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# VII. Dynamic properties of buildings evaluated through ambient noise measurements

Panzera F., Lombardo G., D'Amico S., Galea P., Torrisi A.

## 1. Introduction

It is well known that the damage level and its distribution during an earthquake is due to the combined effects of seismic hazard in the investigated area, the features of the local site response, based on the near–surface and subsurface ground conditions, as well as on the dynamic features of the erected buildings. The extent of building damage and its distribution is indeed tightly linked to the combined effect of local site response and the dynamic features of the human-made structures. The dynamic properties of a building are usually described through its natural frequency (or period $T$) and the damping ratio ($\zeta$), the latter representing the energy loss of an oscillating system. The damping ratio is important in seismic design since it allows to evaluate the ability of a structure to dissipate the vibration energy during an earthquake. Such energy causes a structure to have the highest amplitude of response at its fundamental period, which depends on the structure's mass and stiffness. The knowledge of damping level and fundamental period of the building is therefore particularly important for estimating the seismic base shear force $F$ in designing earthquake resistant structures. Following the Eurocode8 (2003), $F$ can be expressed as:

$$F = Sa(T;\zeta)\cdot m\cdot\lambda \tag{1}$$

where $Sa(T;\zeta)$ is the ordinate of the target spectrum at period $T$ and damping $\zeta$, $m$ is the total mass of the building above the foundation (or above the top of a rigid basement) and $\lambda$ is a correction factor. The $Sa(T;\zeta)$ is evaluated considering the local geological features, which influence the site response in term of amplification of the ground motion, as the seismic input travels from the bedrock to the overlying soil deposits.

In the frame of the joint Italo–Maltese research project (Costituzione di un Sistema Integrato di Protezione Civile Transfrontaliero Italo–Maltese, SIMIT), financially supported by the European Community present research was performed in order to evaluate dynamical properties of erected buildings. The intent is to outline the dynamic response of buildings into the features of the local seismic response of various test areas in order to highlight the regions in which major seismic site effects can occur as a function of the outcropping lithology. In this way it would be possible to point out amplification effects occurring at frequencies comparable with those observed for manmade structures, which may cause a pronounced increase of damage. In the present study we show the results of the buildings dynamic response evaluated in the cities of Catania, Siracusa, Lentini, Carlentini e Lampedusa (see Fig. 1) through experimental measurements based on ambient noise recordings.

## 2. Geology, seismic features and characteristics of the built–up in the study area

The study area is located in the south eastern portion of Sicily and in the Sicily Channel. The Catania area shows complex features with lateral heterogeneities at a local scale, due to the presence of volcanic and sedimentary units (Monaco *et al.*, 2000). The sedimentary substratum of the urban area is formed of a sequence of Quaternary clays, up to 600 meters thick, overlain by several tens of meters of sands which, together with conglomerates and silty clays, several meters thick, outcrop in the southern part of the area. The most extended lithotype outcropping in city area is represented by several meters of lava that cover almost the entire city substratum and altering the original morphology. Finally, in the historic core of the city, the upper stratigraphic horizon consists of several meters of detritus, largely resulting from the destruction of buildings during the 1693 earthquake. The other investigated areas (Siracusa, Lentini, Carlentini e Lampedusa) represent the outcropping part of the Africa foreland domain, the Hyblean plateau, which is mainly formed by a carbonate sequence with interbedded volcanics (Grasso and Lentini 1982; Grasso and Pedley, 1985). These sediments are distinguished in two main units, having similar geotechnical features, known in the literature as Mt. Climiti and Mt. Carruba formations. The former, having thickness ranging between 20 and 80 m, lies on the Cretaceous volcanics and consists of compact and well cemented calcarenites, the latter, with an average thickness of about 20 m, is characterized by alternating calcarenites and marlstones. In some sites, as for instance in the southern part of Siracusa, sands and sandy clays, up to 20 m thick, and alluvial deposits overlie the carbonate bedrock. Moreover, detritus having thickness of about 6-8 m, due to anthropic activity and historical ruins, outcrops in the Ortigia peninsula, the Siracusa downtown (a detailed description of geologic and structural features is reported in Panzera et al, this volume).

The investigated area is one of the Italian zones having a high seismic hazard. Several studies (Azzaro and Barbano, 2000; Barbano *et al.*, 2001; Panzera *et al.*, 2011a,b) show that the seismic history of this region is characterized by large events (1169, 1542, 1693) having a moment magnitude ranging from 6.2 and to 7.3 (Working Group CPTI, 2004), and enhancement of seismic effects was usually observed as a consequence of local geo-lithologic features. The last twenty years of recoded seismic activity show epicentres sparsely located in all the area and the most important moderate size instrumental seismic event occurred on December 13th 1990 which, although its moderate magnitude ($M_W$=5.7; Rovida *et al.*, 2011), was felt throughout Sicily and caused the collapse of a few buildings.

The built–up in the study area consists of both masonry (MA) and reinforced concrete (RC) buildings. Masonry buildings (MA) show some differences in the architectural features that according to Faccioli *et al.* (1999) can be summarized as follows: buildings erected in the 18th and 19th centuries by wealthy citizens, which are regular and well constructed, with well cut volcanic stones cemented with good quality mortar and vaulted ceilings; buildings typically constructed for lower-class people, until the late 1960s, often composed of two–three floors, having a lower quality of construction with ashlars typically obtained from either volcanic stones or from limestone / calcarenites using as mortar lime, sand and ash of volcanics or limestones; buildings constructed in the 20th century, until about 1946–1950, with unreinforced masonry walls and steel or concrete floors, generally having good connections between walls and floors. Masonry buildings typology was predominant until 1950, and it turn out to be the majority of edifices erected in the historical part of the towns. Reinforced concrete buildings (RC) reached the maximum development in the seventies and eighties and represent the widespread architectural typology in the new parts of the city. They were mostly erected after the expansion of the cities in the 1960s. Usually RC buildings have up to about 6 stories and hollow-tile infill walls. It must be noticed that in eastern Sicily the seismic code provisions were enforced only as late as the 1980s. This implies that, in older buildings, beams are present only where they are needed for supporting floors or heavy infills. Consequently, such buildings are likely to have a regular shape with frames that sometimes prevail in one direction only, therefore affecting the strength of the construction to torsional modes (Faccioli *et al.*, 1999).

## 3. Methodology

We know that the dynamic properties of a building are usually described through its natural frequency and the damping ratio.

The seismic performance of a building obviously depends on the progression of the frequencies along the input time–history. Nevertheless the knowledge of its fundamental frequency at low amplitude values and the associated damping are of primary importance to characterize the initial seismic behaviour of a structure (Mucciarelli & Gallipoli, 2007a).

The engineering practice usually derives the dynamic behaviour of buildings through numerical or experimental methods (Gallipoli *et al.*, 2009 a,b; Oliveira and Navarro, 2009). Generally, empirical relationships are achieved which estimate building resonant periods as a function of either the height or the number of floors (Satake *et al.*, 2003; Gallipoli *et al.*, 2009b; Panzera *et al.*, 2013).

The experimental technique typically adopted to evaluate the building fundamental period is to identify the vibration mode shapes obtained by the records of two or more sensors monitoring the motion at different locations in the building. Undoubtedly, the best approach would be to adopt earthquake records as exciting source. However, due to the need of a long observation time and to the high cost, this method can only be used in a small number of buildings which can be taken on as case studies. The results obtained for different typologies of buildings are often processed, through statistical regression analysis, to achieve empirical relationships that let the estimate of building resonant period $T$ as a function of the buildings geometry, usually either the height $H$ or the number of floors $N$ (e.g. Messele & Tadese 2002; Crowley and Pinho 2006; Panzera *et al.*, 2013) and the damping $\zeta$ versus period $T$ (e.g. Navarro & Olivera, 2004; Satake *et al.*, 2003).

In the present study the dynamic response of buildings was estimated through experimental measurements based on microtremor recordings obtaining the fundamental frequency through spectral ratio techniques. This methodology, originally adopted as a quick estimate of the seismic site response (Nakamura 1989), has shown to be in

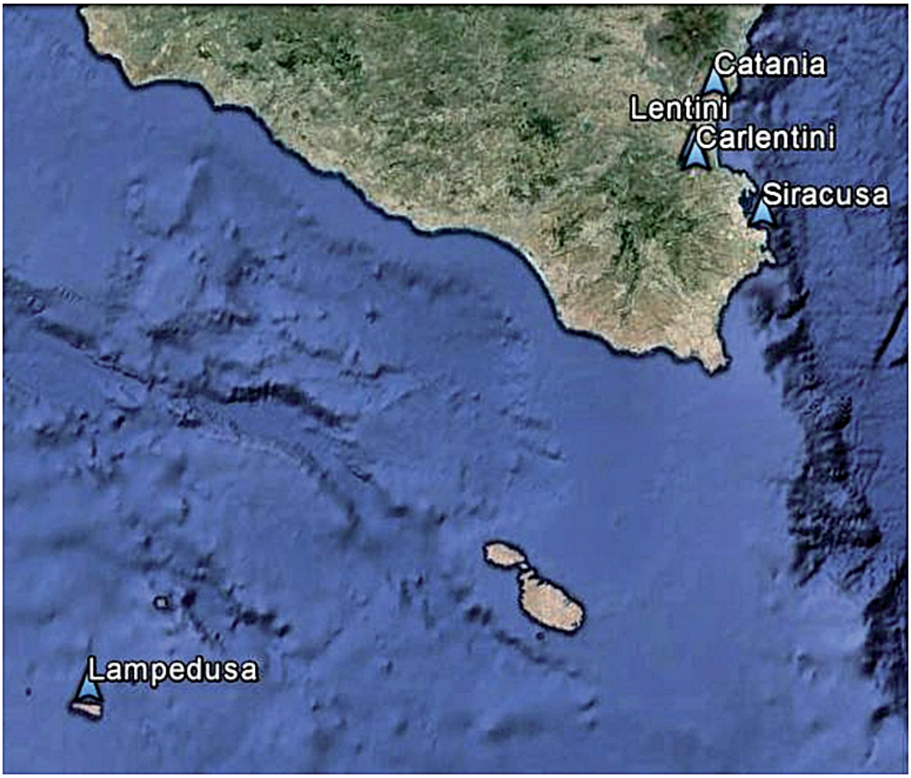

**Figure 1.** Geographic locations of the investigated areas.

good agreement with results obtained from both numerical modelling and other experimental techniques, in estimating the dynamic properties of buildings (e.g. Oliveira & Navarro 2009). The fundamental period of the buildings is obtained by computing the ratio between the amplitudes of the Fourier spectrum of horizontal components of motion, recorded on both the top and the ground floor. This method is also known as standard noise spectral ratio (SNSR) technique. During data acquisition the seismometer is usually placed at the geometrical center of the top floor in the stairwell, assuming that this point coincides with the center of mass of the floor and as close as possible to the RC frame to minimize vertical modes of beams or floors. To observe the influence of the geometry, the two main axes of sensors are oriented as coincident with the main directions of the building (NS ≡ T ≡ transverse ≡ minor axis; EW ≡ L ≡ longitudinal ≡ major axis) in order to better highlight their respective contribution. In the present study, both the horizontal to vertical noise ratio (HVNR) and the standard noise spectral ratio (SNSR) techniques were used to identify the building's fundamental frequencies. Measurements were performed in 106 buildings distinguished according to their construction typology into 44 masonry buildings (MA) and 62 reinforced concrete (RC) buildings. Going into more details, 48 (18 MA and 30 RC buildings were monitored in Siracusa, 37 (20 MA and 17 RC) in Catana, 16 (9 MA and 7 RC) in Carlentini-Lentini and 5 (2 MA and 3 RC) in Lampedusa. As fundamental period for each building we considered the peak with the higher amplitude in both HVNR and SNSR, evaluating for each curve the related average ±1ς confidence interval. Ambient noise was recorded using a three–component velocimeter (Tromino) sampling the signal at a frequency of 128 Hz. In each building, 10 minutes length of ambient noise were recorded both at the top and at the ground floor. According to the guidelines suggested by the European project Site EffectS assessment using AMbient Excitations (SESAME 2004), time windows of 10 s were considered, selecting the most stationary part and not including transients associated to very close sources. Fourier spectra were calculated in the frequency band 0.5–15 Hz and smoothed using a triangular average on frequency intervals of ± 5% of the central frequency. Figure 2 shows few examples for typical MA and RC buildings in the area of Catania and Siracusa whereas, in Figure 3 some examples of HVNRs obtained from measurements performed in both residential and public buildings in Lampedusa, are shown.

The damping ratio evaluation is quite complex being a not intrinsic parameter of the building. Recently, the Random Decrement Technique (Randomdec) has been proposed to determine the damping ratio of RC buildings using ambient noise measurements. This technique, first developed by Cole (1968), has proved to be appropriate for evaluating the damping of dynamic systems excited from an unknown random source, as for instance the microtremor (e.g. Dunand *et al.*, 2002; Navarro *et al.*, 2002). Such analysis is not depending on the excitation input but only requires the measured output of the dynamic response of a structure. In this way the response due to initial displacement, representative of the free vibration decay curve of the system, is obtained. In the present study, damping ratio was estimated in the buildings located in the Siracusa area only since in this area was monitored the highest number of buildings. We adopted the nonparametric analysis (NonPaDAn) approach (see Mucciarelli & Gallipoli, 2007b) which allowed us to plot in a 3D contour the pseudo–frequency, the damping values $\zeta$ and their relative occurrence frequency (see examples in Figure 4 left panels). Moreover, to verify the goodness of damping estimates for each building, the Kolmogorov–Smirnov test (KST) is applied. Such test is in particular used to decide if a sample comes from a population with a specific distribution. The graphs in Figure 4 (right panels) show an example of the empirical distribution function with a normal cumulative distribution function (CDF) for 25 normal random numbers. The KST is based on the maximum distance between these two curves and the null hypothesis is rejected if the two CDFs derive from the same distribution with a 95% confidence level.

Finally, a preliminary test was performed in Lampedusa island in order to set up a computer approach aiming to automate the evaluation of the building heights in an urbanized area. The used method allow us to extract, through a Geographic Information System (GIS), the building tallness as the difference in the heights mapped through a DSM (Digital Surface Model) and a DTM (Digital Terrain Model). Since the DSM plots the earth surface including objects on it whereas, DTM draws into a map the earth surface only without any objects, the difference between the two elevation models gives back the buildingheights (Fig. 5). Such procedure, together with the experimentally obtained period–height relationships could be adopted as a method to perform a quick survey aiming to characterize the dynamic properties of buildings in a urbanized area.

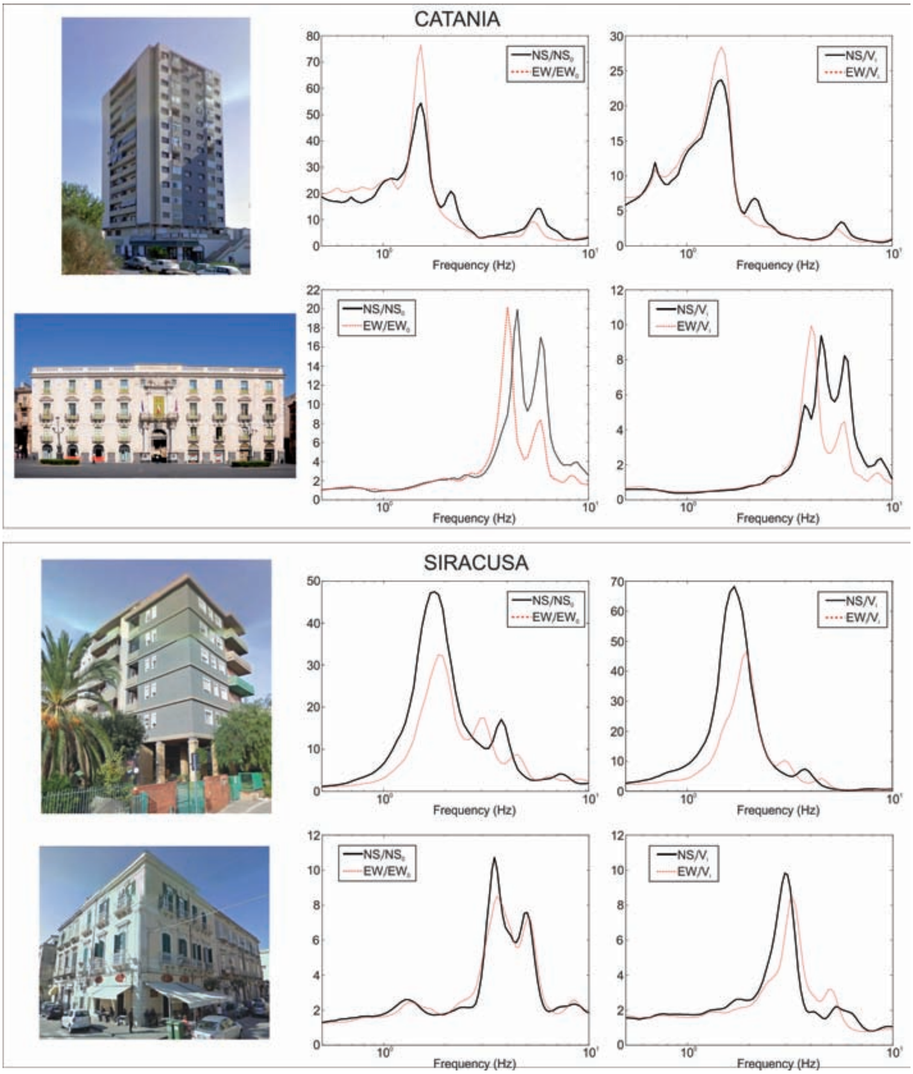

**Figure 2.** Examples of HVNR and SNSR for typical RC and MA buildings in Catania and Siracusa. The y–axis specifies the amplitude ratio.

## 4. Description of results

The inspected buildings, besides their different structural features, exhibit clearly different characteristics both in the plan shape and in elevation with *T* values ranging between 0.09 s and 0.80 s. The fundamental periods obtained through the HVNR technique show values quite similar to the ones obtained through the SNSR method. Another important aspect that was highlighted, through measurements in our tested buildings, concerns the observed difference between periods evaluated for the longitudinal (L) and the transverse (T) directions. This difference, that ranges between -0.09 s to 0.25 s, can be interpreted as a consequence of the different rigidity of the building which is also dependent on its geometry. Indeed, the results show that in most of the examined buildings a larger deformation is observed in the transverse direction rather than in the longitudinal one. Such

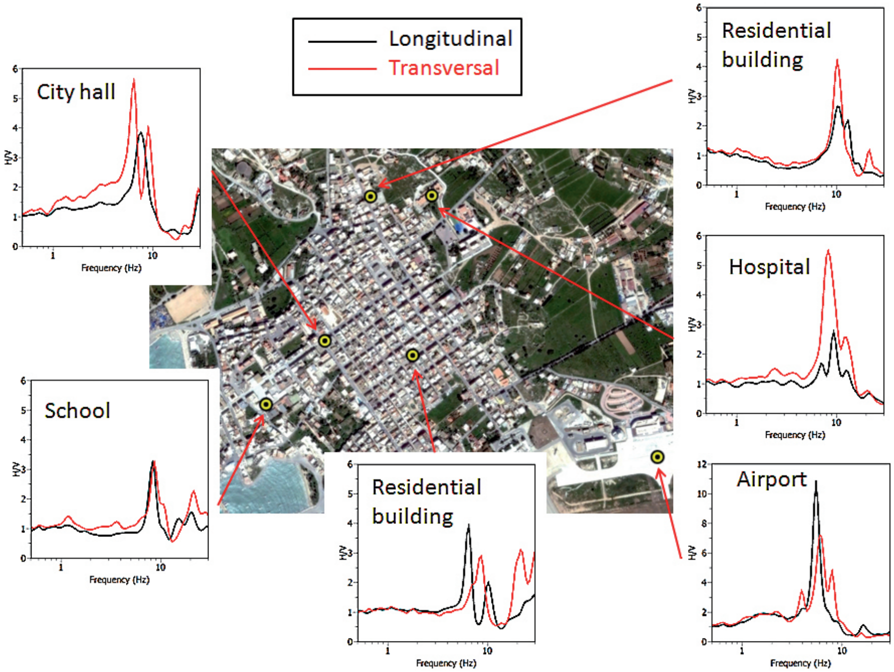

**Figure 3.** Examples of HVNRs from ambient noise recordings performed in some buildings in Lampedusa island.

effect is testified by the lower frequencies which are predominant in the direction parallel to the transverse (shorter) side of the structure.

Figure 6 (left panel) shows the experimental fundamental periods as a function of height for the considered cities, whereas in the right panel the period vs height, discriminating RC from MA buildings, are reported. We also derived a functional form for the fundamental period regressing the observed data and taking into account both HVNR and SNSR periods for both vibration directions.

It is worth noting that significant differences are observed between fundamental periods of buildings in RC and MA which are mostly located in the historical part of each considered city. These differences are likely due to the role played by the stiff masonry infills on the fundamental period of edifices. This aspect has been widely discussed by several authors (Masi & Vona 2009 and references therein) that have pointed out as the existence of infill walls has the effect of increasing the mass and lateral stiffness of the system. Moreover, it was observed that in the evaluation of fundamental periods, the influence due to

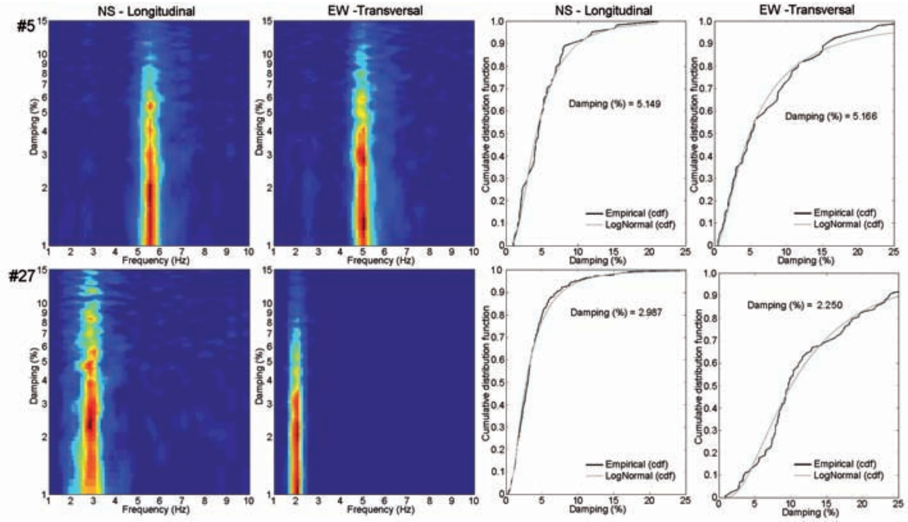

**Figure 4.** Examples of damping ratio evaluated for longitudinal and transverse components of motion, using the NonPaDAn technique. Left panels show the 3D contours of the relative occurrence frequency of each damping value, *x–axis* frequency (Hz) and *y–axis* damping (%). Right panels show the Kolmogorov-Smirnov test to verify the quality of damping computation.

the presence of connected adjacent buildings has to be taken into account. Contiguous structures add indeed their own eigenfrequency to the one of the studied structure, and this as observed by Boutin & Hans (2009), can affect the vibration mode of the studied building, decreasing its original value by about 10%.

The period–height relationships obtained from the present research are also compared with the fundamental period–height relationships (Fig. 6 right panel) provided by the Eurocode8 (2003; EC8–RC; EC8–MA). It is worth noting that the equations provided by the Eurocode8 (2003) both for RC and MA buildings show important differences with the curves obtained in this study.

A possible explanation for this disagreement may be found in the use of ambient noise that is a low energy input source. Hong & Hwang (2000) and Trifunac *et al.* (2010) observe also that the fundamental period of buildings, designed according to the seismic code, usually shows a period much lower than the value expected during earthquakes. However, we believe that the level of shaking cannot be considered as the only issue responsible for the observed discrepancy between experimental and Eurocode8 (2003) period–height relationships. We rather think that the most likely explanation has to be found in the contribution linked to the presence of infill walls. They induce a pronounced stiffness increase that implies a decrease of the fundamental period of the building and consequently a change of its seismic response (Cinitha *et al.* 2012). Through measurements performed on a frame, before and after the implementation of infills, Mucciarelli &

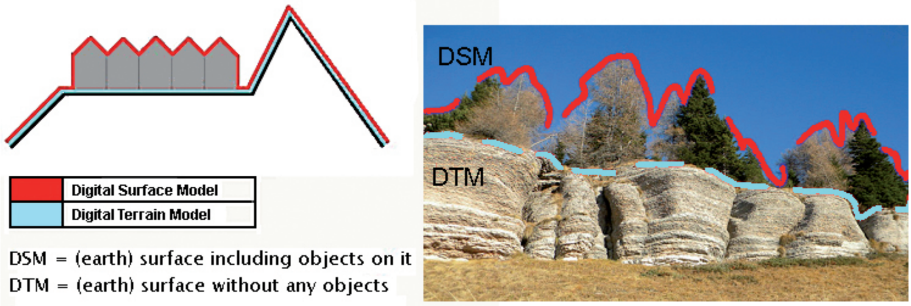

**Figure 5.** Sketch showing the differences between a Digital Surface Model (DSM) and a Digital terrain Model (DTM).

Gallipoli (2007a) observed indeed a frequency increase of 1.5 times due to the role of the stiffness of masonry infills. Modern codes do not consider the contribution of the infills, trying to obtain a diffuse damage on a RC frame that is designed with adequate ductility resources whereas, existing buildings may show a completely different behavior.

A support to the aforementioned explanation that stresses the influence of stiffness on fundamental period, is obtained by analyzing the damping results evaluated for the buildings tested in the Siracusa area. The scatter-plot of damping, performed with the NonPaDAn technique, versus fundamental period is shown in the upper left panel of Figure 7. The results suggest an inverse relationship with the natural period, in agreement with results obtained elsewhere for the low–amplitude damping by other authors (e.g. Lagomarsino, 1993; Satake *et al.*, 2003; Navarro & Oliveira, 2004). The values of the damping factor for longitudinal and transverse components range between 2.1% and 19.2% with an average value of 7.1% showing a large standard deviation (4.1%) as can be deduced from the highly scattered damping values reported in the upper right panel of Figure 7. Summarizing the damping results it can be affirmed that the MA buildings, by and large located in Ortigia and in all the historic parts of the cities, are more stiff than the RC buildings. It is such different stiffness which, obviously, depends on the buildings geometry, that in our opinion

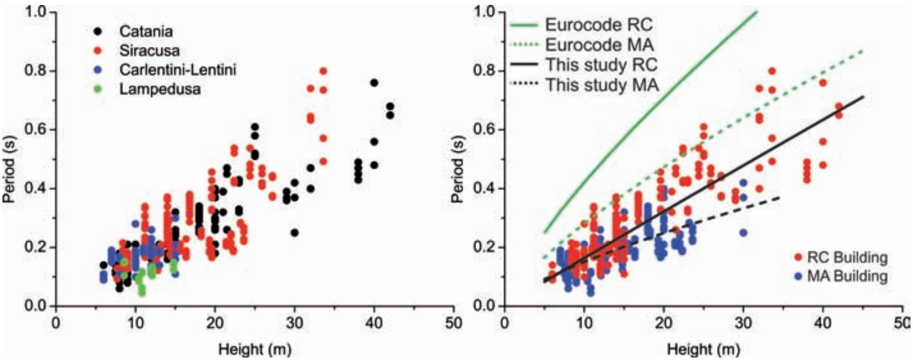

**Figure 6.** Period-Height experimental values observed for the monitored buildings located in the investigated towns (left panel) and comparison with relationships obtained by Eurocode8, 2003 (right panel).

significantly affects the fundamental period behavior.

The stiffness of a building can change with the altitude. For this reason in Figure 7 is displayed the modal shape of two buildings calculated against their height. The RC building (lower left panel in Figure 7) shows a homogeneous mode shape in both the longitudinal and transverse directions with amplitude that increases with increasing height. On the other hand the MA building (lower right panel in Figure 7), built with adjacent constructions as well, shows a modal shape that changes significantly both with increasing height and when the two directions are considered. This behavior is probably linked to its stiffness but, the interaction with neighboring buildings plays an important role on the dynamic properties too.

We also performed a test in Lampedusa island, seeking to achieve the building heights through a computer analysis. Figure reff7-8 shows the results obtained by subdividing the buildings into classes of height distinguished by different colors. It is interesting to observe that the used method of evaluation, allowed a quick survey of the building tallness, obtaining it as the difference between the DSM and the DTM.

As a result, it appears evident that the majority of the buildings erected in the urban area have heights not exceeding 7.5 m (just about two floors). The only exceptions are some public edifices, such as the church, that may reach the tallness of 15 m. As regards the buildings located outsides the urbanized area, almost all of them are made up by one floor only (2.5 m).

## 5. Concluding remarks

In this study we evaluated the dynamical properties of buildings discriminating them into masonry (MA) buildings, mostly erected in the historic parts of each considered city, and reinforced concrete (RC) buildings prevailing wherever the modern urbanization has grown. The results obtained allow us to confirm that spectral ratios of the ambient noise measurements provided reliable estimates of the fundamental period of analyzed buildings. To summarize the findings so far obtained, it can be stated that:

— The measurement performed allowed us to infer the fundamental period of the investigated buildings, showing that there was no particular soil–to–structure effects. More pronounced and dominant spectral ratio peaks were observed in tall and isolated buildings. On the other hand, secondary spectral ratio peaks were observed in case of adjacent buildings, independently from their typology of construction;

- fundamental periods experimentally estimated were used to obtain period–height relationships which set into evidence that the experimental values are lower than those postulated by Eurocode8 (2003). Such finding could be explained by considering the contribution of the infill walls that modern codes do not adequately consider. They induce a pronounced stiffness

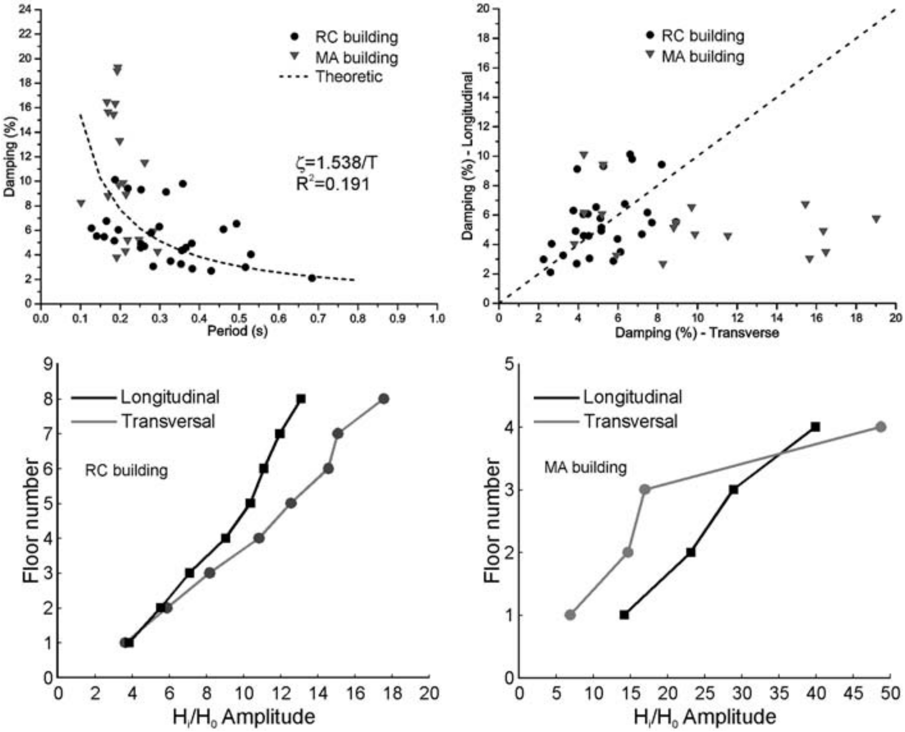

**Figure 7.** Damping vs. Period from experimental values obtained through the NonPaDAn technique (upper left panel) and scatter plot of damping for the longitudinal and transverse components of motion (upper right panel). Modal shape of buildings vs. floor number for an RC building (lower left panel) and a MA building (lower right panel).

increase that implies a decrease of the fundamental period of the building and therefore a change of its seismic response;

- considering separately the evaluation of building periods along the longitudinal direction from that evaluated along the transversal one, different estimates are obtained according to the plan shape of the structure. In particular, lower frequency values are observed in the direction parallel to the shorter side, indicating that larger deformations take place in the transversal rather than in the longitudinal direction of the building;
- significant differences were observed between the fundamental periods obtained for RC and MA buildings, the former being usually higher than the latter. This behaviour appear related, as suggested by the results of damping estimates, to the different stiffness of the structures and to the presence of connected adjacent buildings, especially in the historical centres of the various towns;
- the test survey performed in the Lampedusa urbanized area, set into evidence that the buildings elevation estimate, obtained as the difference between the Digital Surface Model and the Digital Terrain Model, represents a useful tool for a quick assessment of buildings heights.

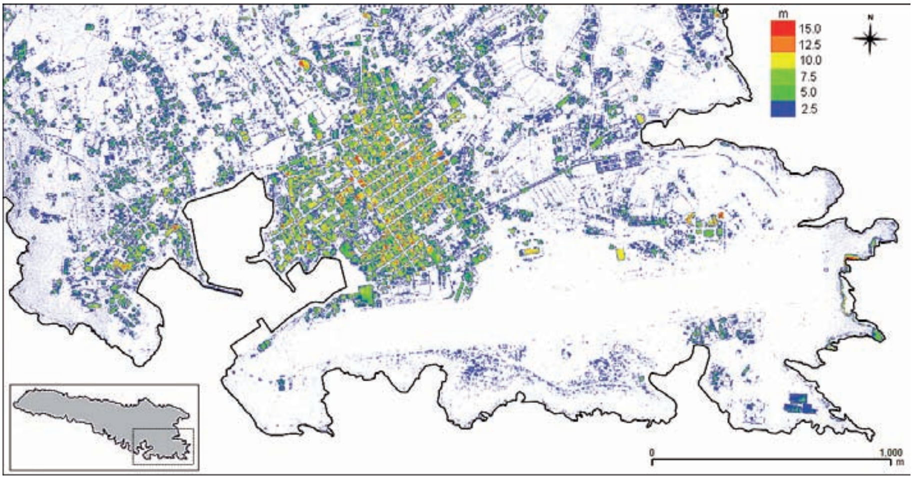

**Figure 8.** Classes of building heights in Lampedusa, obtained as difference between DSM and DTM.

We can in conclusion affirm that the use of ambient noise records showed to be a reliable and not expensive technique for a quick characterization of the local seismic response and the experimental evaluation of building fundamental periods, as well as investigations about potential critical conditions linked to possible soil–to–structure interactions. As a final point, it is worth to remember that this kind of studies appear to be particularly useful to governmental agencies tasked with emergency response and rescue.

Panzera F.[1], Lombardo G.[1], D'Amico S.[2], Galea P.[2], Torrisi A.[3]

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[1] Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Università di Catania, Italy. Corresponding author: Panzera F., fpanzera@unict.it.

[2] Department of Geosciences (previously at Physics Department), University of Malta, Msida, Malta.

[3] Dipartimento della Protezione Civile, Servizio Regionale di Protezione Civile – Catania, Italy.