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PREDICTIVE FORMULATION FOR THE ESTIMATION OF THE FUNDAMENTAL FREQUENCY OF SLENDER MASONRY STRUCTURES

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ABSTRACT

The fundamental frequency of a structure enables better assessment of its seismic demand for an efficient design and planning of its maintenance and retrofit strategy. The frequency is independent of the type of external loads, however, depends on structural stiffness, mass, damping and boundary conditions. In the case of slender masonry structures such as towers, minarets chimneys, Pagoda temples, etc., it is influenced by mass and stiffness distribution, connection to adjacent structures, material properties, aspect ratio and slenderness ratio.

In this present paper, the data collected from various literature reviews on the slender masonry structures regarding dynamic, geometrical and mechanical characteristics have been correlated to identify the major parameters influencing the fundamental frequency of such structures. The database has been used for developing an empirical formulation for predicting the fundamental frequency of such structures. The comparison between the experimental fundamental frequencies and the estimated fundamental frequencies are carried out in order to define reliability and accuracy of these empirical formulae.

INTRODUCTION

The dynamic identification of a structure is important to define its structural health status, after damage generated by an earthquake (Buffarini et al., 2011). Strong damage or complete loss of structures forming part of the architectural heritage when subjected to strong earthquake ground motion has occurred throughout the history of humanity. The behavior of slender masonry structures under seismic loading is generally dominated by the axial stresses that arise from the static vertical loads combined with the dynamic loading induced by the low-intensity earthquakes that is often close to the compression strength of the traditional masonry material and also makes them more vulnerable to base settlements (Salvatore et al., 2003). Moreover, during strong earthquakes, tensile damage is distributed along the height of the structure, while shear damage is concentrated in the lower section (Casolo and Pena, 2007). Thus, such structures have long been considered to be particularly susceptible to seismic actions and therefore, it is crucial to understand the dynamic behavior of these structures to preserve and strengthen them against earthquake excitation.

The knowledge of dynamic properties, together with site seismicity and stratigraphy, is the starting point for an accurate estimation of the seismic safety of these structures (Ferraioli et al., 2011). A reliable evaluation of the dynamic properties of a structure is of importance for the analysis of its

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dynamic behavior, in particular under seismic actions (Rainieri and Fabbrocin, 2011). In this paper, data base regarding the dynamic properties, material and geometric characteristics of slender masonry structures are correlated to propose some empirical formulations. The proposed empirical formulations are capable of efficiently predicting the fundamental frequency of such structures.

The fundamental frequency plays a primary role in the assessment of the seismic vulnerability of slender structures. It can be evaluated by numerical analysis, or even using empirical formulation provided in buildings codes. In the case of slender masonry structures, where reliable results are required from the numerical model analysis for precisely calibrating the interventions work, but systematic studies focused on this issue are still missing. In this paper, a literature reviews has been carried out in order to collect data regarding the dynamic properties, material and geometric characteristics of slender masonry structures. The compiled database has been analysed and correlated to develop an empirical formulation for predicting the fundamental frequency of such structures.

DATABASE COMPILATION AND ANALYSIS

Slender masonry structures (see Fig.1) can be characterized by their distinguished architectural characteristics, age of construction and original function, but their comparable geometric and structural ratios yield to the definition of an autonomous structural type. These structures are characterized by their notable slenderness and also represent one of the main differences from most of the historic structures or even ordinary buildings (Sepe et al., 2008). These structures are scattered over different countries with different densities and features. Database of such structures was compiled through a systematic literature review. Data was acquired from experimental works performed on the determination of dynamic properties and material characteristics.

Figure 1. Slender masonry structures: (a) towers; (b) minarets; (c) chimney; (d) Pagoda temples

Table.1 summarize the database that comprises 59 slender masonry structures, among them 32 are towers, 16 are minarets, 7 are chimneys and 4 are Pagoda temples. The database summarizes the geometric characteristics of slender masonry structures along with theirs dynamic properties. The data base information regarding geometric characteristics indicates the total height of the structures ranging from 10m (shortest) to 74.4m (tallest) and the width of the wall at the base varying from 1.96m (minimum) to 14m (maximum). Moreover, the minimum slenderness which is considered as the height to minimum breadth at base ratio ranges from 1.66 (minimum) to 15.67 (maximum).

Table 1. Database compiled from the literature review carried out

Reference	Type of structure	Type of masonry	Total height, H (m)	Minimum breadth at base, B (m)	Slenderness ratio, H/B	Experimental fundamental frequency (Hz)
Bongiovanni et al. (2000)	Tower	Brick masonry	18.50	3	6.17	2.43
Camata et al. (2008)	Tower	Stone masonry	19	5.40	3.52	3.78
Carone et al. (2013)	Tower	Brick masonry	20	3.5	5.71	2.63
Ramos et al. (2010)	Tower	Stone masonry	20.40	4.50	4.53	2.56
Tomaszewska (2010)	Tower	—	22.65	7.70	2.94	1.42
Bayraktar et al. (2009)	Tower	Stone masonry	23	5	4.60	2.59
Bonato et al. (2000)	Tower	—	26	3.50	7.43	1.66
Sepe et al. (2008)	Tower	Brick masonry	28	8.20	3.41	2.40
Guerreiro and Azevedo (2001)	Tower	Stone masonry	30	8	3.75	1.37
Pelella et al. (2001)	Tower	—	30	4	7.50	1.95
Ceriott et al. (2009)	Tower	Stone masonry	31	8	3.88	1.25
Foti et al. (2012)	Tower	Stone masonry	34.7	4.11	8.44	4.57
Ivorra et al. (2010)	Tower	Brick masonry	35.50	7	5.07	2.15
Gentile and Sais (2013)	Tower	Stone masonry	36.72	5.70	6.44	1.21
Ivorra and Cervera (2001)	Tower	Stone and brick masonry	37.19	4.68	7.95	0.73
Casciati and Al-Saleh (2010)	Tower	—	39.24	5.96	6.58	1.05
Balduzzi et al. (2006)	Tower	Stone and brick masonry	40	4	10	1.36
Ivorra and Pallares (2006)	Tower	Brick masonry	41	5.60	7.32	1.29
Ferraioli et al. (2011)	Tower	Stone and brick masonry	41	11.30	3.63	1.26
Peeters et al. (2011)	Tower	Stone masonry	41	7	5.86	1.57
Kohan et al. (2011)	Tower	—	41.40	7.60	5.45	1.37
D’Ambrisi et al. (2012)	Tower	Brick masonry	41.80	6	6.97	1.08
Buffarini et al. (2011)	Tower	Stone masonry	43	6.50	6.62	1.48
Ferraioli et al. (2011)	Tower	Stone masonry	45.50	14	3.25	1.05
Jaras et al. (2010)	Tower	Stone and brick masonry	49.90	12.60	3.96	1.25
Costa (2011)	Tower	Stone masonry	55	8	6.88	1.05
Diaferio et al. (2013)	Tower	Stone masonry	57	7.5	7.6	2.04
Russo et al. (2010)	Tower	Brick masonry	58	7.60	7.63	0.61
Bartoli et al. (2013)	Tower	Stone and brick masonry	60	9.50	6.32	1.31
Ceroni et al. (2010)	Tower	Stone and brick masonry	68	11	6.18	0.69
Gentile and Saisi (2007)	Tower	Brick masonry	74	6	12.33	0.59
Pieraccini et al. (2009)	Tower	Stone masonry	87.40	14.50	6.03	0.62
Zaki et al. (2008)	Minaret	Stone masonry	20	3.40	5.88	1.84
Oliveira et al. (2012)	Minaret	Brick masonry	23.02	3.73	6.17	1.68
El-Attar et al. (2005)	Minaret	Stone masonry	24.48	3.80	6.44	1.95
Pau and Vestroni (2011)	Minaret	Stone masonry	30	3.55	8.45	1.45

Oliveira et al. (2012)	Minaret	Brick masonry	38.65	3.68	10.50	0.80
Turk and Cosgun (2012)	Minaret	Stone masonry	40.25	3	13.42	0.88
Oliveira et al. (2012)	Minaret	Brick masonry	41.60	3.97	10.48	1.37
Oliveira et al. (2012)	Minaret	Stone masonry	44.96	5.28	8.52	1.03
Krstevska et al. (2010)	Minaret	Stone masonry	47	3	15.67	1.04
Oliveira et al. (2012)	Minaret	Brick masonry	48.70	4.64	10.50	1.18
	Minaret	Brick masonry	51.70	5.12	10.10	0.95
	Minaret	Stone masonry	54.90	4.80	11.44	0.63
	Minaret	Brick masonry	63.20	4.96	12.74	1.02
	Minaret	Brick masonry	66.55	7.52	8.85	1.32
	Minaret	Brick masonry	66.55	7.52	8.85	1.17
	Minaret	Brick masonry	74.40	6.50	11.45	0.83
Aoki and Sabia (2004)	Chimney	Brick masonry	15	1.96	7.65	2.69
Costa (2010)	Chimney	Brick masonry	22.86	2.20	10.39	1.37
Yamamoto and Maeda (2008)	Chimney	Brick masonry	23.10	2.34	9.87	1.00
Grande and Açores (2009)	Chimney	Stone masonry	31	4.00	7.75	1.13
Eusani and Benedettini (2009)	Chimney	Brick masonry	36	3.40	10.59	0.93
Lopes et al. (2009)	Chimney	Brick masonry	41.40	3.70	11.19	0.61
Costa et al. (2011)	Chimney	Brick masonry	45.60	4.30	10.60	0.79
Jaishi et al. (2003)	Pagoda temple	Brick masonry	10	3	3.33	3.10
Shakya et al. (2013)	Pagoda temple	Brick masonry	12.76	3.48	3.67	2.06
Jaishi et al. (2003)	Pagoda temple	Brick masonry	16.93	10.20	1.66	2.32
	Pagoda temple	Brick masonry	27	6.58	4.10	1.68

The database information regarding dynamic properties shows the frequencies of the reviewed structures. It is noticeable in the database that the fundamental frequency of slender masonry structures is highly influenced by height of the structure and slenderness ration (i.e. the taller the structure the lower the fundamental frequency and similarly higher the slenderness ratio lower the fundamental frequency). The database reveals that the tower structures have third mode shape as torsion. All the experimental frequency for various slender masonry structures presented here in database is measured by different authors using ambient vibration test. Note that there is much less information regarding dynamic properties of chimneys and Pagoda temples.

FORMULATION FOR COMPUTING FUNDAMENTAL FREQUENCY/PERIOD

The empirical formulation proposed for the prediction of fundamental period/frequency for bell tower/cantilever structures by different codes and authors are taken as a basis for developing new empirical formulae for such structures. Later, the predictive performance between previous author's formulations and newly developed formulation are compared with reference to the experimental fundamental frequency.

A linear relation between the fundamental vibration period (T_1) and the height (H) of the tower proposed by Faccio et al. (2009) is expressed in Eq.(1).

$$T_1 = 0.0187H \tag{1}$$

The formulation in Eq.(1) better fits the experimental data, for slender structures with a periods lower than 1sec, however, it slightly underestimates the period higher than 1sec (Rainieri and Fabbrocin, 2011).

An empirical correlation for the prediction of the natural period (T_1) of Italian masonry towers as a function of height (H) has been proposed by Rainieri and Fabbrocin (2011) is expressed in Eq.(2).

$$T_1 = 0.01137H^{1.138} \tag{2}$$

Eq.(2) leads to an overestimation for low values of the natural period and to an underestimation at the higher values of the natural period (Rainieri and Fabbrocin, 2011).

From Eq.(3), proposed by the Spanish Standard NCSE-02 (2002), the value of the estimated fundamental frequency of towers (f_1) can be obtained.

$$f_1 = \frac{\sqrt{L}}{0.06\sqrt{\frac{H}{2L+H}}} \tag{3}$$

where, L is the plan dimension of the building in the direction of oscillation, H is the height of tower.

Eq.(3), leads to an overestimation for low values of the natural period and to an underestimation for higher values of the period (Rainieri and Fabbrocin, 2011).

The first frequency of vibration (f_1) for cantilever (Clough and Penzien, 1993) is given by Eq.(4).

$$f_1 = \frac{1}{2\pi}(1.875)^2\sqrt{\frac{EI}{\bar{m}L^4}} \tag{4}$$

where, E is the modulus of elasticity, I the moment of inertia, $\bar{m}$ the mass per unit of length, and L the total length of the cantilever.

EMPIRICAL FORMULAE FOR COMPUTING THE FUNDAMENTAL FREQUENCY OF SLENDER MASONRY STRUCTURES

On the basis of previous formulations and compiled database, four new empirical formulations are developed for the reliable prediction of fundamental frequency of slender masonry structures. Each formulation is further expressed in three sub formulations depending upon different multiplication factors, for three different structures categories (i.e. All types of slender masonry structures, towers (bell tower, clock tower, civic tower etc.) and minarets). Linear R squared approach is carried out to evaluate the predictive performance of these proposed empirical formulations.

On the basis of power correlation with the experimental fundamental frequency, the first formulation for predicting fundamental frequency (f_1) is developed as a function of height (H), which is presented in Eq.(5).

$$f_1 = \frac{1}{\alpha H^{\beta}} \tag{5}$$

where,
α = 0.0517 and β = 0.76 (for all types of slender masonry structures); with R^2 value = 0.59
α = 0.0151 and β = 1.08 (for masonry tower structures); with R^2 value = 0.73
α = 0.1178 and β = 0.533 (for masonry minaret structures); with R^2 value = 0.59

On the basis of Eq.(3) formulation, here is suggested a second formulation (Eq.(6)) for the prediction of the fundamental frequency (f_1) of slender masonry structures as a function of the height (H) and the lowest plan width base dimension at base (W).

$$f_1 = \frac{(W)^{\varphi}}{CH\left(\frac{H}{W+H}\right)^{\delta}} \tag{6}$$

where,
C = 0.038, φ = 0.25 and δ = 1 (for all types of slender masonry structures); with R^2 value = 0.89
C = 0.03, φ = 0.17 and δ = 0.5 (for all masonry tower structures); with R^2 value = 0.96
C = 0.1, φ = 1 and δ = 1 (for all masonry minaret structures); with R^2 value = 0.46

Retaining the basic structures of Eq.(4), where fundamental frequency of a slender structure is expected to be a function of the second moment of area *(I)*, height of the structures *(H)*, young's modulus of elasticity (E) and the mass per unit of length *$(\bar{m})$*, a third formulation (Eq.(7)) for the prediction of the fundamental frequency (f_1) of slender masonry structures is proposed accounting for all these parameters.

$$f_1 = \frac{1}{2\pi}(1.875)^2\sqrt{\frac{XEI}{\bar{m}H^4}} \tag{7}$$

where,
X = 1.425 (for all types of slender masonry structures); with R^2 value = 0.56
X = 1.375 (for all masonry tower structures); with R^2 value = 0.48
X = 1.345 (for all masonry minaret structures); with R^2 value = 0.89

On the basis of power correlation with the experimental fundamental frequency, the formulation for predicting fundamental frequency *(f_1)* is developed as a function of minimum slenderness ratio, i.e. height (H) to minimum breadth at base ratio (B), which is expressed in Eq.(8).

$$f_1 = Y\left(\frac{H}{B}\right)^{-z} \tag{8}$$

where,
Y = 3.648 and z = 0.55 (for all types of slender masonry structures); with R^2 value = 0.33
Y = 3.58 and z = 0.57 (for masonry tower structures); with R^2 value = 0.20
Y = 8.03 and z = 0.86 (for masonry minaret structures); with R^2 value = 0.58

Here, the newly developed formulations expressed in Eq.(5), Eq.(6) and Eq.(8) are basically function of geometrical characteristics whereas Eq.(7) is the function of both geometrical and mechanical characteristics. These formulations have been compared with experimental database and previous formulations by other authors for validation.

PREDICTIVE PERFORMANCE COMPARED AND RESULTS

The fundamental frequency predicted by the proposed empirical formulations is compared with previous authors' estimation and also with the experimental fundamental frequency. Moreover, predictive performance of proposed sub-formulations for various types of slender masonry structures is also compared for validation of their reliability.

Fig.2 illustrates the comparison between the experimental and empirical fundamental frequency expressed according to different predictive formulations for all types of slender masonry structures. Results reveal that empirical formulation proposed by Faccio et al. (2009) (i.e. Eq.(1)) and Rainieri and Fabbrocin (2011) (i.e.Eq.(2)), leads to an overestimation of the fundamental frequency for slender structures of height between 15m to 50m, while the values from Eq.(5) better fit the experimental fundamental frequency.

Fig. 3 illustrates the comparison of empirical fundamental frequency expressed by Eq.(5) for different types of slender masonry structures. Results reveal that the fundamental frequency predicted by three different sub-formulations (i.e. for all types of slender masonry structures, towers and minarets) derived from Eq.(5), using different numerical values for factor α and β, have different trendlines, which suggest, it is not reliable to estimate the fundamental frequency for all types of slender masonry structures using a single formulation. Therefore, for the better predictive performance, it is better to estimate using individual formulation presented in Eq.(5).

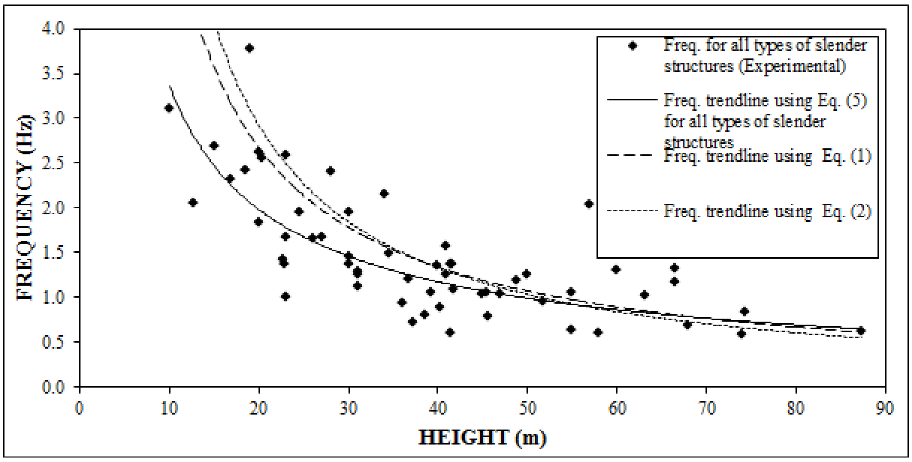

Figure 2. Comparison between experimental and predicted values of the fundamental frequency of slender masonry structures according to different formulation

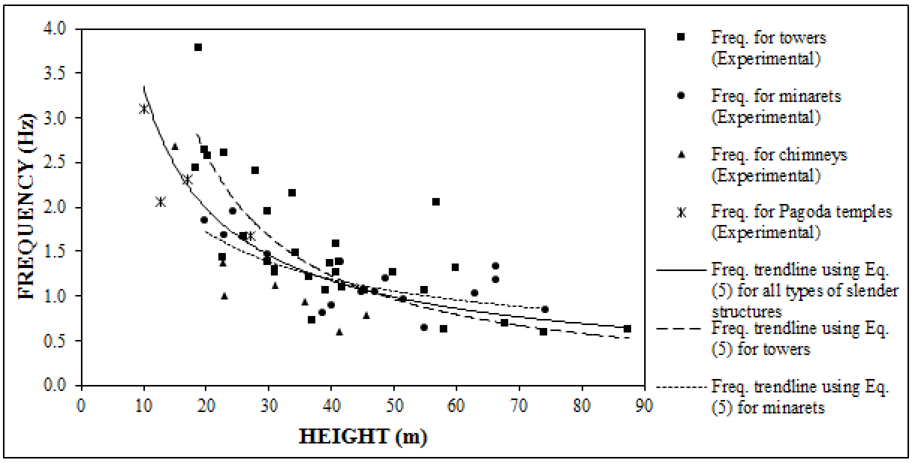

Figure 3. Comparison of the fundamental frequencies predicted by three different sub-formulations of Eq.(5) for all types of slender masonry structures, towers and minarets

Similarly, Fig. 4 illustrates the comparison between experimental and empirical fundamental frequency expressed according to NCSE-02 (2002) and Eq.(6). Results show that empirical formulation proposed by NCSE-02 (2002), leads to an underestimation of fundamental frequency for the slender masonry structures 15m to 40m height, while the values from Eq.(6) formulation better fit the experimental fundamental frequency.

Result of the comparison between empirical fundamental frequencies expressed by Eq.(6) for different types of slender masonry structures is shown in Fig.5. Here, the result reveals that the fundamental frequency predicted by three different sub-formulations (i.e. for all types of slender masonry structures, towers and minarets) derived from Eq.(6), using different numerical values for factor C, φ and δ, have a similar trendline, which suggests that it is reliable to estimate fundamental frequency for all types of slender masonry structures including towers with the same formulation. However, results also show that sub-formulation derived from Eq.(6) for the minarets has a different trendline than others, which means that for the better predictive performance, it is better to estimate the fundamental frequency of minaret structures using different formulation presented in Eq.(6).

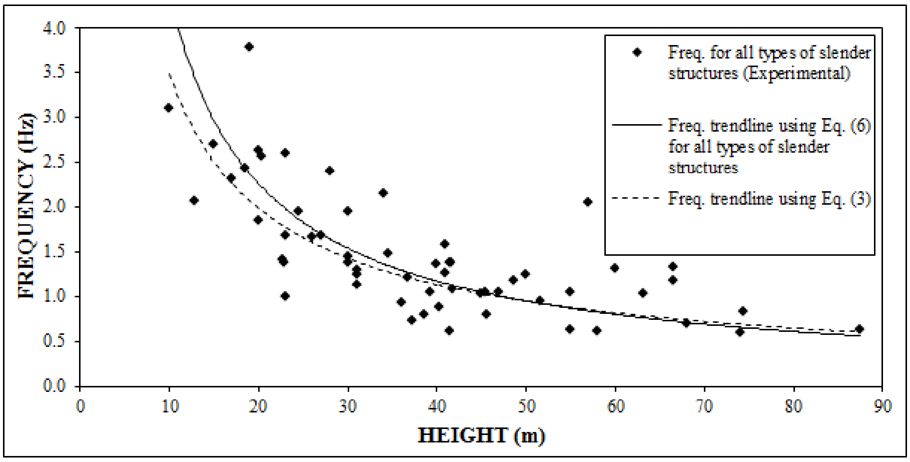

Figure 4. Comparison between experimental and predicted values of the fundamental frequency according to Eq.(3) and Eq.(6) for all types of slender structures

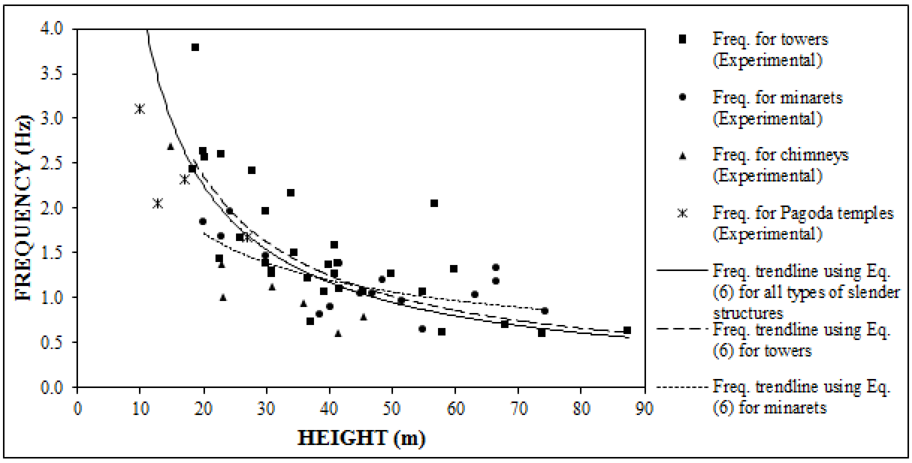

Figure 5. Comparison of the fundamental frequencies predicted by three different sub-formulations of Eq.(6) for all types of slender masonry structures, towers and minarets

Similarly, Fig.6 illustrates the comparison between experimental and fundamental frequency expressed according Eq.(4) and Eq.(7). Results show that formulation proposed in Eq.(4), leads to an underestimation of fundamental frequency, while the values from Eq.(7) formulation better fit the experimental fundamental frequency.

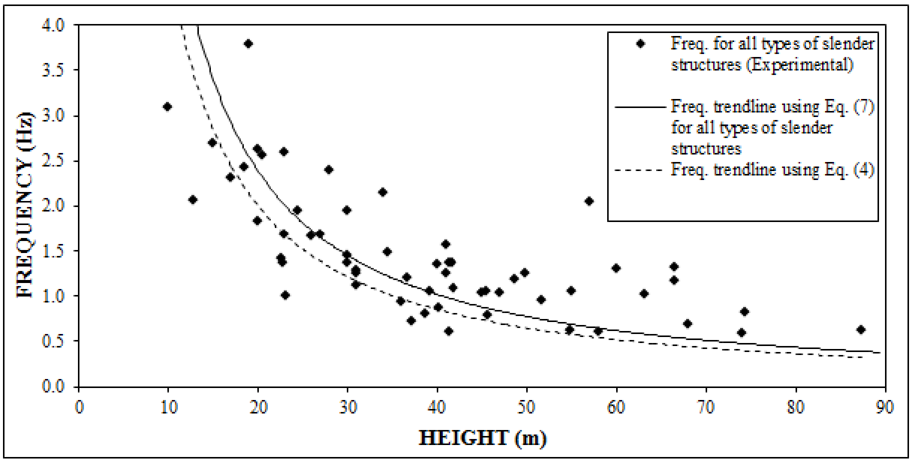

Figure 6. Comparison between experimental and predicted values of the fundamental frequency according to Eq.(4) and Eq.(7) for all types of slender structures

Fig.7 illustrates the comparison of empirical fundamental frequency expressed by Eq.(7) for different types of slender masonry structures. Result reveals that the fundamental frequency predicted by three different sub-formulations (i.e. for all types of slender masonry structures, towers and minarets) derived from Eq.(7), using different numerical values for factor X, have similar trendlines, which suggest that it is reliable to estimate the fundamental frequency for all types of slender masonry structures including towers and minarets resourcing to a single formulation. But, for the better predictive performance, it is better to estimate using individual formulation presented in Eq.(7).

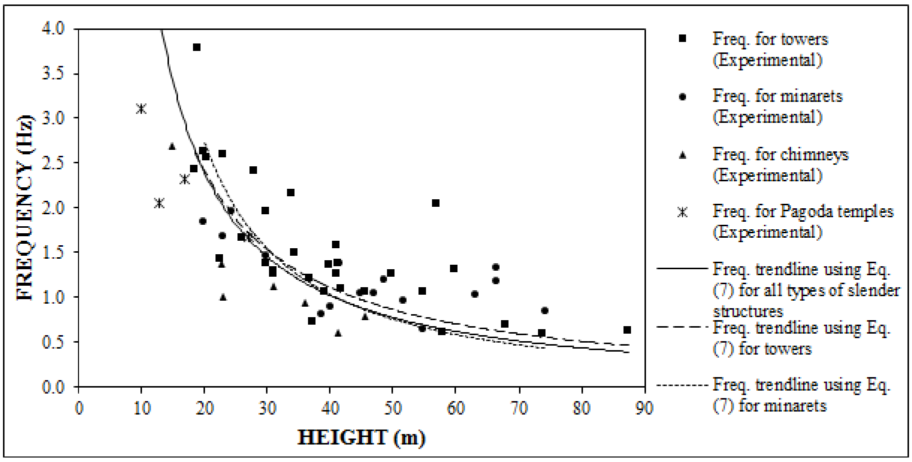

Figure 7. Comparison of the fundamental frequencies predicted by three different sub-formulations of Eq.(7) for all types of slender masonry structures, towers and minarets

Lastly, Fig.8 illustrates the comparison between experimental and empirical fundamental frequency expressed according Eq.(8) for all types of slender masonry structures. Result shows that an empirical formulation proposed, lead to better fit the experimental fundamental frequency.

Fig.9 illustrates the comparison of empirical fundamental frequency expressed by Eq.(8) for different types of slender masonry structures. Result reveals that the fundamental frequency predicted by three different sub-formulations (i.e. for all types of slender masonry structures, towers and minarets) derived from Eq.(8), using different numerical values for factor Y and z, have a similar trendline, which suggest that it is reliable to estimate fundamental frequency for all types of slender masonry structures including towers with the same formulation. However, results also show that sub-formulation derived from Eq.(8) for the minarets has a different trendline than others, which means that for the better predictive performance, it is better to estimate the fundamental frequency of minaret structures using different formulation presented in Eq.(8).

Among all of four empirical formulation proposed, Eq.(6) has the highest linear R squared value, which obviously is the best predictive performance formulation for all types of slender masonry structures.

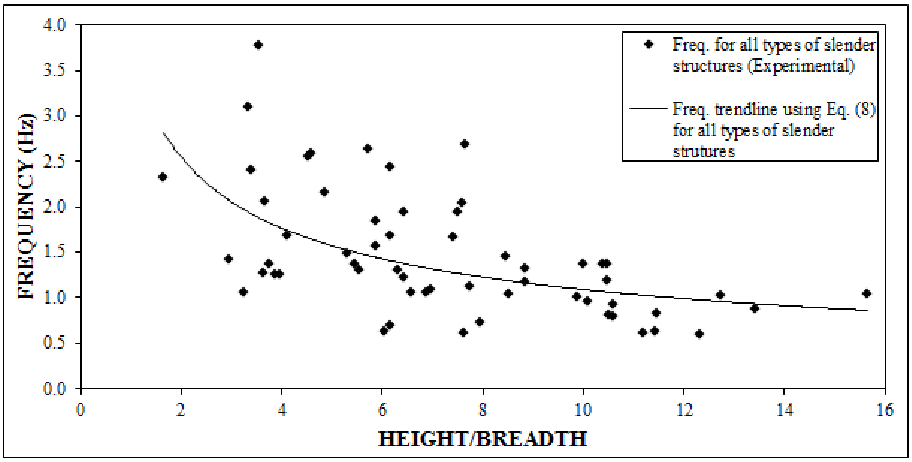

Figure 8. Comparison between experimental and predicted values of the fundamental frequency according to Eq.(8) for all types of slender structures

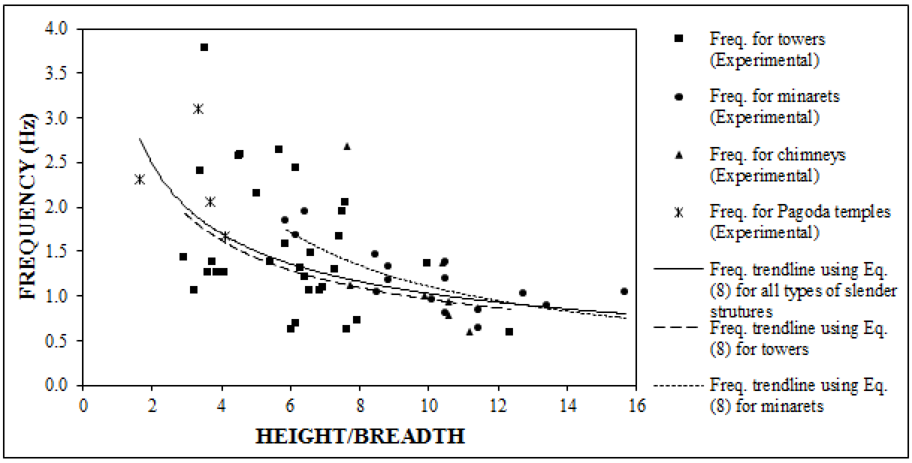

Figure 9. Comparison of the fundamental frequencies predicted by three different sub-formulations of Eq.(8) for all types of slender masonry structures, towers and minarets

CONCLUSIONS

In the present paper the database compiled is the key constituent in the calibration of empirical formulations for the prediction of the fundamental frequency for slender masonry structures. Data was collected through literature review on slender masonry structures regarding experimental natural frequency, geometrical and mechanical characteristics. The experimental fundamental frequencies have been correlated to develop an empirical formulation for the prediction of the fundamental frequency of slender masonry structures. Based on all documented and validated experimental data, reliable empirical formulations for the better prediction of the fundamental frequency for slender masonry structures are proposed. Comparative results confirm that the newly developed formulation has a reliable predictive performance.

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