

DYNAMIC CHARACTERISTICS OF MALTESE BUILDINGS

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Introduction. The Maltese archipelago is classified as having low-to-moderate seismic hazard with a generally low level of seismic activity around the island, while being exposed to rare, large events originating at nearby major tectonic features such as in SE Sicily. However, being exposed to a high building density means that the Maltese Islands are subjected to a considerable seismic risk. To reduce such risks it is important to understand how buildings will respond to seismic shaking and predict possible resonance phenomena.

Building response to ground motion is as complex as the ground motion itself, and depends on numerous properties of the building. Seismic waves released at earthquake sources approach the base of a building from a given direction. Horizontal and vertical ground motions lead to different types of forces on the building, such as tension, shear, compression, bending or torsion forces. As discussed by Albarello (2013), ground shaking can be described as a linear combination of simple harmonic oscillations. For this reason, an earthquake's effect on a structure can be mainly studied by considering the effect of a single oscillation. Buildings experience mostly horizontal ground motion due to seismic body S waves generated during an earthquake. If these horizontal distortions are large, the damage may be disastrous. In fact, most buildings are designed to resist lateral forces in order to minimize the amount of damage

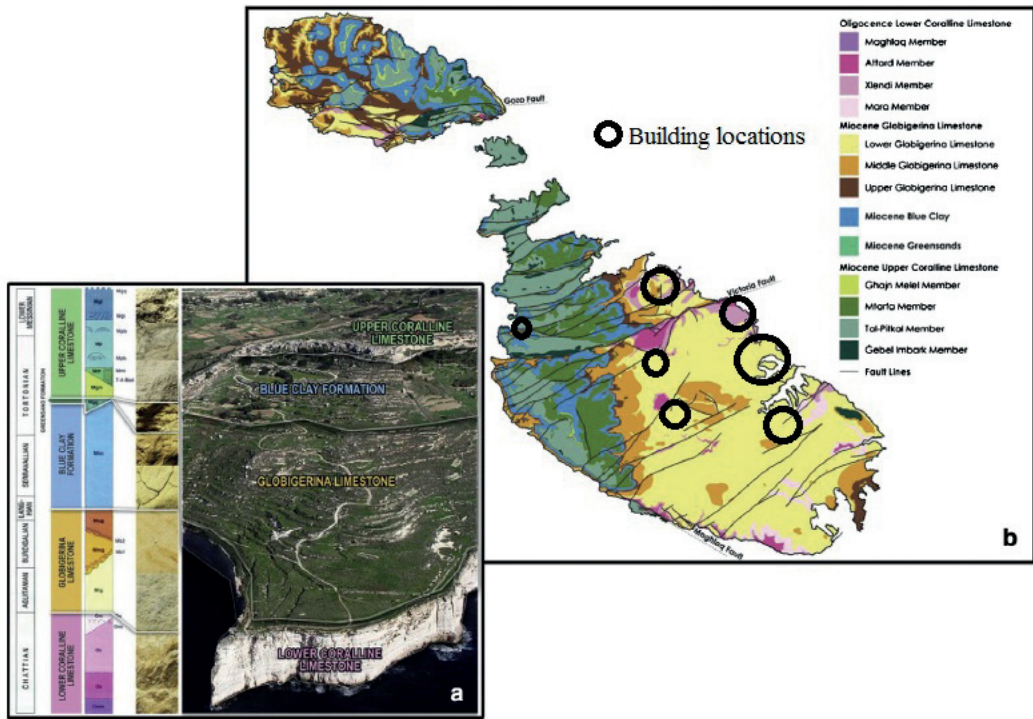


Fig. 1 – a) The geological stratification of the Maltese Islands including the members, sublayers, geological era, texture and outcrop occurrence of all the layers. The same colour code is followed in Fig. 1 (b) [modified from The Geological Map of the Maltese Islands (Oil Exploration Directorate, Office of the Prime Minister, Malta, 1993)]; and (b) outcropgeology of Malta and Gozo (Oil Exploration Directorate, Office of the Prime Minister, Malta, 1993) with topography and major fault patterns (Mapping Unit, Malta Environment and Planning Authority, MEPA, 2010). Location of recording sites are also indicated.

caused. Different buildings respond differently to the same ground motion and will resonate at different frequencies. The building’s vibrations tend to centre around one specific frequency, namely the building’s natural or fundamental frequency, which in general decreases with height (Nelson, 1996).

Seismic building codes are designed to protect people inside buildings by preventing collapse and enable secure evacuation. A structure should withstand minor earthquakes undamaged, withstand moderate earthquakes without large structural damage and withstand major earthquakes without collapse. After any seismic action, the structure needs to be ensured to retain a residual strength and stiffness against horizontal ground motion and retain its entire load bearing capacity against vertical loads. However, even if all new buildings are built properly under more advanced codes, older buildings are still very vulnerable to earthquakes and therefore remain hazardous (MCEER, 2007). Most of the residential buildings around Malta consist of load-bearing unreinforced masonry walls and reinforced concrete roofs (Borg *et al.*, 2008). It is known that this type of construction is very vulnerable under even moderate levels of ground shaking.

This is a first study aimed at investigating the fundamental dynamic behavior of Maltese buildings utilizing the information contained in ambient noise vibrations. In particular it was intended to provide a preliminary idea of which kind of period-height relationship applies to local buildings, compared to similar relationships elsewhere. It was decided to limit this initial study to buildings constructed on bedrock, and, where possible, to isolated buildings. The

ambient noise was measured using MicromedTromino® 3-component portable seismographs located at the top and lowest floors of a building, and intermediate levels in some cases.

Maltese geology. Malta is located in the southern Mediterranean and is composed mainly of marine sedimentary rocks (Fig. 1). The oldest sedimentary formation of the Maltese Islands, of Triassic age, is not outcropping and the main exposed rocks were deposited from the Oligocene-Miocene to Quaternary periods. The litho-stratigraphic sequence is relatively simple, consisting of five major layers namely the Lower Coralline Limestone (LCL), the Globigerina Limestone (GL), the Blue Clay (BC), the Greensand Formation and the Upper Coralline Limestone (UCL). UCL, GL and LCL strata are essentially considered as being stiff rocks, whereas the BC and the Greensands are soft sediments (Pedley *et al.*, 1978, 2002). The LCL is the oldest exposed rock in the Maltese Islands, outcropping to a height of 140 m in the vertical cliffs near Xlendi (Gozo). GL is the second oldest rock and outcrops over approximately 70% of the area of the islands. On weathering and erosion, it assumes a broadly rolling landscape. The thickness of this formation changes considerably, ranging from 23 m near Fort Chambray (Gozo) to 207 m around Marsaxlokk (Malta). The BC formation overlies the GL. It erodes easily when wet and it forms taluses which flow out over the underlying rock. Variations in thickness are considerable, ranging from 75 m at Xaghra (Gozo) to nil in eastern Malta. Greensand consists of bioclastic limestones rich in glauconite that were deposited in a warm sea. The deposit attains a maximum thickness of 11 m in localised depressions at Il-Gelmusin Gozo, but elsewhere is less than 1 m thick. UCL is the youngest Tertiary formation in the islands, reaching a thickness of approximately 160 m in the Bingemma area (Malta). Local tectonic activity appears to have resulted in the brief emergence of the formation above sea level. The UCL is very similar to the lowest stratum (LCL) in the Maltese Islands. These rocks are sporadically overlain by terrestrial, aeolian and alluvial deposits laid down following the emergence of the Maltese Islands above sea level. Much of the central and south-eastern portion of Malta comprises outcrops of GL while the northern and north-western regions are characterized by highlands on which UCL is the dominant outcrop. The geology of Gozo is more varied than that of Malta, with more frequent outcrops of BC being a characteristic feature.

Methodology and data set. The building response survey was carried out by recording 10 – 30 minutes of ambient vibrations at a sampling frequency of 128 Hz, on 21 different buildings (Fig. 1) around Malta with difference in shape, different construction material (reinforced concrete or masonry) and with height in the range of 1 – 23 floors. Considering the respective interstorey height, the range of building height is between 5 and 98 meters. The instruments were aligned with their North-South direction parallel to the long axis of the building.

Studies have shown that the nature and thickness of surface sediments are two important local geological factors that can significantly affect the level of earthquake shaking (Navarro *et al.*, 2004). Site response studies using ambient noise over the Maltese islands (Vella *et al.*, 2013) have shown that sites consisting of Lower Coralline and Globigerina Limestone layers, underlying most of the urban and industrial areas, exhibit mostly flat H/V response curves above 0.5 Hz, which is the essential range for engineering purposes in the construction and design of typical local structures. On the other hand, the presence of the Blue Clay layer, whether outcropping at the surface or as a layer lying under the hard Upper Coralline Limestone layer, was found to induce site amplification. For this reason, all the studied buildings were chosen to lie on hard rock in order to avoid possible effect of ground amplification due to the clay layer. This is an interesting and important effect which will be investigated in a separate study. Where possible, buildings located near construction work or industries were avoided.

Since this study was aimed at investigating the fundamental period – height relationship, we tried to analyse mostly buildings of regular and isolated configuration. This was not always possible as Maltese building density is high and it is difficult to find completely isolated buildings. It is also known that the period-height relationship may differ for unreinforced masonry buildings and reinforced concrete ones (*e.g.* Panzera *et al.*, 2013). In this first study no

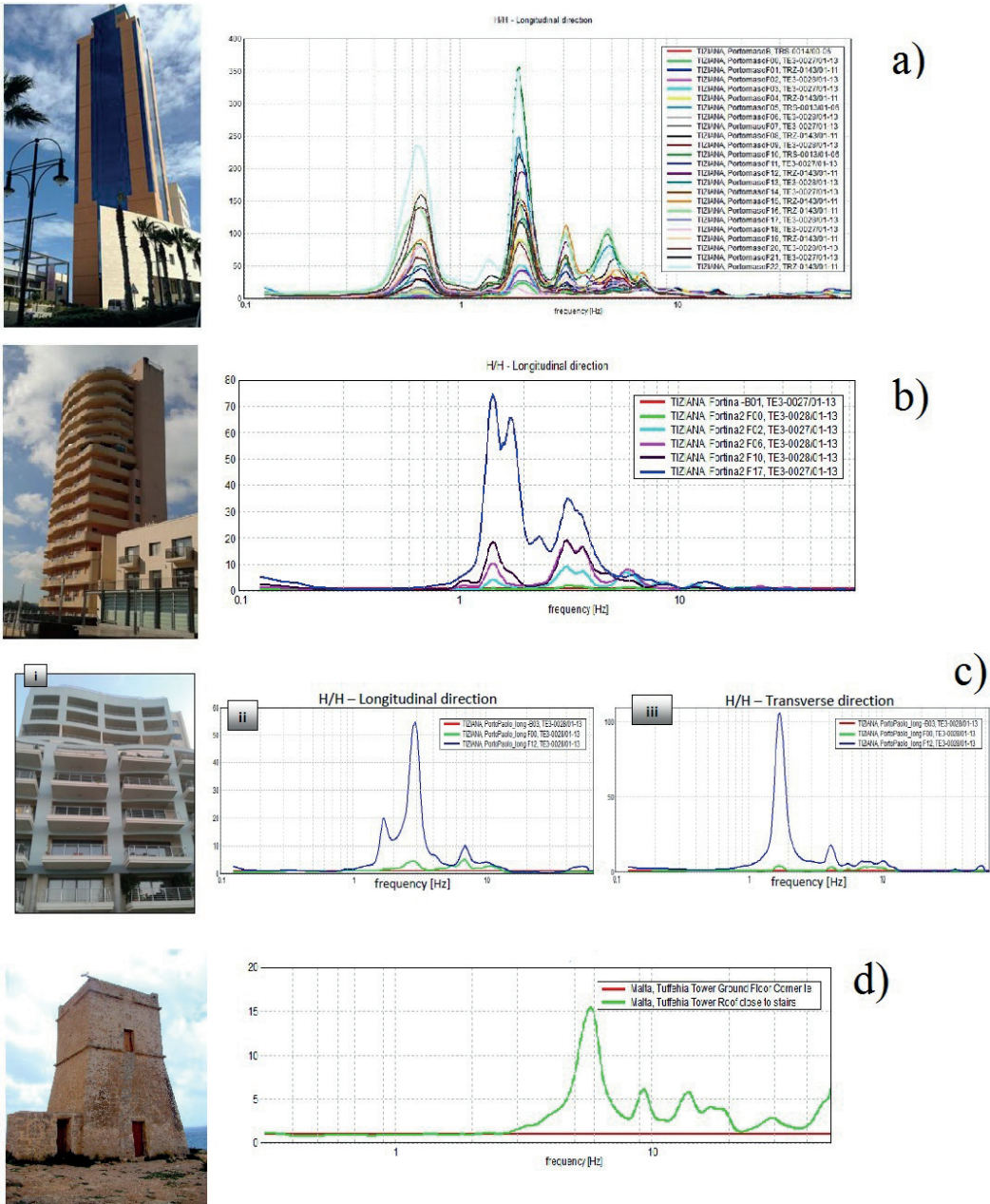


Fig. 2 – Hi/Ho results for four different investigated buildings (see text for details).

distinction was made between the two. The taller buildings were reinforced concrete structures, while shorter buildings, which were generally residential structures and apartment blocks, tended to be unreinforced masonry structures.

Some tall buildings, such as the Portomaso Tower (Fig. 2a) consisting of 23 floors and the Fortina Hotel consisting of 17 floors (Fig. 2b) were investigated in more detail, by measuring ambient noise at several floors in between. This is interesting because it provides potential information on higher modes of vibration. For the shorter buildings (Fig 2c), ambient noise

measurements were taken only at the highest and lowest accessible floors. Ambient noise measurements were also taken on a historical building, a coastal watchtower (Fig 2d), located along the northern coast of the island of Malta.

The data analysis on modal behaviour was carried out using the Grilla software supplied with the Tromino instruments. Reliable estimates of the building's fundamental frequency, as well as higher mode frequencies in some cases, were obtained by computing both horizontal-to-vertical spectral ratios (Nakamura, 1989) at a given level of the building, as well as the horizontal-to-horizontal spectral ratio of a given level to the basement level. The latter was carried out along two axes corresponding to the long and short dimensions of the building. The Non-Parametric Damping Analysis (NonPaDAn) method (Mucciarelli and Gallipoli, 2007) was also used to obtain an estimate of the damping at the fundamental frequency of each building investigated, although the results are not presented here..

Results and discussion. Some examples of the results from individual buildings are presented in Fig. 2. The Portomaso Business Tower, shown in Fig. 2a, is the tallest building in Malta, located in the heart of St Julian's, that has been open since 2001. It is 98 m tall, spread over 23 floors. To a first approximation, a building like the Portomaso Tower is similar to a cantilever beam fixed in a vertical position to the ground. However, its construction and architecture make it different from a simple cantilever because from the first to the sixth floor it is attached to another building with different dimensions. Readings were taken on all floors of the tower, placing the instrument in the stairwell. The Hi/Ho amplitude spectral ratio as a function of the frequency for the longitudinal direction is shown in Fig. 2a. The fundamental (lowest) frequency is 0.65 Hz, with the transverse frequency being slightly lower (0.59 Hz) as expected. On the other hand, the fundamental frequency measured from the H/V plot at the highest floor is 0.72 Hz. Higher mode frequencies are also observed in both longitudinal and transverse directions, and are also clearly identified by plotting the modal shapes at the given frequencies. Such measurements permit the observation of modal behaviour of tall structures relatively easily, however the interpretation and analysis of such behaviour is not simple and is best carried out in parallel with numerical modelling of the building.

Another tall building studied in Malta is the Fortina Spa Resort located in Sliema (Fig. 2b). It is 52 metres tall spread over 17 floors with a basement underneath. This building has a regular oval in-plan shape and from the ground floor till the ninth floor it is joined to another building, similar to the Portomaso tower. The fundamental frequency, which is the lowest frequency of the building, is clearly identified in this case for both the longitudinal direction at a frequency of 1.47 Hz and transverse direction at a frequency of 1.05 Hz. Several higher frequency modes are observable in both the longitudinal and transverse directions, but no discussion of such modes will be attempted here.

Fig. 2c shows results from the Porto Paolo apartment block. This building is situated in St Pauls' Bay, Malta and is 12 floors high, spread over 38 m with three levels underground car park. It is an isolated building however it has a different structure than usual since from the ground till the fifth floor it has a larger in-plan area than from the sixth till the thirteenth floor. The Hi/Ho spectral ratio plots in the longitudinal and transverse directions give very sharp peaks representing the fundamental frequency of the building at 2.88 Hz in longitudinal (longest side) and 1.71 Hz in the transverse (shortest side) direction of the building. The H/V method gives fundamental frequencies of 2.80 Hz and 1.70 Hz for the longitudinal and transverse directions respectively.

Fig. 2d shows the analysis for the Ghajn Tuffieha watchtower on the Northwest coast of Malta. These kind of structures were built by the Knights of Malta in the 17th century for impending incursions into the Maltese territory. The watchtowers were occupied by local guards who would alert the army of any intruding visitors. The response of the structure is relatively simple, and the measured fundamental frequency lies between 5 – 6 Hz.

The period - height relationships for the set of buildings covered in this study for orthogonal

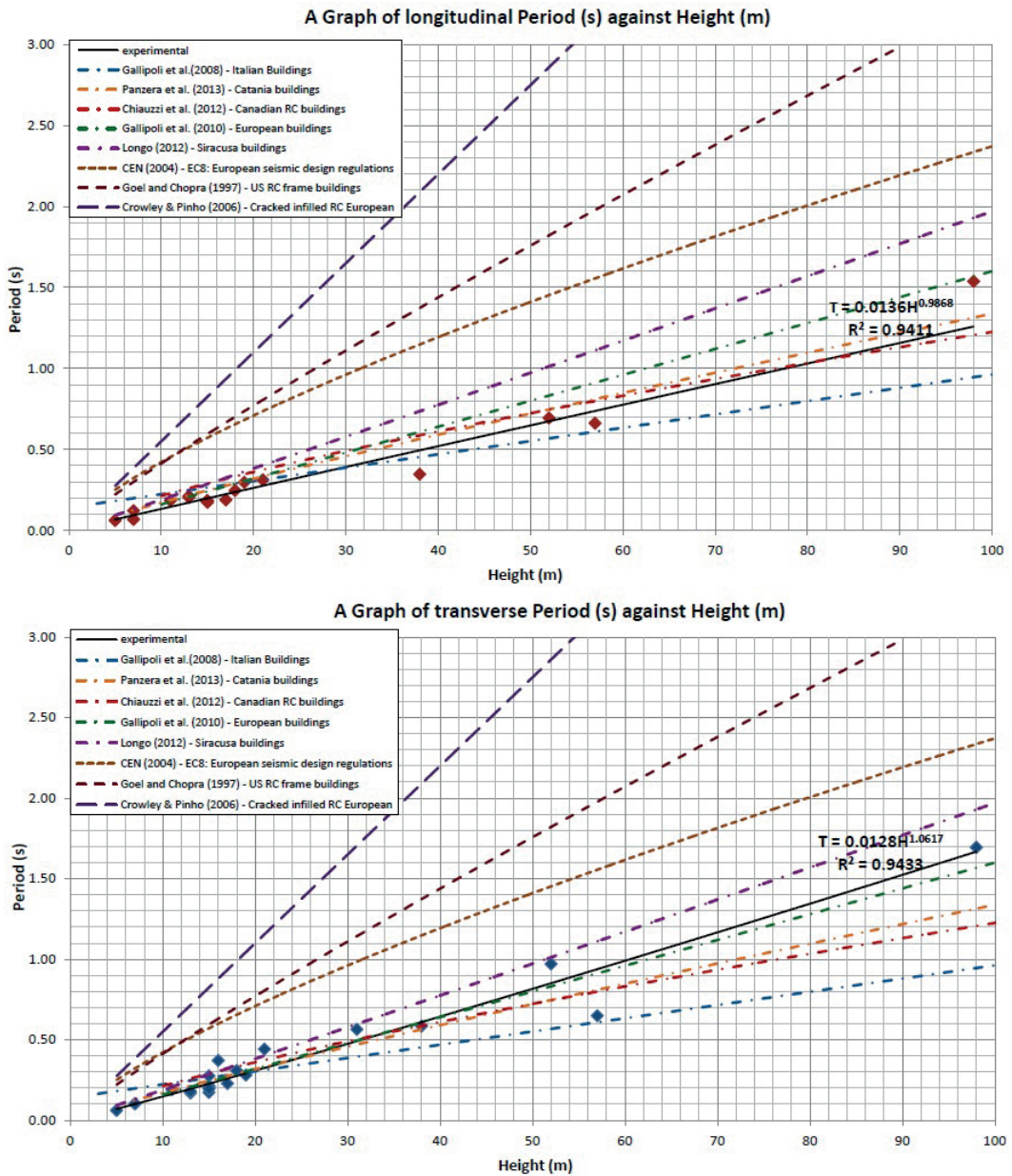


Fig. 3 – a) Experimental period – height relationship in the longitudinal direction (longest side) of the Maltese buildings studied, in relation to other similar relationships by several authors. b) Same as (a) but in the transverse direction (shortest side).

translational directions are shown in Fig. 3. In order to conform with most similar relationships obtained for different cities and countries in the world, a power law was used for the calculated regression of data. The best-fitting relationships together with their R^2 values are shown on the graphs. The regression was carried out separately for both (longitudinal and transverse) vibration directions. As a first observation, it is evident that the relationships are markedly different from those provided by the Eurocode 8 (CEN, 2003) and Goel and Chopra (1997) for the US. However, the experimental results obtained are in very good agreement with the others.

In particular, for heights up to 30 m, the experimental period – height relationships are very similar to the relationships provided by Gallipoli *et al.* (2008) for Italian buildings, Gallipoli *et al.* (2010) for European buildings (consisting of buildings from Italy, Slovenia, Croatia and Republic of Macedonia), Panzera *et al.* (2013) for Catania, and Longo (2012) for Siracusa, as well as for Chiauzzi *et al.* (2012) for Canadian RC buildings. It is important to remember that in this study, a low energy input source (ambient noise) was used for estimating the fundamental period of a building. In addition, this might influence the linear elastic response, thus causing the fundamental period to be underestimated as it is not based on strong seismic actions. As observed by Celebi (1998), the first mode periods and damping ratios obtained from strong motion response were about 20 to 50 % more than those corresponding to ambient vibration data. In fact, longer periods of vibration due to a limited amount of cracking during earthquakes are expected. Conversely, Hong and Hwang (2000) observed a much lower period than expected during strong earthquake shaking in RC Taiwan buildings, designed according to the Uniform Building Code (UBC). It is therefore likely that the shaking level (whether it is weak or strong) may not be the only responsible factor for the observed differences between experimental and numerical period – height relationships. Another important factor would be attributed to the role of stiff masonry infill walls. Studies have shown (*e.g.* Kose and Karslioglu, 2006; Pujol *et al.*, 2008; Kose, 2009) that continuous infill masonry walls aim to reduce the vulnerability of a RC structure. In fact, the presence of infill walls tends to strengthen the mass and lateral stiffness of the system (Panzera *et al.*, 2013), hence decreasing the fundamental period of the building and consequently changing its seismic response (Ricci *et al.*, 2009).

Concluding remarks. The motivation for this work arose from the need to understand the local dynamic behaviour of Maltese buildings, especially in the case of earthquake ground shaking. Knowing the behavior of local buildings is essential for understanding how buildings will respond under earthquake ground motion and hence an essential part of seismic risk assessment.

The dynamic behaviour of 21 Maltese buildings based on ambient noise measurements were analysed, using both H/V spectral curves as well as spectral ratios H_i/H_o . Fundamental frequencies were also deduced from non – parametric damping analysis (NonPaDAn), although these results are not presented here. These methods gave comparable results for the estimation of the fundamental frequency of buildings. However, in most cases, the H_i/H_o spectral ratio method appears to be the most reliable method for assessing frequency, especially for the identification of higher mode frequencies in tall buildings. Furthermore, with a short, single measurement of ambient noise at the top of a building, the non – parametric damping analysis (NonPaDAn) was able to provide the damping estimations at the relative fundamental mode of the building. Results from different methods show that for a rapid survey of a large number of buildings, and where only an approximate value for the fundamental frequency is required, it is enough to use one portable seismograph on the roof of the building and measure the fundamental frequency from the HVSR plots, since this is a good approximation to the one obtained from the H_i/H_o plots. This would mean that the study of one building can be done in about 15 minutes. The study presented in this paper has led to two simplified relationships, between the fundamental period of vibration in orthogonal translational directions and the height of 21 different buildings, situated in Malta. These relationships obtained through the H_i/H_o spectral ratio technique were fitted by a simple power law relationship for the transverse and longitudinal directions. Moreover, experimental results show that the fundamental periods for Maltese buildings are very similar to other buildings particularly in Sicily and southern Europe, when measured from ambient noise data. However, significant differences exist from other relationships. In particular, the experimental period results show lower values than those proposed by the Eurocode 8 (CEN, 2003) for elastic behaviour of buildings, Goel and Chopra (1997) for US reinforced concrete frame buildings and Crowley and Pinho (2004) for cracked infilled reinforced concrete European buildings. The discrepancy with the EC8 recommendations is particularly important

since design criteria are usually based on this relationship. These differences can be attributed to various factors that affect the dynamic response of buildings, including the presence of connected adjacent buildings, the geometry of the building, the construction material, the soil condition under the building, the level of shaking, the role of stiff masonry infill walls and others. More detailed studies are required to better understand whether the major causes of the discrepancies lie in the building typologies or in the method of measurement. In the case of the local scenario, further studies will investigate the effects of underlying geology, different construction materials, historical buildings, as well as the effect of building aggregates, especially with regard to different adjoining heights, as opposed to individual buildings.

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