Applied Earthquake Engineering in the Research of Vulnerable Masonry Structures

Spyridon S. Kouris

Civil Engineer, Msc., Ph.D, Thessaloniki, Greece

spyridon.k@gmail.com

***Abstract*- Strong earthquakes caused damages or collapses of vulnerable masonry structures. Over the last few decades, a great number of historical masonry bell towers which were erected in areas of relatively high seismic activity, have suffered from damages and cracking by earthquakes. In addition to these damages other causes, as thermal and hydroscopic strain and cyclic stress caused by wind action can act in combination with the long term phenomena and contribute to worsen the damages. Consequently, some of the most known bell towers have collapsed today or have been reconstructed. So, the medieval tower of Pavia (Italy) collapsed on March 17th, 1989, the bell tower of Cathedral of Monza (Italy) collapsed in May, 1993, the Cathedral of Noto (Sicily-Italy) collapsed in March 1999, the bell tower of St. Mark in Venice collapsed in 1902 and it was rebuilt later and many other cases. The few survived till today masonry "slender" bell towers are under considerable damages (such as the bell towers on Corfu island in Greece) and many of them are masterpieces of architecture in the past centuries. The aim of this paper is to describe the behavior of these bell towers under dynamic loading and to research how the geometry of these structures and the ground soil has affected their response to earthquakes. The finite element program SAP 2000 has been used for the study of the dynamic analysis of bell towers.**

Keywords- Frequencies; Dynamic Analysis; Masonry Bell-tower

I. INTRODUCTION

Historical bell-towers in Europe have many morphological and typological traits, depending on the country they are in. Although characterized by different stylistic decorations, age of construction and original function, their comparable geometric and structural ratios yield to the definition of an autonomous structural type. In a very concise definition, they can be described as monuments in which the total height is the prevalent dimension. Consequently, these monuments are featured by notable slenderness and vulnerable masonry structures. This also represents one of the main differences from other historic monuments (churches, palaces, etc.) or even ordinary buildings.

In Greece, there exist many impressive high bell towers. Especially on Corfu island in north-western Greece there are many bell towers which are extremely high, as can be seen in Fig. 1. Bell towers are some of the only tall structures in the town of Corfu, which allowed them to be invaluable surveying posts during times of war. In the past, these towers were built as a symbol of strength, ability, and faithfulness to God (in accordance with Venice structural tradition) [1]. Their purpose lies in pointing to heaven and looking forth to survey. In times of peace, the towers were rung for celebration and mourning, to mark the hours, in correlation with the Christian Orthodox festivals. In the past, bells were rung frequently to call people to mass, celebrate Christian events and holidays, or even just to keep time. There is at least one bell-tower in every neighborhood and typically, the inhabitants look upon their local bell tower with great pride.

Fig. 1 Bell towers on Corfu island (St. Spyridon, St. Mathias, St. Barbaros, Platitera)

Nowadays, it has become common that the bells are played automatically, and there is no reason for a bell ringer to inspect them. Since there is no bell ringer visiting the tower daily, there is no one there to observe the towers' condition and the bell-towers can easily fall into a state of disrepair. Also, Corfu bell-towers were erected in areas of relatively high seismic activity. So, in addition to that, it has become evident that Corfu bell-towers have suffered from damages and cracking caused by earthquakes and lack of repair, as in Fig. 2. It is obvious that a research in these vulnerable masonry structures is essential, in order to avoid a total collapse and help bell towers structural system against earthquake action [2].

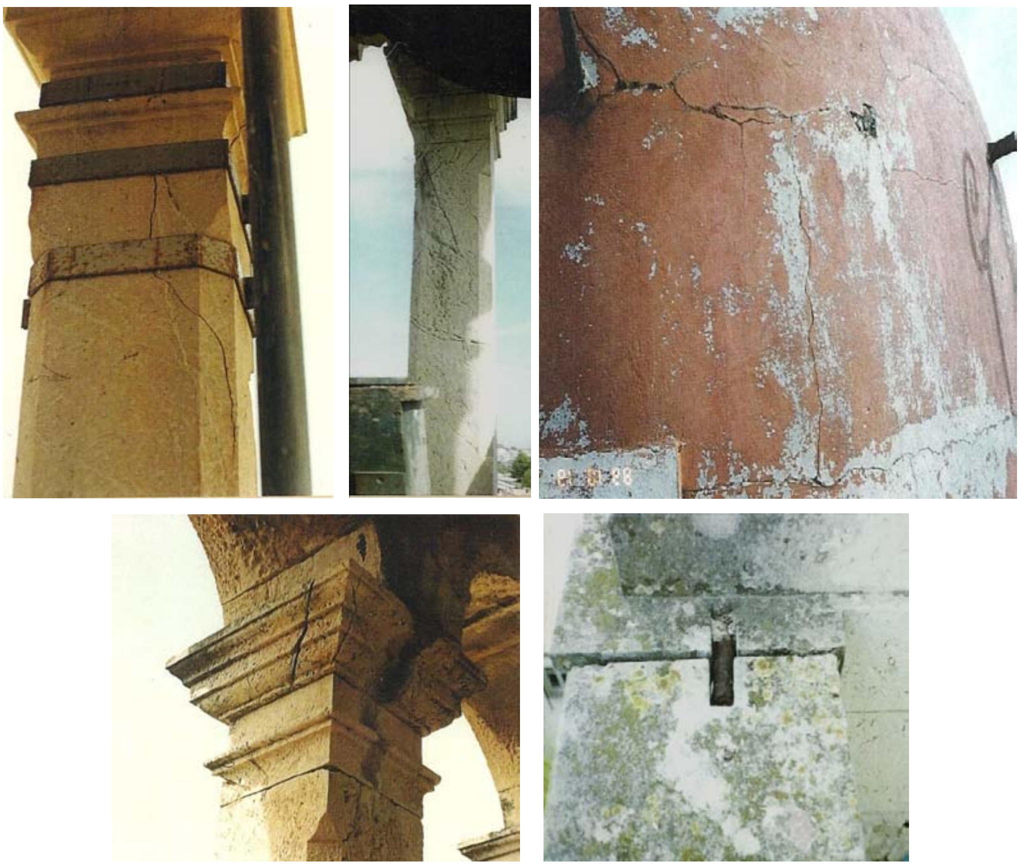


Fig. 2 Corfu bell-towers have suffered from damages and cracking from earthquakes

II. STRUCTURAL PARTS OF A MASONRY BELL-TOWEL

On Corfu there are many bell-towers, of which the oldest dates back to 1394 and the most recent dates to the end of 1800. Perhaps the most characteristic one of high bell-towers is St. Spyridon bell-tower, which was built in 1590. It has a square ground plan with a very high body that ends in belfry part. It reminds you of the bell-tower of St. Giorgio dei Greci in Venice (Fig. 3) [2].

Fig. 3 The bell-tower of St. Giorgio dei Greci in Venice and the bell-tower of St. Spyridon on Corfu

For the investigation of a bell-tower's dynamic behavior, it is important to have a clear understanding of its structural parts. A bell tower usually consists of a strong base and a high body with the belfry. The foundation and the ground floor of the tower are constructed with heavier and thicker walls than its top parts near the belfry. Thus the most important parts of a bell tower are the base, the shaft, and the belfry. The base is usually the heaviest part and it is constructed with a non-porous stone or brick material which should be strong enough to bear the structural pressure of the tower [3].

The shaft of a bell tower is by far the largest physical component of the tower. There are staircases and/or ramps that traverse the shaft, often with several landings on the way up. The shaft is usually made of bricks joined by mortar.

The type and the strength of the bricks that are used vary according to the year the tower was erected, as brick-makers improved the formula for bricks over the time, allowing their products to withstand higher pressures.

The properties of the bell towers' mortar also vary depending on the year the bell tower was built [3]. In some bell towers, metal tendon was used to add flexibility and support to the bell tower shaft. The belfry is the large open area at the top of the bell tower where the bells are hung. On each of the belfry sides there is a double arch supported by a pier on either side and by a stone column in the center (Fig. 4) [3]. Above the belfry is the bell-tower roof, that is a curved dome, which is of bright red color and it is based on a cubic drum. The belfry is usually constructed using bricks and in many cases elaborated decorations of stone or clay are added. Generally, inside the belfry bells are supported by wood beams, but also in some of the more modern bell-towers metal beams are used. This of course adds to the deterioration of the tower, since the vibrations pass through the metal frame into the supporting brick walls [3].

Some bell-towers have another area above the belfry called the attic, generally reachable by some kind of ladder, or possibly a stairway. The attic can have many purposes, such as storage or providing an avenue for maintenance workers to reach the top of the tower. It also often provides access to the balustrade, a railed stone balcony that surrounds a tower, giving a beautiful view and more maintenance access [2].

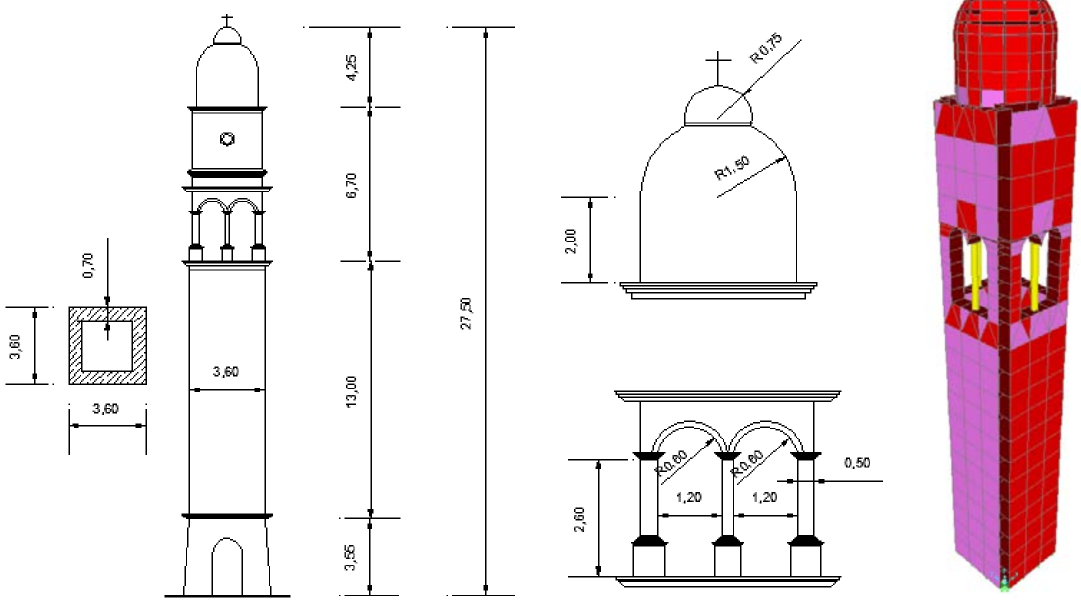


Fig. 4 A typical geometry of a bell-tower on Corfu and it's simulation model with 3D shell and frame elements (F. E. M.) in SAP software

III. DYNAMIC ANALYSIS OF STRUCTURE

To evaluate the dynamic behavior of a typical Corfu bell-tower, an analytical model with 3D shell and frame elements (Finite Element Method) was developed [3], as shown in Fig. 4. The bell tower of Platitera monastery, built in 18th century, is constructed by solid bricks and lime mortar has a square ground plan and its height is 30m approximately. The mass of masonry structure is distributed throughout the wall. So, masonry structures should be analyzed by F.E.M. with shell or solid elements.

Eurocode-6 has been chosen to define the mechanical properties of masonry [5]. So, the characteristic compressive strength is given by relation:

$$f_{wc} = k \cdot f_b^{0.65} \cdot f_m^{0.25}$$

where k is the constant concerned with the characteristic compressive strength of masonry, f_b is the normalized compressive strength of a masonry unit, and f_m is the compressive strength of mortar. The design compressive strength is given by:

$$f_d = f_k / \gamma_M$$

where the γ_M factor for masonry depends on the category of construction control (A↔ high, C ↔low), and the category of manufacturing control of masonry units (I↔ high quality control, II↔ normal quality control). So it belongs to C-II category (γ_M = 3.0) and group 3 (k = 0.40). The modulus of Elasticity is given by: $E_{wo} = 1000\ f_{wc}$ (EC-6, part 6-1, 3.8.2), but the existing pattern of cracking in vertical masonry reduces the initial module of Elasticity. We assume that the relationship between module of Elasticity of masonry with cracking and the initial could be [4]:

$$E_{wcr} = 2 / 3E_{w0}$$

So, according to EC-6 [5], the following are computed:

$$f_{wc} = k \cdot f_b^{0.65} \cdot f_m^{0.25} = 1.977\text{MPa},\ f_b = 10\text{MPa},\ f_m = 1.5\text{MPa}$$

$$\gamma_M = 3.0,\ f_{wd} = 1.977 / 3.0 = 0.659\text{MPa} = 0.66\text{MPa}$$

$$\gamma_s = 18\text{KN/m}^3,\ m_s = 1.83\text{t/m}^3,\ v_s = 0.15$$

$$E_{w0} = 1000 \cdot f_{wc} \approx 1000 \cdot 1.977\text{MPa} = 1977\text{MPa},$$

Take into account the cracking on the masonry walls of the bell-tower, the modulus of Elasticity [4] is considered:

$$E_{wcr} = \frac{2}{3} \cdot E_{w0} = 1318\text{MPa}$$

As mentioned above, linear elastic analysis was carried out using SAP 2000 software [6] for bell-tower. The direction of ground acceleration corresponded to the X, Y, and Z directions within SAP 2000. The elastic spectrum from Eurocode-8 [7] was used anchored to a basic ground acceleration of 0.24g in agreement with the Greek Code which defines that Corfu belongs to seismic zone II, [8]. The seismic effects were then computed according to the current Greek Code, which is in agreement with international recommendations in the field. For the modal-superposition analysis of the campanile subjected to dynamic loads, the Ritz-vector analysis was carried out. As it shows in Table Ⅰ, the first four modes are activated up to 70% of the mass of the structure.

The reason that Ritz-vectors yield such excellent results is that they take into account the spatial distribution of dynamic loading, whereas the direct use of the natural mode shapes neglects to consider this important piece of information [4]. From the results of analysis it was observed that the maximum tensile stress in the bell-tower wall occurs in and beneath the arched areas of the structure, as shown in Fig. 5.

TABLE I RESULTS OF DYNAMIC ANALYSIS: PERIODS AND MODAL PARTICIPATING MASS RATIOS FOR THE FIRST 12 MODES

TABLE: Modal Participating Mass Ratios						
OutputCase	StepType	StepNum	Period	Sum X	Sum Y	Sum Z
Text	Text	Unitless	Sec	Unitless	Unitless	Unitless
MODAL	Mode	1	0,804665075757687	0,668088266720404	0,269050824814542	0,326614495946
MODAL	Mode	2	0,804455755016951	0,937222642478108	0,937294521854523	0,342717051450069
MODAL	Mode	3	0,212709743387249	0,93722805917312	0,937295851377053	0,577575609146506
MODAL	Mode	4	0,180149087725579	0,962382698363414	0,952399660717094	0,725058159804196
MODAL	Mode	5	0,179919323666419	0,977499812580864	0,977372937779653	0,727327438238441
MODAL	Mode	6	0,097052126918034	0,988780467356508	0,988793766898423	0,727327970356743
MODAL	Mode	7	0,089594901548331	0,988782474356307	0,988795870222625	0,868269794564422
MODAL	Mode	8	0,072873496569045	0,988986719108734	0,989172571874361	0,868297509032224
MODAL	Mode	9	0,072591757981155	0,989372927218454	0,989401032238826	0,868549652096247
MODAL	Mode	10	0,062773389254450	0,989807455836377	0,990183935978465	0,931823929789266
MODAL	Mode	11	0,062659722221446	0,990625535821399	0,990581489970038	0,933742377853662
MODAL	Mode	12	0,036460877453832	0,992706971961866	0,992745097568064	0,933746669803796

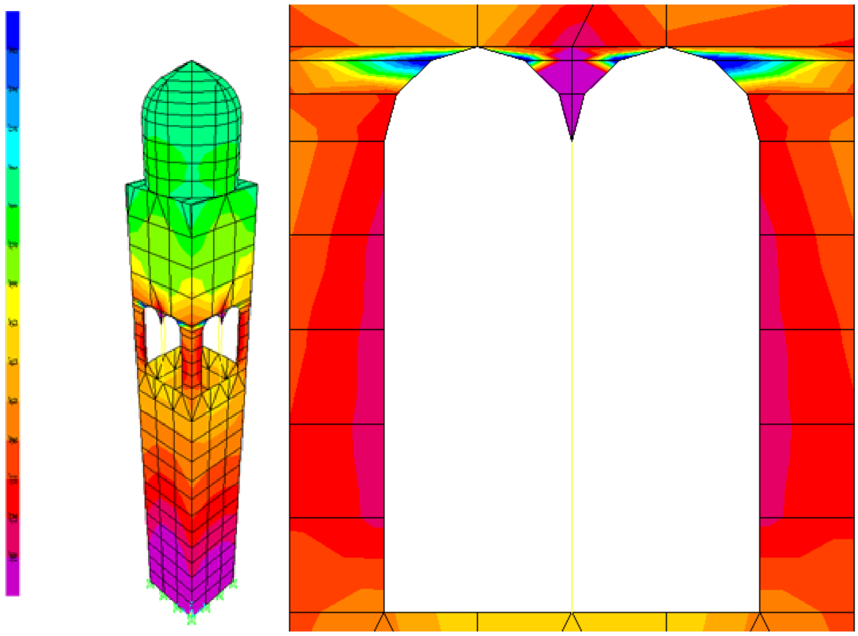


Fig. 5 Stress patterns of the model under seismic loading. The maximum tensile stress in the bell-tower wall occurs in the arched areas and in the heaviest base of the structure

The results of dynamic analysis show the predicted stress-pattern (horizontal normal stress) of the structure under seismic loading. The maximum tensile stress in the bell-tower walls occurs in the arched areas of belfry and in the heaviest base of the structure, as shown in Fig. 5. However, in comparison with the rest of the building, the base of the bell-tower is the strongest and carefully constructed part. It is therefore to be expected that in such areas, no signs of seismic generated distress will be apparent, as opposed to the belfry area where cracks have appeared in actuality. Thus the results of the theoretical analysis are in agreement with the actual present state and cracking pattern of the historical bell tower, as shown in Fig. 2.

IV. RESEARCH ON THE DYNAMIC BEHAVIOR

In areas of high seismic activity, such as Corfu island (0.24g), earthquakes will be the main cause of damage or collapse of monuments and historical buildings. Over the centuries, bell towers have periodically suffered from seismic phenomena and only those which were well planned and constructed have survived until today. Thus, it is very important to assign the main parameters that are affected on the dynamic behavior of the structure. As it is known the main parameters that assign dynamic characteristics are the geometry of the structure and the type of soil in the foundation. The focus of this assessment is to find out how these parameters influenced the frequencies of the structure.

A. Masonry Thickness

From the situ autopsy in Corfu island, it was observed that there is a variation in thickness of masonry walls of the bell towers. Therefore, it is interesting to examine how important the effect of the thickness of the walls on the dynamic behavior of the structure is. So, in accordance with the initial simulation model of the bell-tower, the next four models are examined:

- (1.25t): Increase 25% in the thickness of masonry walls, with respect to the initial model
- (1.50t): Increase 50% in the thickness of masonry walls, with respect to the initial model
- (0.75t): Decrease 25% in the thickness of masonry walls, with respect to the initial model
- (0.50t): Decrease 50% in the thickness of masonry walls, with respect to the initial model

where t is the thickness of masonry wall.

Linear elastic analysis was carried out using SAP 2000 software [4], for each of the above occasion of the bell-tower. From the results of dynamics analyses it can be computed that the diagram of the variation of frequencies regarding the thickness of the bell-tower, as shown in Fig. 6.

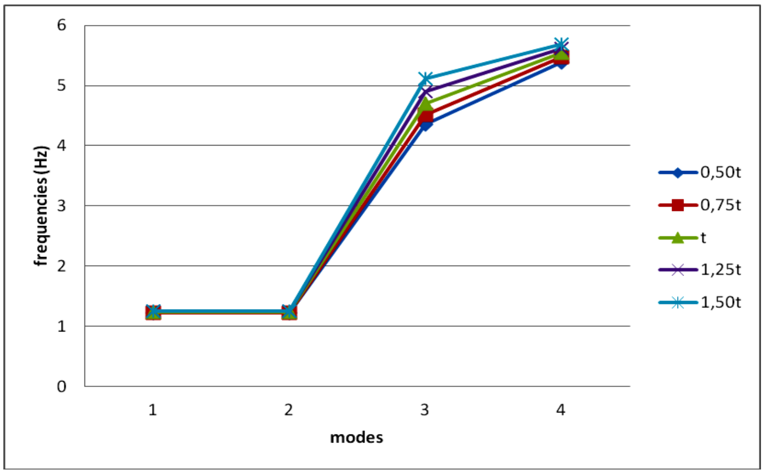


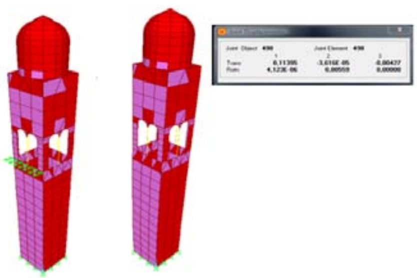
Fig. 6 Diagram of the variation of frequencies regarding the wall thickness

A careful inspection of the above diagram, as shown in Fig. 6, leads to the conclusion that the thickness of masonry walls does not have any effect on the dynamic behavior of the structure. The variation of frequencies related to masonry thickness is practically negligible. Especially the natural frequency is the same for each simulation model.

In order to assess these results of the diagram, it is necessary to consider the fundamental principles of earthquake engineering. The principle of dynamic analysis may be illustrated by considering the simple simulation model, linearly elastic structural system subjected to external dynamic loading. The model is subjected to force F. K and m are the stiffness and mass of simulation model accordingly. The equation of motion of the system may be written as:

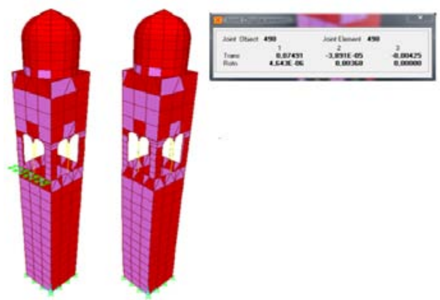
$$F = Kdx.$$

It considers the case of horizontal loading F to the shell elements simulation model of the bell tower as shown below. The total force F is, for example, equal to 700KN (100KN in each of 7 nodes of model). m_1 is the mass of structure. It was computed that the displacement of structure, which is subjected to the force F is dx_1 = 0.114. It can be written as Equation (1) as below:



$$F = K_1 d_1 x \Rightarrow K_1 = \frac{F}{dx_1} = \frac{700}{0.114} = 6140.351 KPa \qquad (1)$$

As a second step it examined a model which had increased 50% the thickness of masonry wall comparing with the initial model. Thus, the mass m_2 of this model is equal to 1.50 m_1. It was computed that the displacement of structure, which is subjected to the force F (700KN) is dx_2=0.075. It can be written as the Equation (2) as below:



$$F = K_2 dx_2 \Rightarrow K_2 = \frac{F}{dx_2} = \frac{700}{0.075} = 9333.333 KPa \qquad (2)$$

From the Equations (1) and (2) we give the following:

$$\frac{K_2}{K_1} = \frac{9333.333}{6140.351} \approx 1.50 \Rightarrow K_2 = 1.50 K_1$$

Therefore, it can be said that the variation of frequencies related to masonry thickness is negligible because of the accordingly variation of mass and stiffness of the structure.

B. Ratio H/L (Height/Length) of The Bell-Tower

A typical bell tower on Corfu has a square ground plan LxL and total height H. The ratio H/L is not stable but it was observed that there is a disturbance between 7.0 to 8.0 for the historical bell towers on Corfu island. So, it is examined how the value of the ratio H/L can be affected by the dynamic behavior of the structure.

In accordance with geometrical data of Corfu bell towers, the following four models were examined:

- A simulation model with H/L=7.0
- A simulation model with H/L=7.33
- A simulation model with H/L=7.67
- A simulation model with H/L=8.0

Linear elastic analysis was carried out using SAP 2000 software [4], for each of the above four models. From the results of dynamics analyses it is observed that the ratio H/L is an important factor for the dynamic behavior of the masonry bell towers, as we can see in Figs. 7-10. As it is shown in the diagrams, it indicates a line variation of frequencies relating to ratio H/L. There is a decreasing variation line of frequencies accordingly with the increasing of ratio H/L.

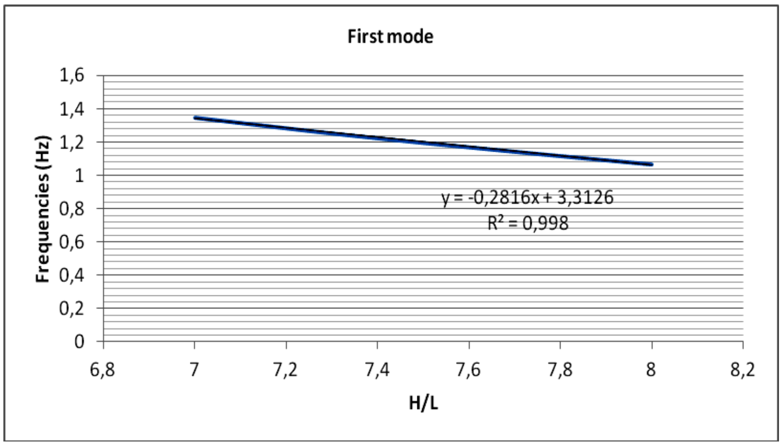


Fig. 7 Diagram of frequencies relating to ratio H/L, for the first mode

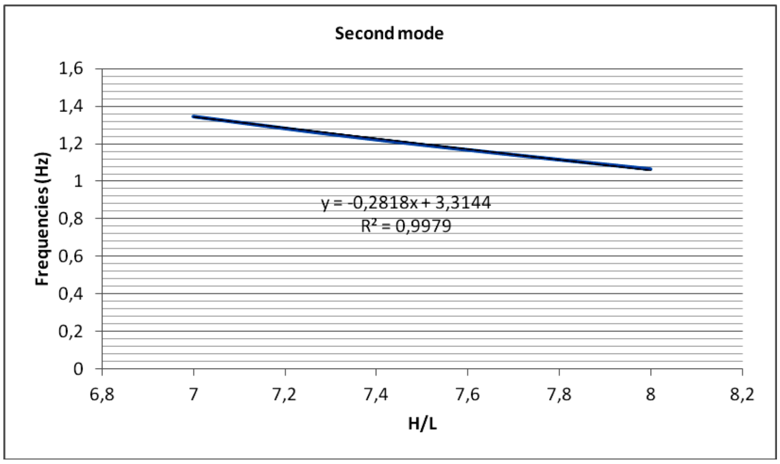


Fig. 8 Diagram of frequencies relating to ratio H/L, for the second mode

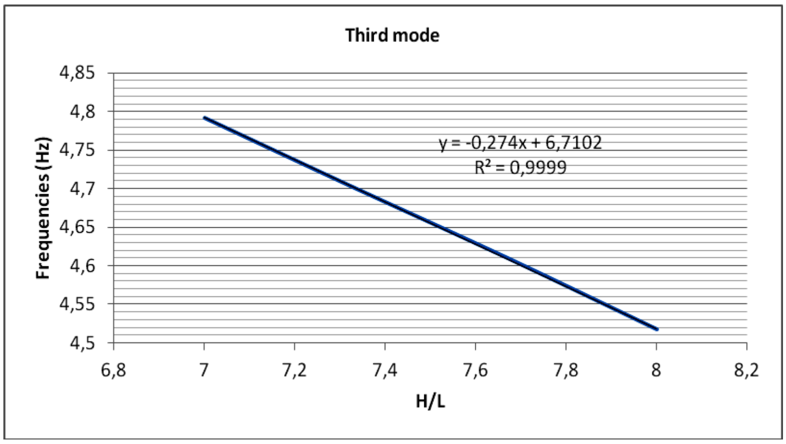


Fig. 9 Diagram of frequencies relating to ratio H/L, for the third mode

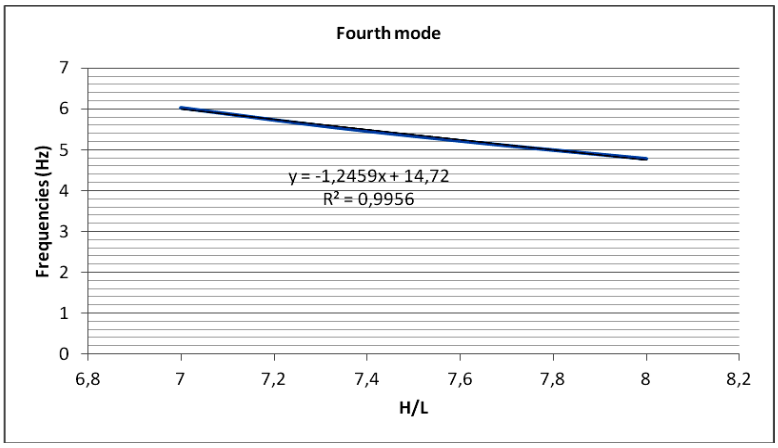


Fig. 10 Diagram of frequencies relating to ratio H/L, for the fourth mode

C. Type of Soil Foundation

The interaction between soil and bell tower foundation is simulated by springs. Springs are flexible connections to ground and are always linear elastic. All kinds of soils is simulated in accordance with the stiffness of springs. Linear elastic analysis was carried out for each kind of soil as it is shown in the Table Ⅱ.

Table Ⅲ shows the results of dynamics analyses for the frequencies for the different type of soils. It is observed that the variation of the natural frequency of the structure in case of the different type of ground soils is represented by a logarithmic curve, as shown in Fig. 11. Increases of modulus of ground elasticity correspond to a decrease of natural frequency of the structure.

TABLE Ⅲ TYPE OF GROUND SOIL RELATING TO THE STIFFNESS SPRINGS

Type of Soil	Symbol	E_s	ν	C_z	$C_{\varphi z}$	$I_{\varphi z}$	$K_{\varphi z}$	K_z	
loose sand	SC	14000	0,3	7411,277	7781,84	21,33	166012,597	44467,66	KPa
medium dense sand	SM	17000	0,33	9190,282	9649,797	21,33	205862,327	55141,695	KPa
dense sand	SP	23000	0,35	12626,62	13257,95	21,33	282836,277	75759,717	KPa
silty sand	SW	45000	0,4	25807,12	27097,48	21,33	578079,579	154842,74	KPa
sand and gravel	GM	120000	0,2	60216,62	63227,45	21,33	1348852,35	361299,74	KPa

TABLE Ⅲ FREQUENCIES FOR THE DIFFERENT TYPE OF SOIL

TABLE: Modal Frequencies								
			SW	SC	SC	SP	GM	GW
OutputCase	StepType	StepNum	Frequency	Frequency	Frequency	Frequency	Frequency	Frequency
Text	Text	Unitless	Cyc/sec	Cyc/sec	Cyc/sec	Cyc/sec	Cyc/sec	Cyc/sec
MODAL	Mode	1	0,975730	0,769376	0,769376	0,855317	1,094647	1,173219
MODAL	Mode	2	0,975874	0,769441	0,769441	0,855410	1,094858	1,173485
MODAL	Mode	3	4,699294	4,621651	4,621651	4,698119	4,700256	4,700805
MODAL	Mode	4	4,907962	4,627606	4,627606	4,725616	5,143529	5,340188
MODAL	Mode	5	4,914208	4,697188	4,697188	4,731674	5,150048	5,346965
MODAL	Mode	6	8,445595	6,099205	6,099205	7,195665	9,408375	9,920171
MODAL	Mode	7	11,147444	11,132322	11,132322	11,139160	11,154312	11,158235
MODAL	Mode	8	14,623253	14,417776	14,417776	14,502982	14,597431	14,251401
MODAL	Mode	9	14,679102	14,462731	14,462731	14,550603	14,669405	14,318131
MODAL	Mode	10	16,793499	18,623669	18,623669	17,871833	15,919852	15,761490
MODAL	Mode	11	16,885640	18,764007	18,764007	17,990390	15,989644	15,806604
MODAL	Mode	12	22,910507	20,148397	20,148397	21,136742	25,018800	26,432432

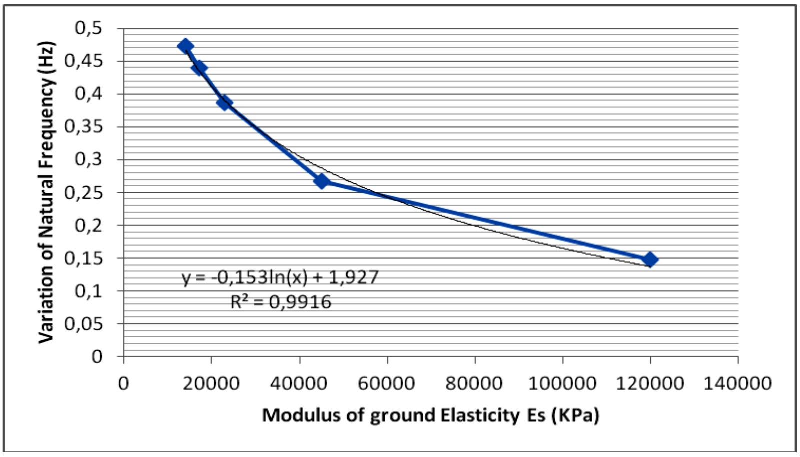


Fig. 11 Diagram of the variation of natural frequency relating to Modulus of ground Elasticity

V. CONCLUSION

In Southern Europe and, especially in Greece, earthquake actions are the main actions responsible for structural failure on vulnerable masonry structures. In order to face the seismic actions, it is very important to assign the main parameters that have been affected on the dynamic characteristic of the structure. Therefore, in this paper some crucial parameters have been examined in accordance with the dynamic behavior of historical masonry bell towers on Corfu.

It was proved that the masonry thickness walls do not have any influence on the frequencies of the structure because of the simultaneous variation of mass and stiffness of the structure. Another parameter that was examined is the value of the ratio Height/Length of the structure. It was proved that this is an important factor on dynamic behavior which indicates a decreasing variation line of frequencies accordingly with the increasing of ratio H/L. For the natural frequency of the bell towers, this variation was computed that is given by the equation:

$$F_n = -0.2816\,(H/L) + 3.3126 \qquad (3)$$

where F_n is the natural frequency of bell tower for full fix restrain of the joints of foundation.

It also researched the interaction between soil and bell tower foundation and it was proven that the variation of the natural frequency of the structure in case of the different type of ground soil is represented by a logarithmic curve that is given by the equation:

$$F = F_n + 0.153\ln(E_s) - 1.927 \qquad (4)$$

where F is the natural frequency of bell tower and E_s is the Modulus of ground Elasticity.

The Equation (4) because of the Equation (1) is as follow:

$$F = -0.2816(H/L) + 0.153\ln(E_s) + 1.3856 \qquad (5)$$

which is the equation that determines the natural frequency of the Corfu type bell towers for the main parameters such as the geometry of structure and the type of ground soil.

May be finally it is useful to make some research in other less important parameters, in order to obtain more accurate results for the natural frequency of the Corfu type bell towers.

REFERENCES

[1] Preservation of Venetian Bell-Tower, Venice Project Center, Italy, 2004.

[2] Kouris S. S., Karaveziroglou-Weber M., Structural Analysis and Diagnosis Of Masonry Towers, 3rd International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering , COMPDYN 2011, Corfu, Greece 25-28 May 2011.

[3] Kouris S. S., Karaveziroglou-Weber M., Numerical Analysis of Masonry Bell-Towers Under Dynamic Loading, Journal of Civil Engineering and Architecture, Vol. 5, No 8, 2011, pp. 715-722.

[4] Kouris S. S., Karaveziroglou-Weber M., Research on the Seismic Strengthening of Medieval Masonry Campanile, The Structural Engineer, 87 (7) 2009, pp 20-24.

[5] Eurocode 6: Design of Masonry Structures: Commission of the European Communities, ENV1996.

[6] Integrated Software for Structural Analysis and Design ANALYSIS REFERENCE MANUAL SAP 2000, 'Computers and Structures', University Avenue, Berkeley, California, USA, 1995.

[7] Eurocode 8: Design Provisions for Earthquake Resistance of Structures: Commission of the European Communities, ENV1998.

[8] EAK 2000: Greek Code for Earthquake Resistance of Structures, OASP, Greece,1996.