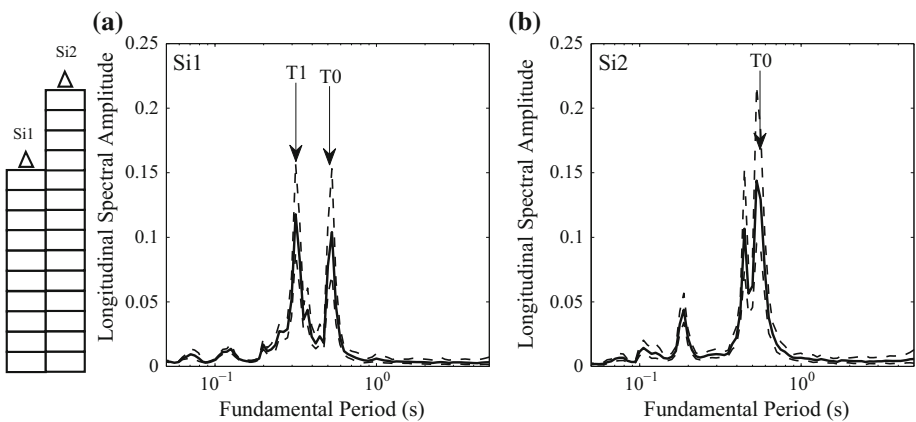

Fig. 7 Example of coupling between 2 connected buildings in Sioufi region (Beirut): period spectrum of the longitudinal component of **a** Si1 and **b** Si2 buildings: the peak of 0.53 s in Si1 spectrum is evidently associated to Si2 block. The *continuous line* corresponds to the average spectrum and the *dashed lines* correspond to the two standard deviation bounds

$T_1 = 0.31$ s; the peak of 0.53 s is evidently associated to Si2 bloc (14 floors), the fundamental period of Si1 is not T_0 but T_1. In our study, 14 % of the buildings were found to be part of a complex block and the remaining 86 % of them are isolated buildings. The lack of joint does not only affect the recognition of the dynamic parameters of the structure, but also causes a major problem when an earthquake occurs: this might lead to mutual pounding, and may eventually result in much higher structural damage:

5.2 Measurement of building damping

Damping is extracted from the ambient noise measurements using the Random Decrement Method (RDM) (Caughey and Stumpf 1961; Dunand et al. 2002). This method consists of decomposing the response of the oscillator into two parts: natural and forced response. The latter becomes negligible with respect to the natural response when stacking a large number of time windows having the same initial parameters. The computation is done using "geopsy" (geopsy.org, last accessed February 2016) software, by taking a band pass of ± 10 % T_0 (s) and a window containing 20 periods with a butterworth filter with an order range from 1 to 5. The graph obtained includes 4 curves representing the mean (solid black line) and mean $\pm$ one standard deviation (dashed black lines) of the Random Decrement and an exponentially decreasing function (solid red line) fitting the envelope of the mean curve (Fig. 6c). In the example illustrated the 7-story building has a damping of 1.14 % in the longitudinal direction at $T_0 = 0.41$ s.

6 Empirical relationships specific to Beirut using ambient vibration

6.1 Comparison with building codes and other empirical relationships

A statistical analysis has been done on the data set of periods (longitudinal and transverse) measured on Beirut buildings in order to find correlations between dynamic and geometrical parameters of the buildings considering also various soil types. All the buildings display a width/length ratio between 1:1 and 1:8 (Fig. 8a). Both longitudinal and transverse fundamental periods (Fig. 8b) are very similar, indicating that the horizontal dimensions of the building do not affect strongly the fundamental period, confirming previous observations in France (Michel et al. 2010) and Peru (Guillier et al. 2014). Figure 8c also shows that the longitudinal and transverse dampings are close leading to the conclusion that the
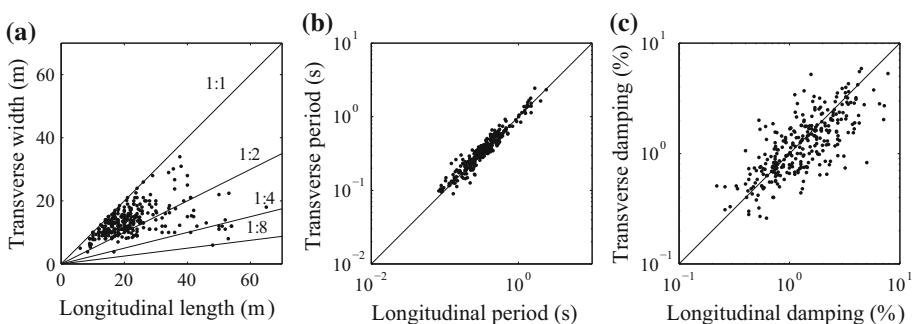

Fig. 8 Geometrical distribution of the measured buildings: **a** transverse width versus longitudinal length, **b** transverse period versus longitudinal period, **c** transverse damping versus longitudinal damping

geometry of the building does not have any significant statistical influence on these two dynamic parameters.

Measured periods are then compared to the values provided by the American, European and old French seismic codes (UBC97 and EC8 [Eq. (6)], PS92 [Eq. (4)]). Figure 9a, b show that the building codes significantly overestimate the experimental period derived from ambient vibrations. In average the ratio between the regulatory period ($T_{theoretical}$) and the measured period ($T_{measured}$) is 2.2 with standard deviation of 0.58 when comparing with UBC97/EC8/Lebanese Code, and 1.5 with standard deviation of 0.44 for PS92. Comparison of the experimental periods with the empirical relationships (linear regression) derived by using ambient vibrations in various countries (Guillier et al. 2014, in Peru; Michel et al. 2010, in Grenoble and Nice; Midorikawa and Jigyodan 1990, in Chile) shows better correlations: in average the ratio between the regulatory period ($T_{theoretical}$) and the measured period ($T_{measured}$) is 0.91, 0.85, 1.07 with standard deviation of 0.2, 0.18, 0.22 in Peru, France and Chile respectively (Fig. 9c). Therefore the measured periods on the buildings in Beirut will be statistically analyzed by using linear regression analysis without any dependence on the building's horizontal dimension, the height being the only parameter statistically meaningful for the fundamental period. These results show that the seismic design in Beirut is not on the conservative side if force-based design is considered (longer periods are associated to lower spectral accelerations). Since seismic actions are generally inversely proportional to the period in the classical force design approach, these actions will be underestimated if the period is overestimated. However an opposite conclusion stands for displacement based design: the oscillator displacement increases with its period, and an overestimation of the period results in an overestimation of the associated displacement, the seismic actions account for designing a structure are then larger.

Thus the overestimation of the period is in this case on the conservative side (Priestley et al. 2007).

Then the second dynamic parameter, the damping ξ, is compared in Fig. 10 with respect to other expressions established using ambient vibration. Lagomarsino (1993) proposed an equation that depends only on the fundamental period T_0:

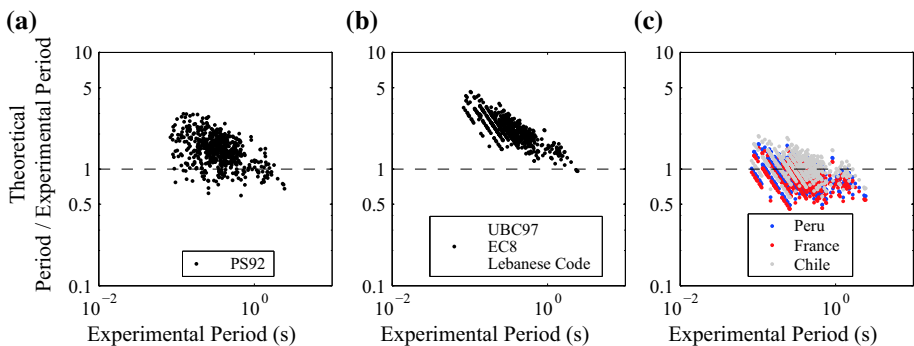$$\xi = 0.72 \times T_0 + \frac{0.70}{T_0} \tag{14}$$

Fig. 9 Comparison between experimental period obtained with ambient vibration method and theoretical period in: **a** PS92 [Eq. (4)], **b** UBC97/EC8/Lebanese code [Eq. (6)], **c** experimental linear correlations obtained in Peru (Guillier et al. 2014), France (Michel 2007), Chile (Midorikawa and Jigyodan 1990)

Fig. 10 Measured damping versus fundamental period in Beirut compared to other relations based on ambient vibration method. The *dashed line* constant value equal to 5 % considered in seismic codes. The *dash-dotted lines* correspond to the 95 % confidence interval for the Beirut buildings trend
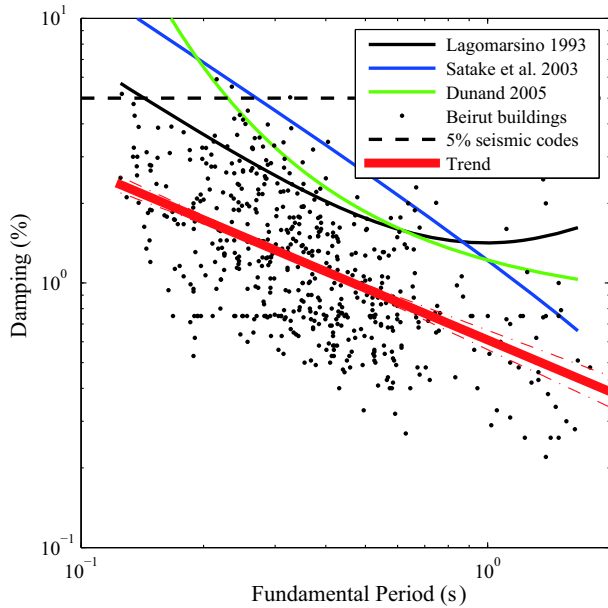
Satake et al. (2003) established a correlation with the period and the amplitude of vibration:

$$\xi = 1.4/T_0 + 47000 \times \frac{x}{H} - 0.18 \tag{15}$$

x is the measured displacement on the top of the building (in meters), H is the height of the building (in meters). The second term can be removed since the amplitude of oscillation from ambient vibration is negligible. Dunand (2005) derived a relationship for periods ranging between 0.125 and 1.7 s:

$$\xi = e^{-0.22+0.42/T_0} \tag{16}$$

Figure 10 shows that the computed modal damping found on Beirut buildings exhibits a clear correlation with fundamental period (hence building height): the higher the building the lower the damping, with typical values around 1 % for 0.5 s (≈ 12 story) buildings and around 2–4 % for 0.125–0.17 s (≈ 3–4 story) buildings. A linear trend seems to exist between the logarithms of damping and fundamental period. In most seismic codes, damping is considered as a constant usually equal to 5 % without any correlation with the fundamental period of the structure. It must be emphasized however, that damping values on Beirut buildings are extracted from very weak motion and caution must be taken to extrapolate these values to higher ground motion levels. Nevertheless, such results underline however the need for a better in-depth understanding of the origin of damping, and its sensitivity to material, structural type, building size, ground motion level and foundations.

6.2 Empirical relationships for Beirut buildings accounting for the soil stiffness

A linear regression is used to correlate the fundamental period to the number of stories as aforementioned. The statistical analysis (Fig. 11a) shows the following correlations [Eq. (17), (18), (19)]:

$$T \approx \frac{N}{23}, \quad \text{on rock site with } R^2 = 0.9 \tag{17}$$

$$T \approx \frac{N}{18}, \quad \text{on soft site with } R^2 = 0.92 \tag{18}$$

$$T \approx \frac{N}{19}, \quad \text{for all data with } R^2 = 0.9 \tag{19}$$

where R^2 is the coefficient of determination. Based on the very good correlations between the period and the number of floors, and given the lack of any influence of the structural horizontal dimension, the building height (or the equivalent number of floors) was identified as the dominant parameter in this relationship. Moreover the close relationships between the two data sets on different types of soil raise the question on whether the two regressions are statistically robust. Statistical tests comparing the residual variances (Fisher–Snedecor Test) and the slopes of the two regressions (Student Test) reveal that the two period-building height correlations for soft and rock sites are statistically different. A linear regression between the logarithms of damping and fundamental period seems to exist for the two types of soil, however with low coefficients of determination due to the large scattering in measured damping values [Eq. (20), (21)]:

$$\log \xi \approx -0.28 - 0.65 \log T, \quad \text{on rock site} \tag{20}$$

$$\log \xi \approx -0.20 - 0.85 \log T, \quad \text{on soft site} \tag{21}$$
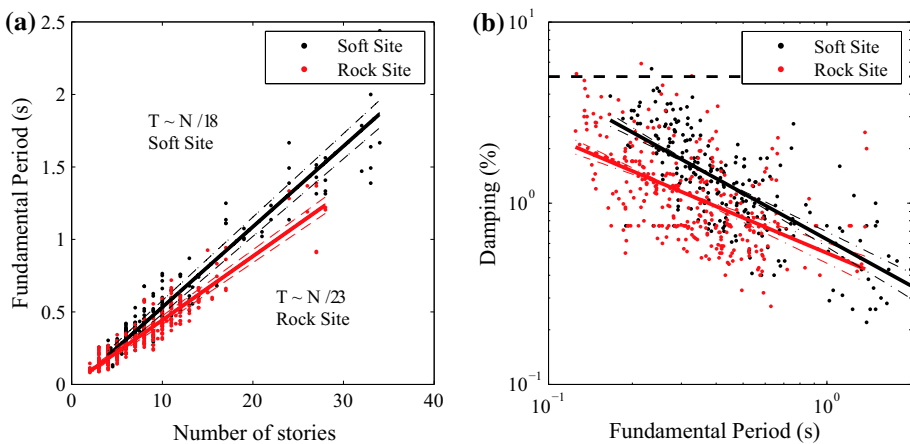

Fig. 11 Correlation, for rock and soft sites, between: **a** fundamental periods (T) and number of floors (N), **b** damping and fundamental period. The *solid lines* correspond to the linear regression and the *dash-dotted lines* to the 95 % confidence interval. The *heavy dashed black line* represents the 5 % damping considered in seismic codes

The Eqs. (20) and (21) show that the higher is the period (or the lower the frequency) the lower is the damping. On the other hand the slight increase of period on soft soils (about 25 %) is associated with a slightly higher damping, as illustrated in Fig. 11b: such observations are consistent with an interpretation in terms of soil-structure interaction: the increased foundation flexibility lengthens the period of the soil-structure system, and the associated wave radiation from the foundation increases the system damping. Finally, statistical hypothesis test (Student Test) shows that, under the null hypothesis H_0, $\xi = 5\ \%$ is rejected and damping is significantly different than the value of 5 % used in the seismic codes (with a 5 % significance level).

Further correlations are made to investigate whether the introduction of the Lebanese seismic code in 2005 had some influence on the fundamental period of the buildings in Beirut. Figure 12 indicates that no significant difference can be found between fundamental period-number of floors relationships before and after 2005 whatever the soil types. Additional measurements should be carried out in order to have a better statistical database for such comparison.

Another comparison is performed between the measured periods and periods related to the linear part of the capacity curve used in the empirical methods of large-scale vulnerability estimation such as HAZUS (FEMA 1999) or Risk-UE (Lagomarsino and Giovinazzi 2006; Milutinovic and Trendafiloski 2003). In these methods, building is defined with respect to its typology and its height: for reinforced concrete buildings, Low-Rise = 1–3 floors, Medium-Rise = 4–7 floors, High-Rise = higher than 7 floors. Most of the buildings in Beirut correspond to the RC1 (concrete moment-resisting frames) category according to the RISK-UE typology (Lagomarsino and Giovinazzi 2006), whereas they correspond to the C1 (Reinforced Concrete Moment Resisting Frame) or C3 (Concrete Frame Buildings w/Unreinforced Masonry Infill Walls) category according to the Hazus typology (FEMA 1999). It is in addition considered that they correspond to the "moderate code" case, i.e. Beirut buildings are designed for moderate seismic loading. Figure 13 reveals that such large-scale vulnerability methods largely overestimate the experimental period for buildings up to 25 floors and probably underestimate it for buildings over 25
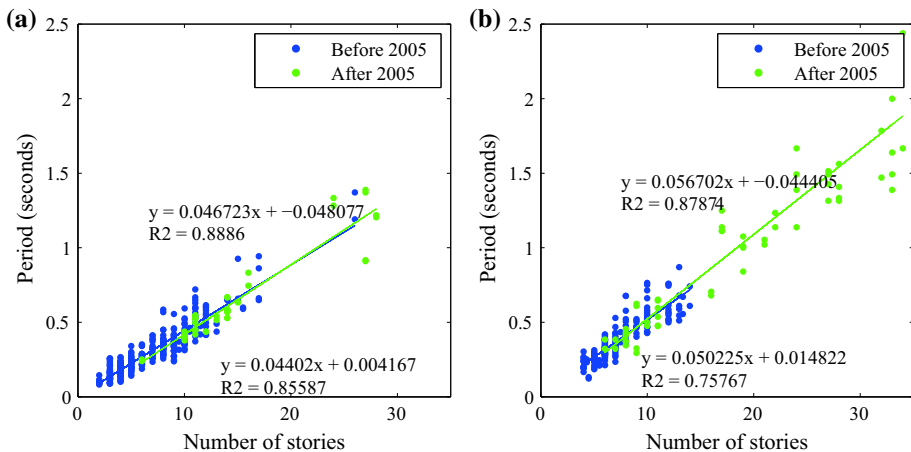

Fig. 12 Correlations of the fundamental periods (T) and number of floors (N), for pre and post seismic code (2005): **a** for rock sites, **b** for soft sites

Fig. 13 Comparison between the experimental periods based on ambient vibration method on rock and soft sites and the theoretical periods used in large-scale empirical methods for vulnerability estimation Hazus (FEMA 1999), Risk-UE (Lagomarsino and Giovinazzi 2006)
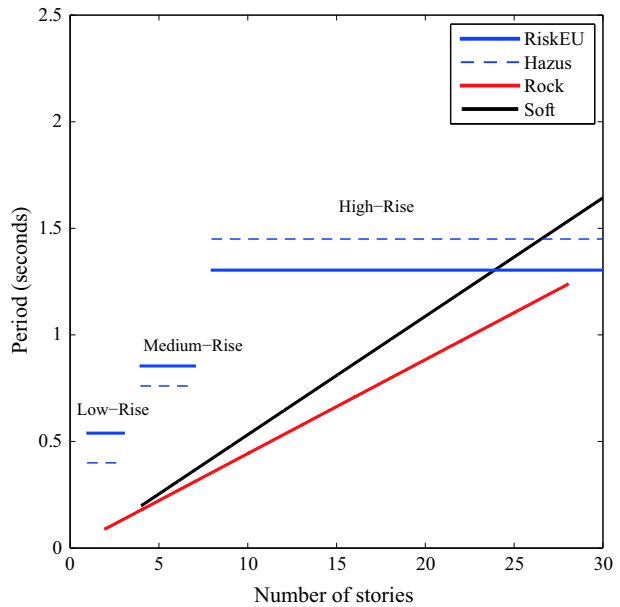
floors. Obviously such large overestimation may have a strong influence on the damage and seismic risk assessment. Therefore the in situ recording of ambient vibrations can be a very important tool to calibrate and adjust the linear part of the capacity curves.

7 Discussion

It can be observed that the database acquired in Beirut is very large (330 RC) compared to the ones obtained in different countries in the world giving more statistical weight to the study.

The analysis of the buildings set shows that the fundamental period of the structure does not depend on its horizontal dimensions but only on its height, a conclusion that was found by most authors using ambient vibration methods (Michel et al. 2010; Guillier et al. 2014);

A linear regression rather than a power-law form exists between the fundamental period T and the number of floors N (or equivalent height) similar to the relationships found in various countries in the world with the following form: $T = N/C_N$, C_N being a constant;

One originality of this study lies in the heterogeneity of the soil in Beirut. Two different correlations between the period and the height (or equivalent number of floors) are found whether the structure is built on rock ($T \approx N/23$) or soft sites ($T \approx N/18$). The larger period on soft soil is consistent with the larger damping witnessing soil-structure interaction phenomena. The constant C_N is thus significantly influenced by soil stiffness. The value obtained in this study is close to the ones found in Portugal by Oliveira (2004) ($C_N \approx 24$), in Peru by Guillier et al. (2014) ($C_N \approx 24$), in France by Michel et al. (2010) ($C_N \approx 25$).

As for the second dynamic parameter (damping), a linear regression correlates the logarithms of the damping and the fundamental period without any clear influence of the

horizontal dimension; the decrease of damping with period is not consistent with what is considered in the seismic design codes. The decrease of damping with increasing period is larger for soft soil than for rock site which can be explained by radiative damping when buildings are constructed on soft sites. Indeed, the oscillations in the structure generate waves that propagate in the soil dissipating a part of the energy of deformation (Guéguen 2000). This result was also noticed by Dunand (2005).

Consistently with the previous ambient vibration measurements listed in Table 1, the measured periods are much shorter than those recommended by most building codes. The overestimation raises the alarm on whether the application of the code is conservative when an earthquake occurs. This fact is also noticed in the large-scale vulnerability methods that associate constant values for the period for three categories of buildings related to their height whereas the experimental results clearly show that period linearly increases with building height.

8 Conclusion

A campaign was held in Beirut since 2012 to perform ambient vibration measurements in nearly 330 RC buildings equivalent to 660 measures along the length and width of the buildings both on soft sites and rock conditions. The correlation between the measured fundamental periods and associated damping values and the building geometrical and soil stiffness characteristics is investigated, and compared not only with similar and previously established relationships worldwide, but also with the recently introduced Lebanese seismic code. Statistical analysis shows that only the height of the building has a significant influence in the determination of the fundamental period of the structure. The latter is found to be linearly correlated with the number of floors ($T = N/C_N$) or alternatively with building height H, with a proportionality coefficient, C_N, that increases for soft soils due to soil-structure interaction. Two relationships that are statistically different are defined according to the soil type:

- $T \approx N/23$, for rock sites
- $T \approx N/18$, for soft sites

It can be concluded that the fundamental period depends on the soil type the building is constructed on. These equations are very similar to the ones obtained in different areas of the world using the ambient vibration method. In addition, structural damping is found to decrease with increasing fundamental period which is again consistent with previous observations. The comparison with the values recommended in the Lebanese Code that uses UBC97 and EC8 provisions indicates that the latter overestimate the periods by a factor around 2, while the constant 5 % damping values largely overestimate the measured ones for high-rise buildings (around 1 %). The measured damping ξ in percent is correlated with the period with respect to the following equations:

- $\log\xi \approx -0.28$ to $0.65\log T$, for rock sites
- $\log\xi \approx -0.20$ to $0.85\log T$, for soft sites

This overestimation is also noticed when comparing with French seismic code PS92 and the large-scale vulnerability methods (Hazus and Risk-UE). Therefore it seems that the Lebanese seismic code is not on the safe side when using the force-based design approach,

especially as the measured damping for high-rise building is much lower than 5 % conventional value.

Seismic provisions generally tend to increase stiffness of buildings, thus one may expect a decrease in the fundamental period of the structure for post-2005 buildings. However the database acquired in Beirut does not exhibit any significant difference. Additional measurements are required to better conclude whether the introduction of the Lebanese code in 2005 for buildings of 4 stories and above (or more than 10 m) has some influence on dynamic parameters.

Ideally, independent correlations should be established for the buildings with construction periods from 1950 up to now which require additional measurements, with special emphasis on the civil war period buildings from 1975 to 1990. This will help in analyzing whether the civil war (1975–1990) has a certain impact on the structure. In fact this chaotic period has faced a lack of quality control of material and a series of construction and reconstruction of buildings.

These results could be used to improve the seismic code with some specific provisions for the Beirut area; therefore it is recommended to review the Lebanese seismic design based on experimental measurements, and may be additional ones.

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