RESONANCE FREQUENCY CHARACTERISTICS OF BUILDINGS IN MALTA AND GOZO USING AMBIENT VIBRATIONS

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Introduction

The Maltese islands, lying in the Sicily Channel between Sicily and Tunisia, cover a total area of around 317 km2 and have a present population of around 452,000, which inflates in the summer season by the arrival of over 1 million tourists. The population density of 1,346 km-2 is one of the highest in Europe. A large proportion of residential buildings in the Maltese islands are traditionally constructed of loadbearing unreinforced masonry blocks, utilising local Globigerina limestone blocks, having roofs and diaphragms of reinforced concrete. Older buildings having stone slab roofs are still found in town and village cores, sometimes more than 5 floors in height. Other building stock, in particular taller buildings, are a mix of reinforced concrete frames and masonry construction. The last earthquake to produce some building damage on the islands occurred almost 100 years ago in 1923 (Galea, 2007), while in historical times, the earthquake known to have produced the maximum local intensity of VII – VIII (EMS98) was in 1693. This event was a magnitude 7.4 earthquake along the east coast of Sicily that caused more than 50,000 casualties on that island.

Over the past 50 years, construction in the Maltese islands has mushroomed, with most towns and villages growing steadily outwards along their peripheries. The Northern and Southern Harbour districts, around the Valletta Grand Harbour, have developed into one large conurbation housing almost half the whole population of the islands. The western half of Malta and the smaller island of Gozo are more rural and still relatively sparsely populated, although pockets of urbanisation, especially in coastal areas, are growing rapidly to cater for tourism. The exposure of the islands to earthquake risk has thus increased significantly, while the public perception of earthquake hazard is still low.

The islands are composed entirely of an Oligo-Miocene layer-cake sequence of marine carbonates and clays, heavily disrupted by mainly normal faulting, with a patchy cover of Quaternary deposits and soils of terrestrial origin. The main formations in order of deposition are the Lower Coralline Limestone (LCL), the Globigerina Limestone (GL), the Blue Clay (BC) and the Upper Coralline Limestone (UCL). In the eastern half of Malta, which is the more populated and industrialised, the two youngest layers of the sequence are absent, and the GL outcrops over most of the area. In the western half of Malta, and on most of Gozo, however, the full sequence is present, so that a number of urban centres are constructed on the UCL which is underlain by the soft, and easily weathered BC layer, which can reach thicknesses of up to more than 50 m.

The behaviour of local constructions under dynamic earthquake loading is a problem that has begun to draw attention in recent years. Moreover the effect of the thick buried layer of clay on the dynamic seismic response is also being investigated. In this paper, we report on preliminary measurements of ambient vibrations in a set of buildings to yield information on fundamental resonance frequencies and period-height relationships. Although it is expected that building resonance frequencies would depend on a number of factors, such as construction typology, connectedness with other buildings, plan shape, etc. this study does not attempt to investigate such factors, but only the effect of building height, and the transfer of the site response to the building in the case of underlying clay. Nonetheless, most buildings studied are either of unreinforced masonry, or mixed masonry/reinforced concrete structures.

Methodology

An extensive, free-field ambient noise study carried out in 2010 (Vella et al, 2013) as well as other, denser surveys in various areas (Pace et al, 2011; Panzera et al, 2012; Galea et al, 2014) mapped the site seismic resonance frequency over all the geological outcrop lithologies in the whole archipelago. The method used was the Horizontal-to-Vertical Noise Spectral Ratio technique (HVSR) (Nakamura,1989) which is a fast and cost-effective method that reliably reveals the resonance frequency, if any, of the stratigraphic column. The study showed very clearly that the GL/UCL can be regarded as the bedrock of the local stratigraphic sequence, in that the HVSR curves on these outcrops are always relatively flat. On the other hand, free-field sites on UCL outcrop are consistently and ubiquitously characterised by a significant peak in the HVSR at a frequency between 1.0 and 2.0 Hz, which is attributed to the BC layer. Sites lying directly on the BC outcrop show higher resonance frequencies, varying between 2.0 and 10.0 Hz, depending on the thickness of the BC remaining after erosion. The same ambient noise methodology was applied in the present study to investigate the resonance of buildings. Such measurements have been widely used in a number of countries and settings (e.g. Michel et al, 2008, Gallipoli et al, 2010; Gosar et al, 2010; Oliveira and Navarro, 2010; Chiauzzi et al, 2012)

Two main surveys were carried out, in 2013 and 2014 respectively, targeting different building characteristics. In the first survey, carried out in Malta, 21 buildings were selected, that stood on Globigerina limestone outcrop, so that there was no "free-field" response, and which were relatively isolated. This geological foundation represents the majority of buildings on the islands. The second survey was carried out on 19 buildings in Gozo, targeting buildings constructed on UCL (Nadur and Victoria plateaux) or BC (Victoria) outcrops. The instruments used were of the type Micromed Tromino (www.tromino.eu) , a lightweight, portable, battery-operated, 3-component tromograph that can easily be placed at any location inside or outside a building with minimum disturbance.

Measured buildings in Malta ranged in height between 1 and 22 floors, while those in Gozo ranged between 1 and 7 floors. One seismometer was placed on the ground floor, or basement level if available, while another was placed at roof level. When possible, measurements were carried out also on intermediate floor levels. The N axis of the Tromino was always aligned with the long plan dimension of the building (longitudinal direction) so that the E component corresponds to the transverse direction. Ambient noise time series of 15 – 30 minutes were recorded, and analysed for spectral ratio by the software Grilla ™. In the case of the Gozo buildings lying on UCL and BC, free-field measurements were also taken close to the buildings in order to evaluate the stratigraphic response of the site.

Results and Discussion

Figure 1 shows three examples of results of ambient vibration measurements in buildings constructed on UCL, BC and GL (bedrock). The left-hand panels show the HVSR on each measured floor, while the right-hand panels show the Floor Spectral Ratio (FSR) in the transverse direction on each floor. The FSR represents the ratio of the horizontal component spectrum at the ith floor, Hi, to that at the basement level Ho, and may be thought of as the transfer function of the building. Since the response at basement level is generally identical to that in the free-field, the ratio Hi/Ho essentially deconvolves the stratigraphic site response from the building response, and distinguishes the site resonance frequency from the building's fundamental resonance frequency. In buildings lying on bedrock (Figure 1 (e), (f)), the HVSR on all floors and the FSR yield approximately the same values for the fundamental frequency. Thus, for a rapid survey of a large number of buildings, it would be enough to perform a single HVSR measurement on the roof of the building. In buildings lying on the UCL it can be clearly observed in Figure 1(a) that the site response peak at 1.5 Hz on UCL is transferred upwards through the floors of the building, without any appreciable increase in amplitude, as opposed to the building oscillation at 5.5 Hz which increases in amplitude nearer the top. The building's natural frequency is given by the FSR which eliminates completely the free-field response (Figure 1(b)). The FSR in this example also shows a second resonance peak at around 8.0 Hz. It is highly unlikely that this corresponds to some higher mode of vibration, and is most likely due to coupling with the adjacent building, which is of a different height. In buildings on the BC in Gozo, the total building response appears more complex and furthermore varies greatly from one building to another. It should be said that building directly on Blue Clay outcrop may involve a number of different methodologies, such as concrete platform construction and different types of piling. Such methods, although expected to influence the building behaviour, are not directly investigated in this study, and will be more rigorously examined in further work. In the example given (Figure 1(c)) the site response (observed separately in the free-field at close to 3 Hz, typically of BC outcrops) appears to mask the building resonance in the HVSR curves, with the lower floors exhibiting a higher overall HVSR ratio than the upper floors. The FSR, on the other hand, reveals a building natural frequency of 5.5 Hz.

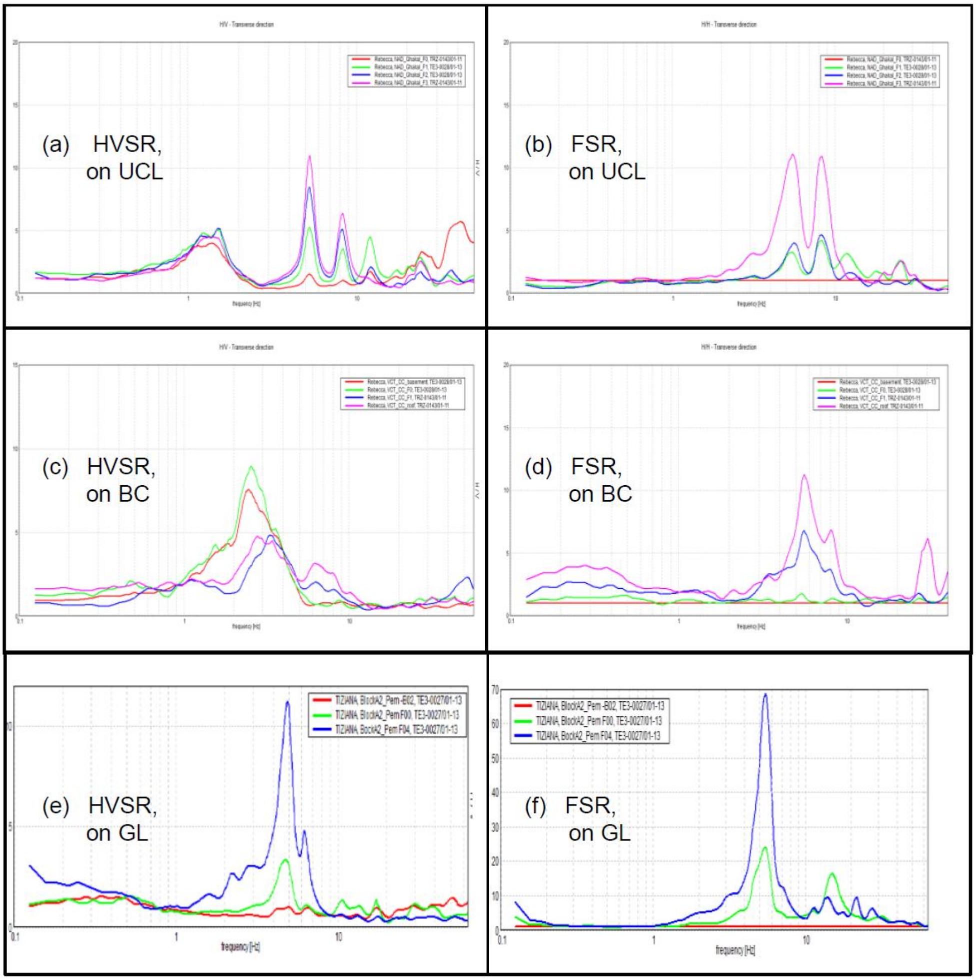

Figure 1. Horizontal-to-Vertical Spectral Ratios (HVSR) and Floor Spectral Ratios (FSR) for: (a), (b) a 5-storey building on UCL outcrop; (c), (d) a 4-storey building on BC outcrop; (e), (f) a 4-storey building on GL outcrop (bedrock).

Figure 2 shows the relationship between the fundamental resonance period (*T*, in seconds) measured from the FSR in the transverse direction as a function of the height of the building (in number of floors, *N*). The buildings in Malta and Gozo are shown in different symbols. Although the sampled number of buildings in Gozo is too small to be statistically reliable, there appears to be an appreciable difference between the two, the buildings in Gozo having higher fundamental frequencies than their Maltese counterparts. This is true for buildings lying on bedrock as well on UCL/BC. It is not yet clear what the reason for this difference is, however, it is likely due to the fact that buildings sampled in Gozo were not isolated, as in the case of most of the sampled buildings in Malta, and generally consisted of more intricate plan shapes. In any case, a much wider sample of buildings needs to be measured in order to derive a suitable relationship. The linear regression for the buildings in Malta yields the relationship $T= 0.051N$ for the fundamental frequency in the transverse direction, for buildings up to 12 floors high (taller buildings, including the 22-floor Portomaso Tower in St. Julian's, have been left out of this relationship because they involve very different construction typologies, although their behaviour merits a separate study). This is very similar to relationships derived for the Catania area (Italy) by Panzera *et al* (2013) and for Slovenia (Mucciarelli and Gallipoli, 2007), although in general it predicts much higher frequencies than the commonly quoted Goel and Chopra (1997) as well as the EC8 guidelines (CEN, 2004).

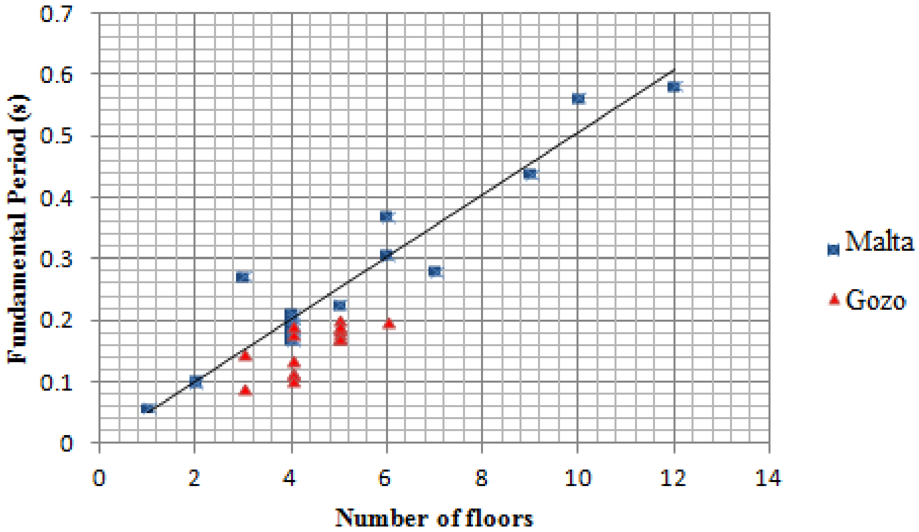

Figure 2. Period – Height relationships for fundamental, transverse oscillations of the sampled buildings in Malta and Gozo

Conclusion

This study represents a first, preliminary attempt at characterising Maltese buildings in terms of their fundamental resonance frequency. Such information is important when assessing the performance of buildings subjected to earthquake shaking, and will eventually contribute towards a national seismic risk evaluation. The danger of building collapse or heavy damage during an earthquake is intensified if the resonance frequency of the underlying soil is close to that of the building – a phenomenon known as double resonance. The probability of strong earthquake shaking on the islands is small but not negligible, and may be larger in areas where the geology includes a thick clay layer. In the case of buildings in Malta and Gozo, the large majority of buildings are constructed on bedrock (mostly GL), so that the phenomenon does not occur. Double resonance may occur in buildings constructed directly on Blue Clay outcrop (a situation encountered in a few areas in Gozo and Malta), since the resonance frequency related to the surface clay layer (2 – 10Hz) falls in the same range as that of short - to - medium height buildings. It could also occur in buildings in the approximate height range of 10 - 15 floors that are built on UCL outcrops since these will have a building resonance frequency in the range of that measured on such outcrops (between 1.0 and 2.0 Hz). Although such buildings are not at present found in the western half of the archipelago, where this lithology exists, it is important to keep such considerations in mind when planning future development. Further studies will attempt to derive more specific relationships based on construction typology and geometrical parameters.

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