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# Seismic Hazard Analysis for Archaeological Structures – A Case Study for EL Sakakini Palace Cairo, Egypt

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Additional information is available at the end of the chapter

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## 1. Introduction

The modern architectural heritage of Egypt is rich, and extensively variable. It covers all kinds of monumental structures from palaces, public buildings, residential and industrial buildings, to bridges, springs, gardens and any other modern structure, which falls within the definition of a monument and belongs to the Egyptian cultural heritage. We present herein a comprehensive geophysical survey and seismic hazard assessment for the rehabilitation and strengthening of Habib Sakakini's Palace in Cairo, which is considered one of the most significant architectural heritage sites in Egypt. The palace located on an ancient water pond at the eastern side of Egyptian gulf close to Sultan Bebris Al-Bondoqdary mosque, a place also called "Prince Qraja al-Turkumany pond". That pond had been filled down by Habib Sakakini at 1892 to construct his famous palace in 1897.

Various survey campaigns have been performed comprising geotechnical and geophysical field and laboratory tests, aiming to define the physical, mechanical and dynamic properties of the building and the soil materials of the site where the palace is founded. All these results together with the seismic hazard analysis will be used for the seismic analysis of the palace response in the framework of the rehabilitation and strengthening works foreseen in a second stage. We present herein the most important results of the field campaign and the definition of the design input motion.

The seismic hazard analysis for El Sakakini Palace has been performed based on historical earthquakes, and maximum intensity.PGA with 10% probability of exceedance in 50 and 100 years is found equal to 0.15g and 0.19g respectively. P-wave and S-wave seismic refraction indicated a rather low velocity soil above the seismic bedrock found at depths higher than 20m. Ambient noise measurements have been used to determine the natural vibration frequency of soil and structure of El-Sakakini Palace. The fundamental frequency of El-

Sakakini palace is 3.0Hz very close to the fundamental frequency of the underlying soil, which makes the resonance effect highly prominent.

Some floors are considered dangerous since it show several resonance peaks and high amplification factors (4<sup>th</sup> and 5<sup>th</sup> floors) these floors are made of wood so, warnings to decision makers are given for the importance of such valuable structures.

The seismic design and risk assessment of El Sakakini palace is performed in two steps. In the first one we perform all necessary geotechnical and geophysical investigation together with seismic surveys and seismic hazard analysis in order to evaluate the foundation soil properties, the fundamental frequency of the site and the structure, and to determine the design input motion according to Egyptian regulations. The second phase comprises the detailed analysis of the palace and the design of the necessary remediation measures. IN the present pare we present the results of the first phase.

## **2. Seismic hazard**

### **2.1. Historical seismicity**

Egypt possesses a rich earthquake catalogue that goes back to the ancient Egyptian times. Some earthquakes are reported almost 4000 years ago. Figure 1 shows the most important historical events affecting ElSakakini palace. We can see that the Faiyum area as well as the Gulf of Suez is the most important earthquake zones affecting the place.

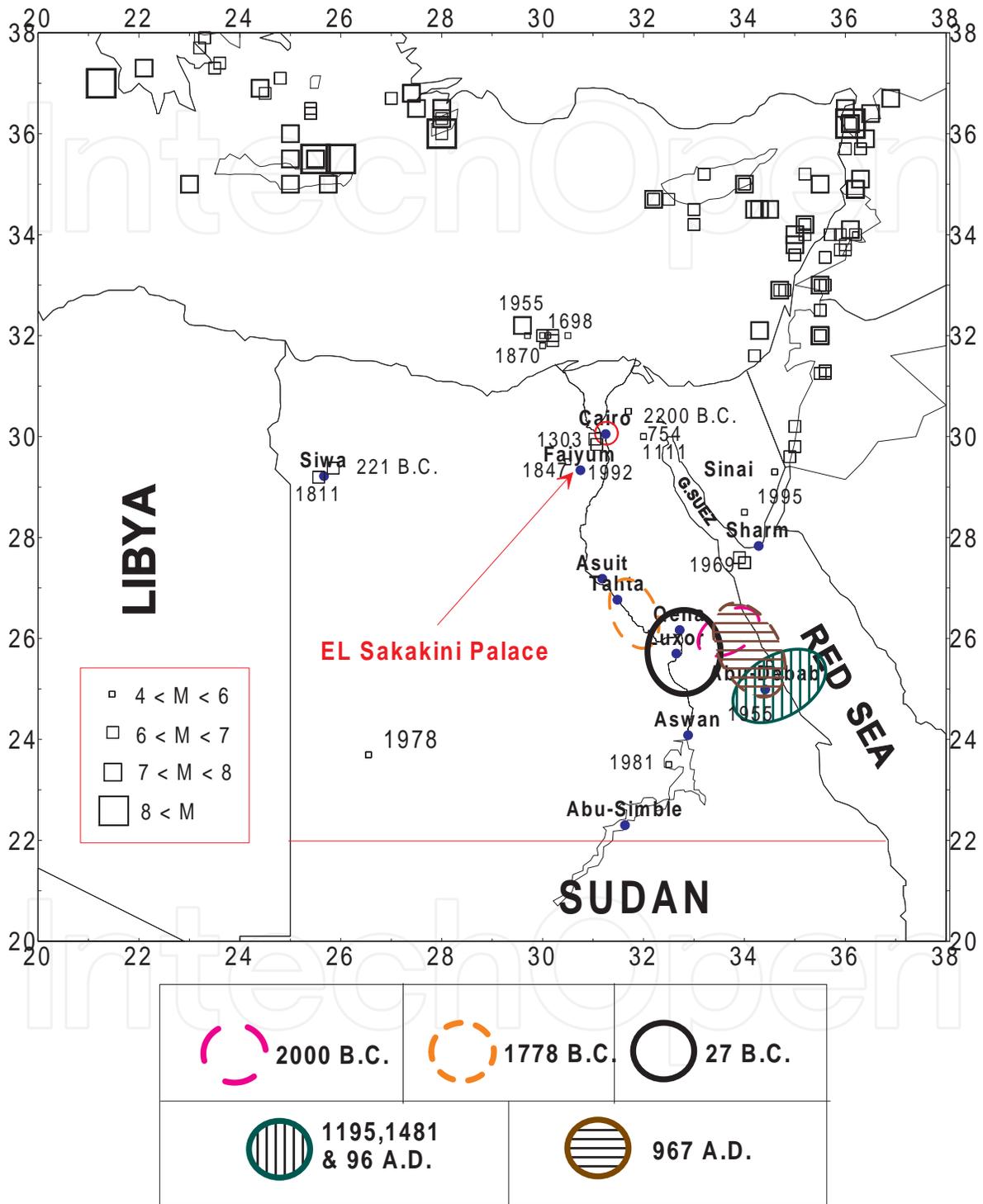
### **2.2. Maximum intensity**

Historical seismicity and maximum reported intensity is a good preliminary index of the expected severity of a damaging earthquake. Available isoseismal maps in the time period 2200 B.C. to 1995 were digitized and re-contoured to determine the maximum intensity affecting the place. This was done using a cells value of equal area 0.1 lat. × 0.1 long. Figure 2 present the produced IMM intensity showing that a maximum IMM of VII is good design value.

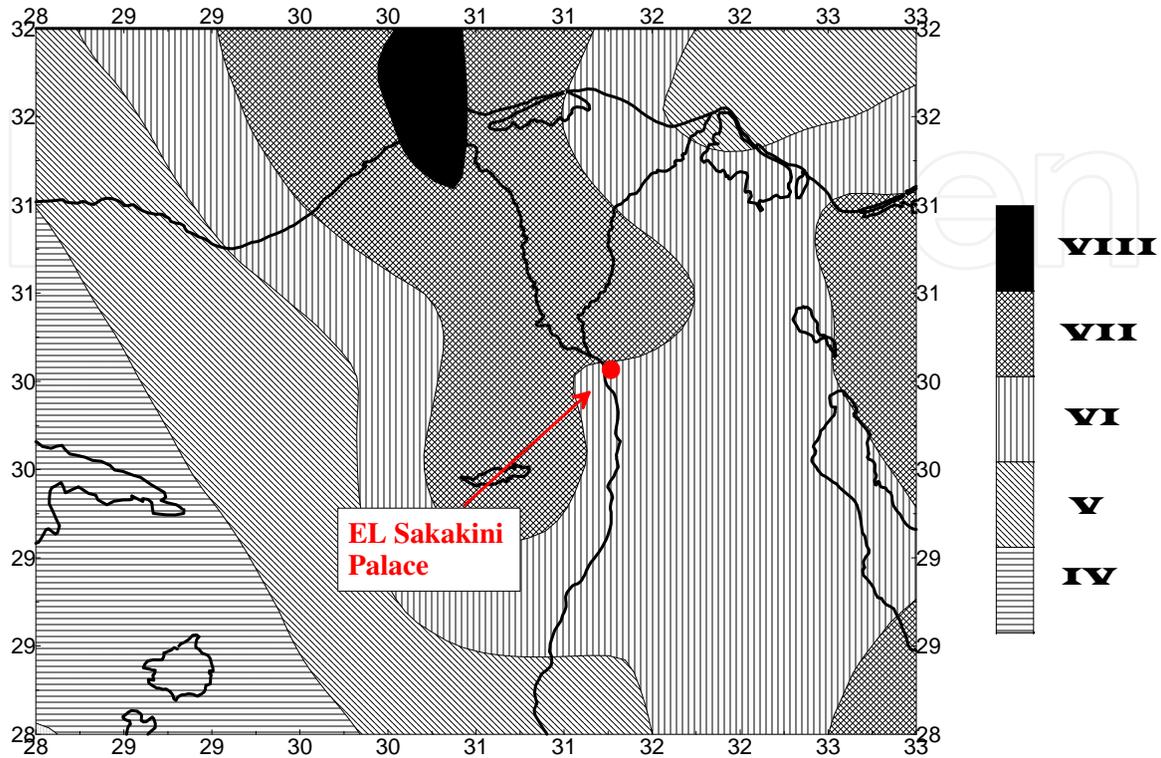
### **2.3. Probabilistic hazard assessment**

An improved earthquake catalogue for Egypt and surrounding areas affecting El Sakakini Palace has been prepared for the purposed of this study partially based on recent work of Gamal and Noufal, 2006. The catalogue is using the following sources:

- For the period 2200 B.C to1900: Maamoun,1979; Maamoun et al., 1984 ; Ben-Menahem 1979 and Woodward-Clyde consultants, 1985.
- For the period 1900 to 2006: Makropoulos and Burton, 1981; Maamoun et al., 1984 ; Ben-Menahem 1979; Woodward-Clyde consultants, 1985; Riad and Meyers, 1985; Shapira, 1994 and NEIC, 2006; Jordan seismological observatory 1998-2000.



**Figure 1.** Important and historical earthquakes occurred in and around EL Sakakini Palace area in the period 2200 B.C to 1995.

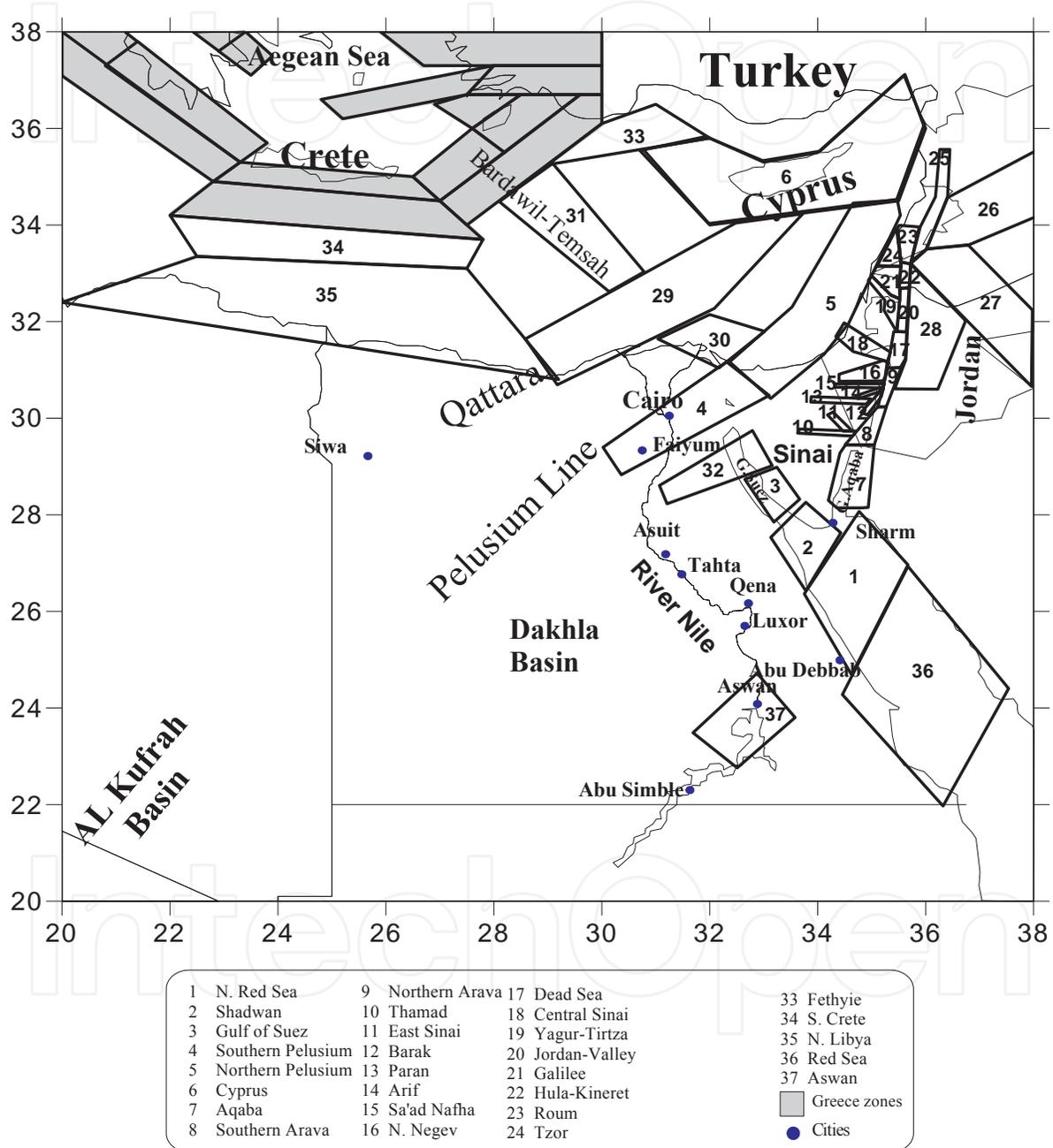


**Figure 2.** Maximum intensity zonation map based on the historical seismicity reported in the time period 2200 BC to 1995

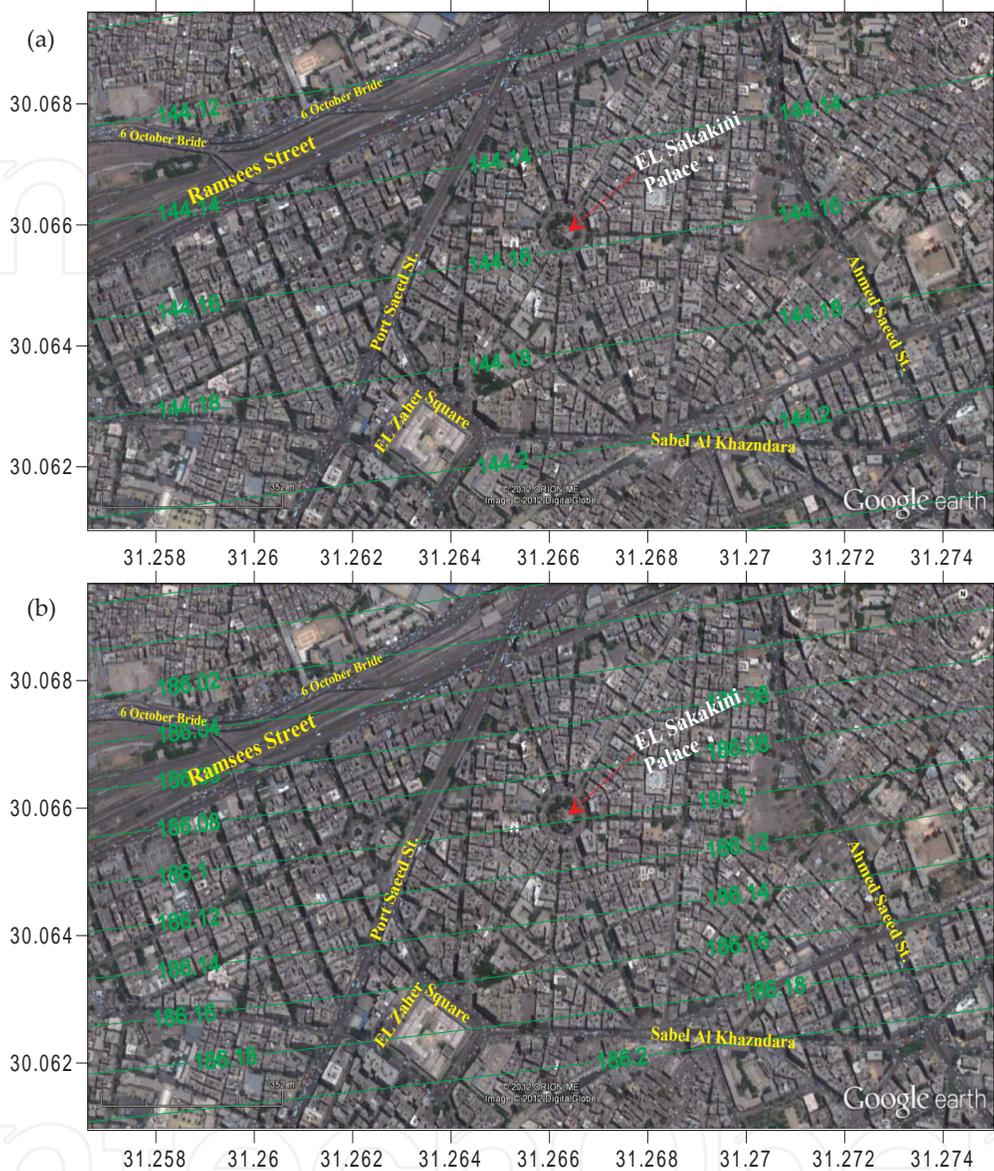
The horizontal peak ground acceleration over the bedrock of El Sakakini area was estimated using Mcguire program 1993. 37 seismic source zones were used to determine the horizontal PGA over the bedrock (Figure 3), while PGA attenuation formula of Joyner and Boore, 1981 was used because of its good fitting to real earthquake data in Egypt. A complete analysis for the input parameters to estimate the PGA values over the bedrock can be found in Gamal and Noufal, 2006.

$$(PGA) = 2.14 e^{1.13M} D^{-1} e^{-0.00590 D} (R^2 + 4.0^2)^{0.5} \quad (1)$$

The probabilistic analysis provided the following results: The peak horizontal acceleration in gals with 10 % probability of exceedance over 50 years is 144cm/sec<sup>2</sup>(or 0.147g) For 10% probability in 100 years the estimated PGA for rock conditions is 186 (cm/sec<sup>2</sup>) (or 0.19g) (Figures 3 and 4). These values are quite high and considering the local amplification they may affect seriously the seismic design and stability of El. Sakakini Palace.



**Figure 3.** Seismic source regionalization using 37 seismic source zone (except greece zones) adopted for Egypt and surrounding areas (Gamal and Noufal, 2006).



**Figure 4.** a: Peak Horizontal Acceleration in gals (cm/sec<sup>2</sup>) for the seismic bedrock with 10 % probability of exceedance in 50 years. b: Peak Horizontal Acceleration in gals (cm/sec<sup>2</sup>) for the seismic bedrock with 10 % probability of exceedance over 100years

### 3. Geotechnical investigation

Core drilling is among the routine methods for subsurface exploration. Most commonly, NX-size core drill is used, representing a hole diameter of 76 mm (3") and a core diameter of 54

mm (2 1/8"). The drilling often has multiplier purposes, of which the following are in most cases the most important:

Verification of the geological interpretation. Detailed engineering geological description of rock strata. To obtain more information on rock type boundaries and degree of weathering. To supplement information on orientation and character of weakness zones. To provide samples for laboratory analyses. Hydro geological and geophysical testing. Input data for engineering classification of rock masses.

The geotechnical investigation, six geotechnical boreholes with Standard Penetration Test (SPT) measurements have been carried out in the archaeological site included the drilling of three geotechnical boreholes with integral sampling to a depth 20 meters, one borehole to depth 15 meters and two boreholes to depth 10 meters at six locations in the site. The geotechnical data also indicated the ground water level at the archaeological site. We did all the boreholes inside the site with hand boring machine.

The results of laboratory tests which have been carried out on the extracted soil samples from the boreholes, which include specific gravity ( $G_s$ ), water content ( $W_n$ ), saturated unit weight ( $\gamma_{sat}$ ), unsaturated unit weight ( $\gamma_{unsat}$ ), Atterberg limits and uniaxial compressive strength (UCS), in addition to the ground water table (GWT), are shown in the figures (7a,7b).

The shear wave profile obtained by using ReMi compared very well to geotechnical boreholes and geophysical survey data. In addition, the shear wave profile obtained by using ReMi Performed much better than commonly used surface shear-wave velocity measurements.

Geotechnical boreholes (1) through (3) indicated that:

Filling of Fill (silty clay and limestone fragments, calc, dark brown) From ground surface 0.00m to 3.50m depth. Sand Fill (silty clay, medium, traces of limestone & red brick fragments, calc, dark brown) From 3.50m to 5.00m depth. Silty clay, stiff, calc, dark brown From 5.00m to 6.50m depth. Clayey silt, traces of fine sand & mica, yellowish dark brown From 6.50m to 8.50m depth. Silty sand, fine, traces of clay & mica. Dark brown. From 8.50m to 11.00m depth. Sand, fine, some silt, traces of mica, yellowish dark brown. From 11.00m to 14.00m depth. Sand, fine to medium, traces of silt & mica, traces of fine to medium gravel, traces of marine shells, yellowish dark brown. From 14.00m to 16.00m depth. Sand, fine, traces of silt & mica, yellowish dark brown. From 16.00m to 18.00m depth. Sand & Gravel, medium sand, graded gravel, traces of silt, yellow dark brown. From 18.00m to 20.00m depth. End of drilling at 20.00m.

Geotechnical boreholes (4) through (6) indicated that:

Fill (silt, clay and fragments of limestone and crushed brick, from ground surface 0.00m to 4m depth. Fill (silty cal with medium pottery and brick fragments, calc dark brown) from 4 to 5 m depth. Brown stiff silty clay and traces of limestone gravels, from 5.00m to 7.50m depth. silt, traces of brown fine sand & traces of clay from 12.00m to 14.00m depth. Dark brown clay silt with traces of fine sand. from 14.00m to 15.00m depth.

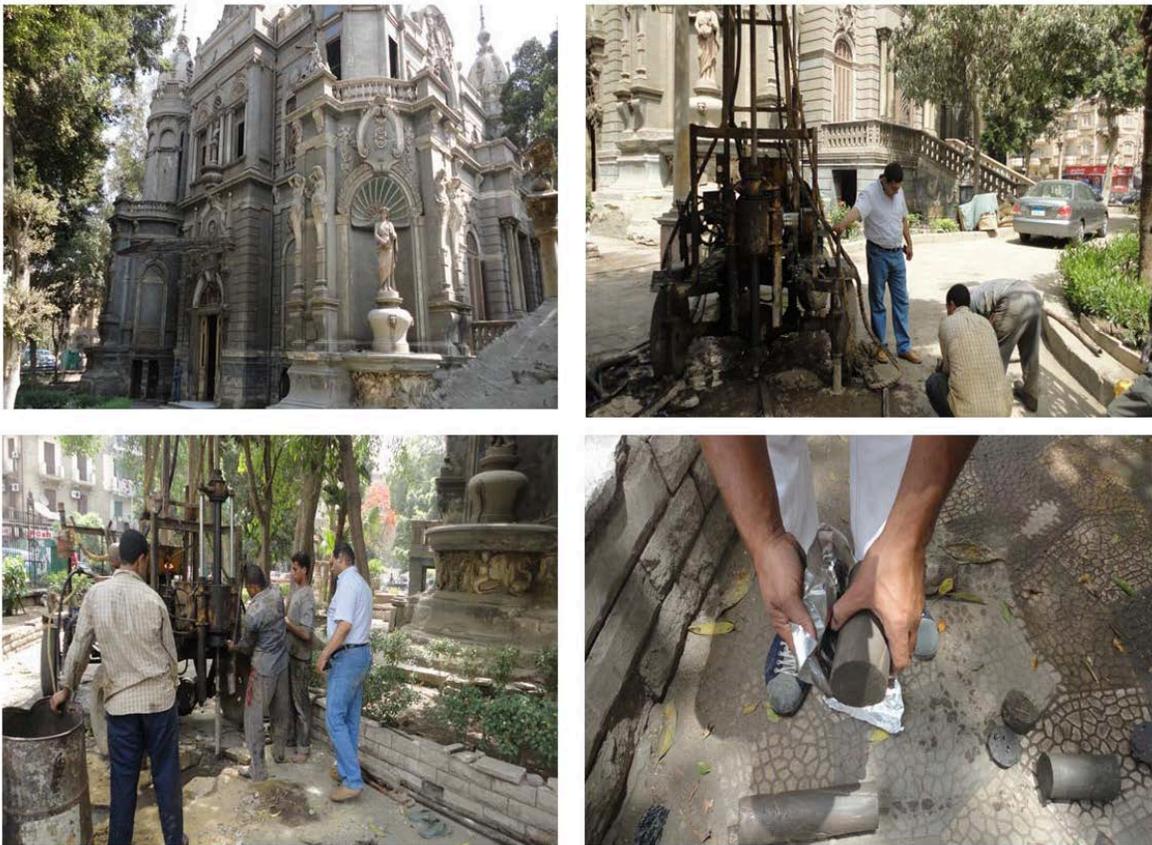


Figure 5. El- Sakakini palace and the Geotechnical investigations.

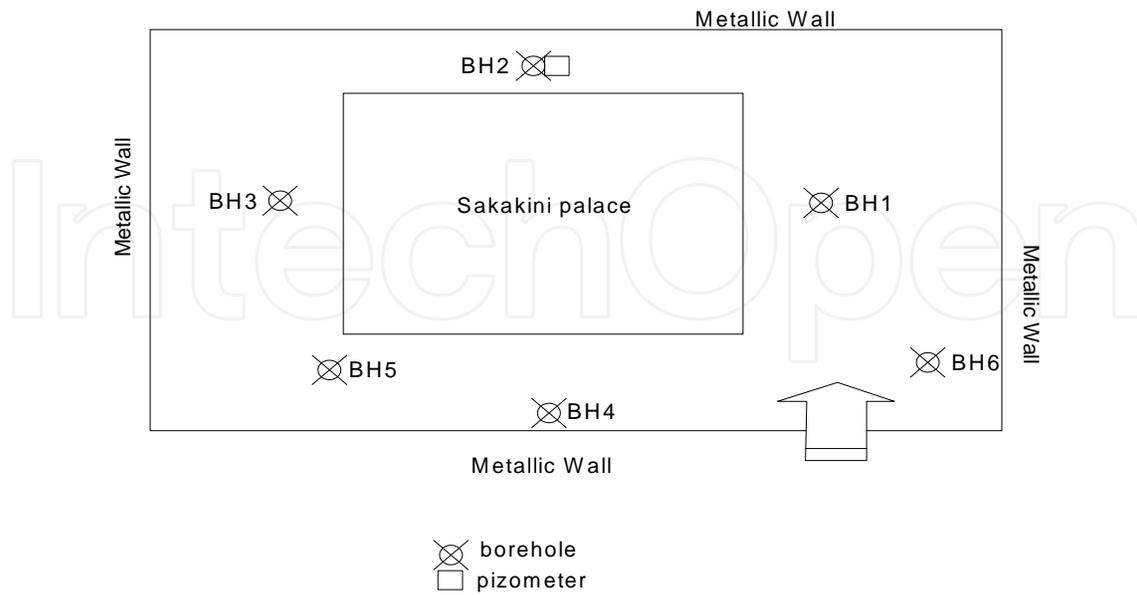


Figure 6. General layout & boreholes locations.



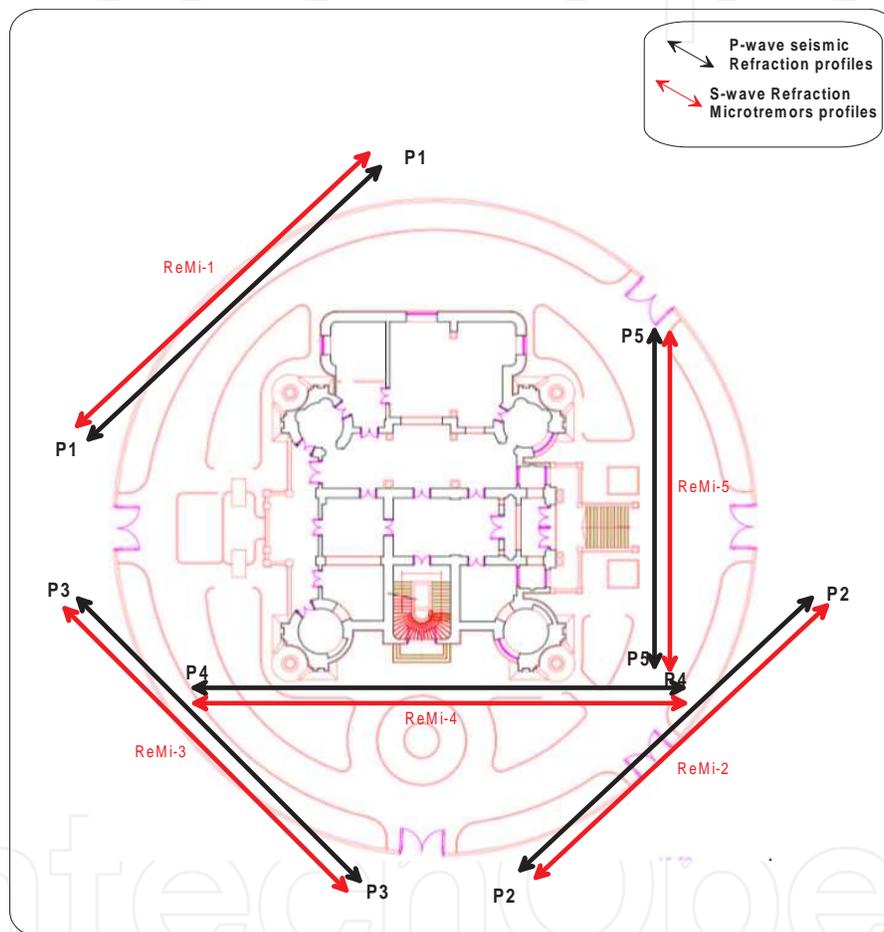
project : existing . habib pasha elsakakeeny palace		file no : sakakeeny feb10										
location : eldaher-cairo		date commenced : May . 15- 2012										
Boring. no : 4		date completed : May . 18- 2012										
DRILL METHOD : MANUAL DRILLING		weather : cold										
drill fluid : none		ground level :										
driller : alaa amin drilling co		initial / final gwd : 1.10 m										
depth ( m )	legend	classification	end of layer ( m )	qu ( kg/ cm2 )	spt n/30 cm	yb ( um3 )	f.s. ( % )	wL ( % )	WP ( % )	RECOVERY ( % )	R.Q.D. ( % )	
1		fill( limestone fragments concrete frag.sand&silt calc dark brown )										
2												
3												
4												
5				fill( silty clay .medum u of pottery fragments .calc dark brown )					51 75	23 95		
6												
7					7.40							
8		clayey silt . traces of mica .dark brown		2.75								
9					2.00							
10						2.25						
11						2.20						
12				clayer silty sand . fine . traces of rubble		2.00			35 76	18 09		
13				dark brown silt clay with traces of fine sand			31					
14					14.00							
15				fine brown silt and sand with traces of clay &	15.00							
end of drilling at 15.00m												

Figure 7. a. Geotechnical Borehole\_1, El Sakakini Palace. b. Geotechnical Borehole\_4, El Sakakini Palace.

## 4. Geophysical campaign

### 4.1. P-wave refraction

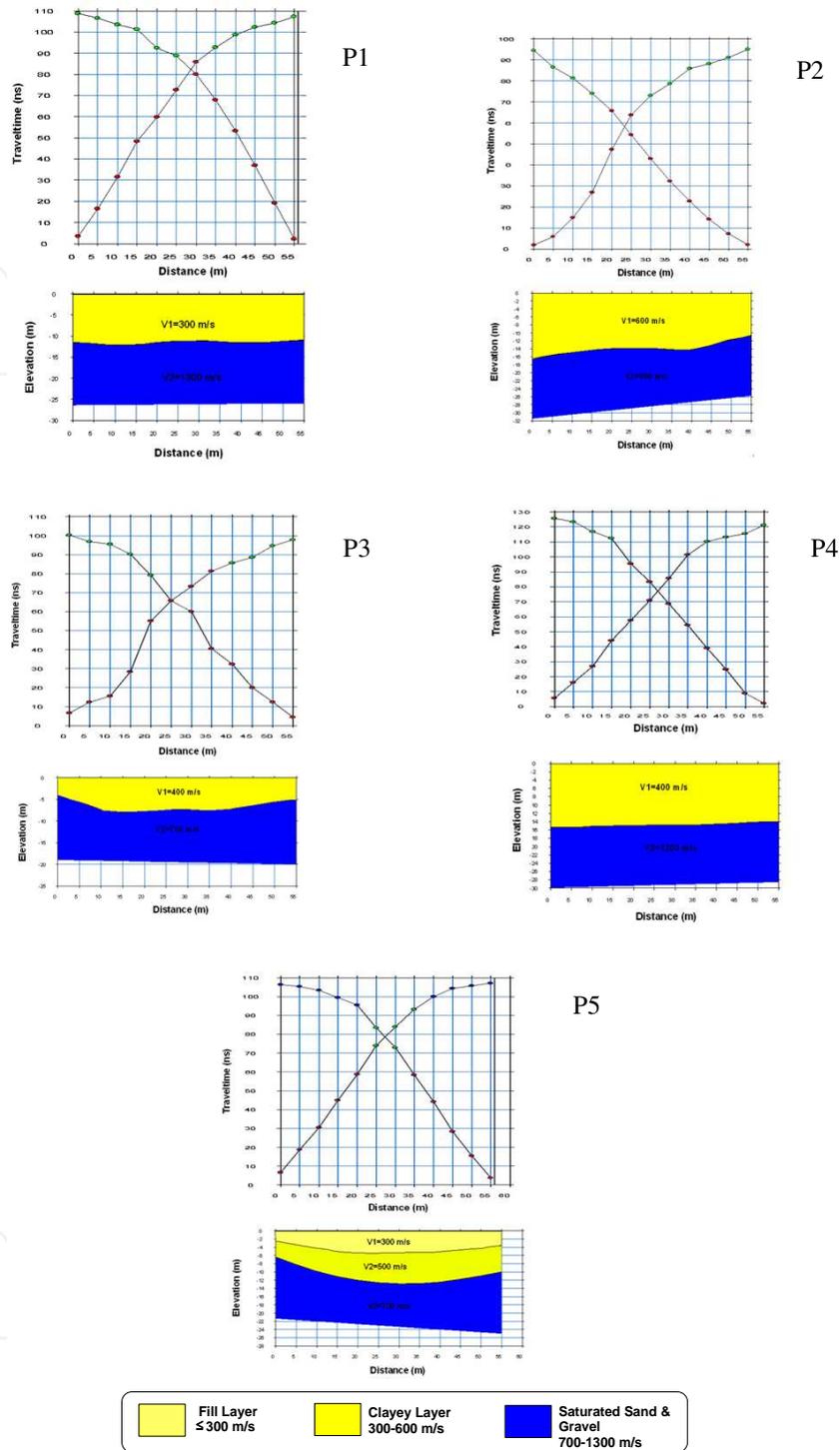
A total of 10 seismic profiles are conducted at El Sakakini palace area (Figure 8). All profiles are carried out using 12 receivers, P-type geophones with 5m intervals and 2 shots. The forward and reverse shots were carried at a distance of 1 m at both ends. The seismic shots layouts are described in Table 1.



**Figure 8.** Location of the P-wave seismic refraction, S-wave refraction and ReMi profiles conducted at ELSakakini Palace.

Shot #	Name	Offset X (m) (relative to R1)
S2	Forward	-1
S4	Reverse	56

**Table 1.** Seismic shots.



**Figure 9.** P-wave travel time distance curve and its corresponding geoseismic model for profiles # P1-P5 (Figure 8).

The conducted profiles are interpreted using time-term inversion method; an example of the conducted profiles and corresponding geoseismic model is shown in Figure 9. Table 2 summarizes the measured Vs values and the corresponding soil thicknesses. The soil stratification is not uniform and horizontal, as it should be expected for a filled area. However it is

possible to distinguish the following three main layers: the soil layering can be summarized in the following (table 2).

**Soil A- Fill (<300 m/s):** A surface highly heterogeneous material (mainly man-made fill) with an average thickness of 10 m and an average velocity  $V_s$  lower than 300m/s. It is composed of very loose and low strength sediments such as silt, clay and limestone fragments. It is not found in all locations.

**Soil B-Clayey soil (400-600 m/s):** Below the surface layer (soil A) there is a clayey or silty clay layer with an average thickness of 10 m meters and  $V_s$  velocity 400-600 m/s.

**Soil C-Saturated Sand & Gravel (700-1300 m/s):** Below soil B there is a stiff soil layer with various thicknesses. it shows a considerable increase of  $V_s$  seismic velocity reaching sometimes values as high as 1300m/s. The soil is composed of compacted stiff saturated sand and gravel with an average  $V_s$  velocity equal or higher than 700m/s. It may be considered as the “seismic bedrock” for the local site amplification analyses.

Profile N°	Layer A		Layer B		Layer C	
	Velocity in m/s	Velocity in m/s	Depth (m)	Velocity in m/s	Depth in (m)	
1		300	10	1300	25	
2		600	16	900	32	
3		400	9	700	20	
4		400	14	1200	30	
5	< 300	300	5	500	10	

**Table 2.** P-wave refraction geophysical campaign conducted at El-Sakakini palace area.

#### 4.2. Refraction- microtremor (ReMi method)

We have used the ReMi (refraction microtremors) method to determine the S-wave seismic velocity with depth. The method is based on two fundamental ideas. The first is that common seismic-refraction recording equipment, set out in a way almost identical to shallow P-wave refraction surveys, can effectively record surface waves at frequencies as low as 2 Hz (even lower if low frequency phones are used). The second idea is that a simple, two-dimensional slowness-frequency (P-f) transform of a microtremors record can separate Rayleigh waves from other seismic arrivals, and allow recognition of true phase velocity against apparent velocities. Two essential factors that allow exploration equipment to record surface-wave velocity dispersion, with a minimum of field effort, are the use of a single geophone sensor at each channel, rather than a geophone “group array”, and the use of a linear spread of 12 or more geophone sensor channels. Single geophones are the most commonly available type, and are typically used for refraction rather than reflection surveying. There are certain advantages of ReMi method: it requires only standard refraction equipment, widely available, there is no need for a triggering source of energy and it works well in a seismically noisy urban setting. (Louie, 2001, Pullammanappallil et al. 2003).

A 12 channel ES-3000 seismograph was used to measure background ‘noise’ enhanced at quiet sites by inducing background noise with 14Hz geophones in a straight line spacing 5m Figure 5 shows the map where ReMi measurements were made. Almost all the sites were noisy. In particular big hammer used to break some rocks generated noisy background at El Sakakini Palace.30 files of 30sec records (unfiltered) of ‘noise’ were collected at each site. Five profiles were taken inside the Palace (Figure 8). Figure 10-11 shows an example of the dispersion curves and its P-F image (Remi Spectral ratio of surface waves) for refraction microtremors profile ReMi-1. The estimated average Vs for all profiles are shown in Figure 12.

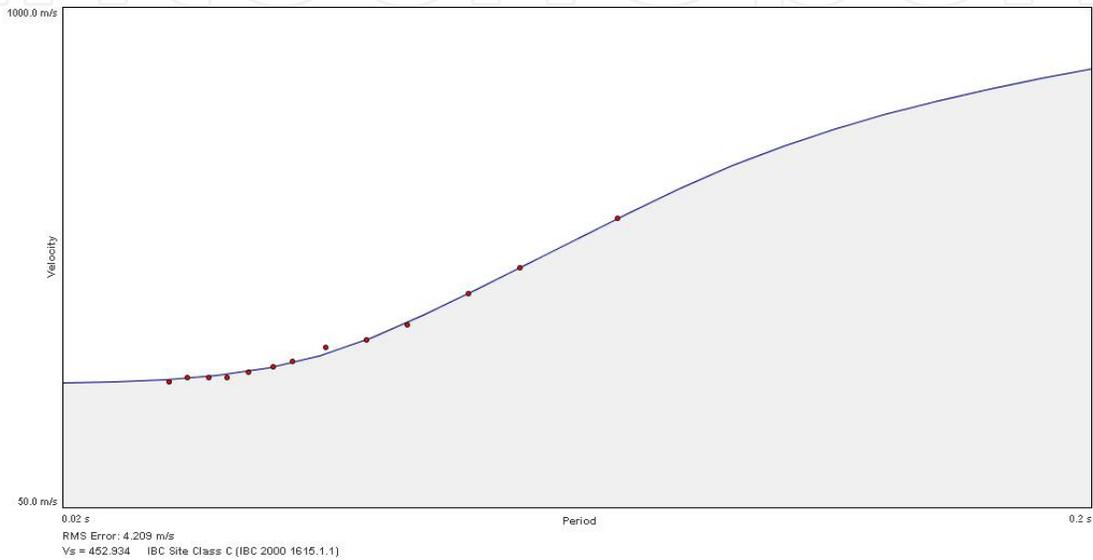


Figure 10. Dispersion curve showing picks and fit for Profile ReMi-1

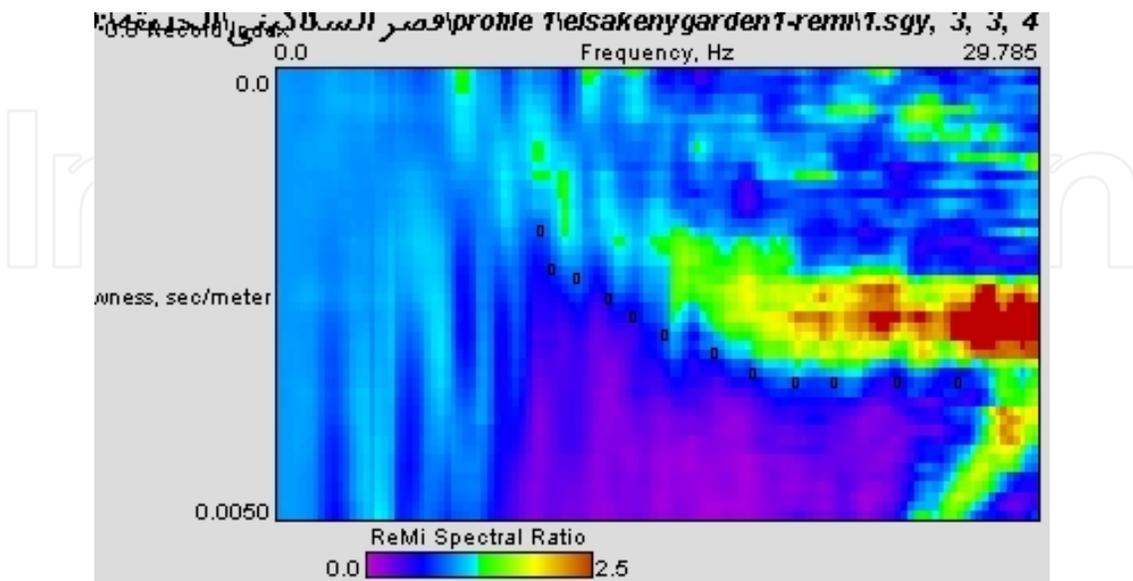


Figure 11. P-F image with dispersion modeling picks for Profile ReMi-1



Figure 12. Shear wave velocity model calculated for refraction microtremors profiles ReMi-1 To ReMi-5 (Figure 9).

## 5. Frequency characteristics of the soil and the building using microtremors

Microtremors are omnipresent low amplitude oscillations (1-10 microns) that arise predominantly from oceanic, atmospheric, and urban or anthropogenic actions and disturbances. The implicit assumption of early studies was that microtremors spectra are flat and broadband before they enter the region of interest (soil or building). When microtremors enter preferable body it changes and resonate depending on the nature of the material, shape, and any other characteristics of this body.

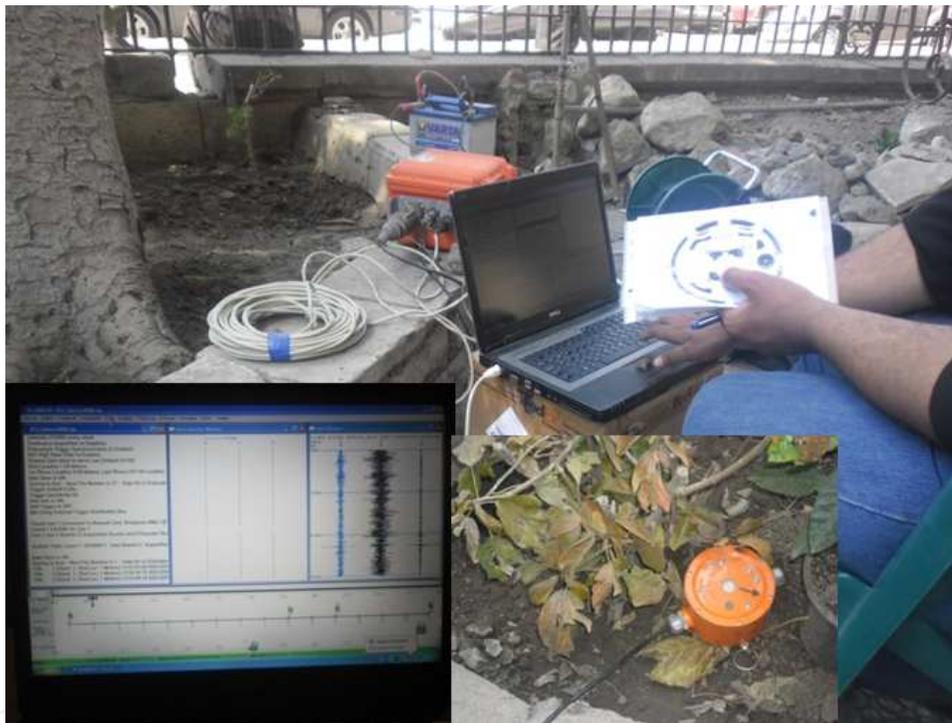
It may be considered to compose of any of seismic wave types. We have two main types of microtremors, Local ambient noise coming from urban actions and disturbances and long period microtremors originated from distances (e.g. oceanic disturbances). There is still a debate ongoing on the characteristics of the ambient noise that should be used for site characterization and ground response. While some are using only the longer period microtremors originated from farther distances (e.g. Field et al, 1990), others considered that traffic and other urban noise sources are producing equally reliable results. In general low amplitude noise measurements comparable results give with strong motion data (Raptakis et al, 2005., Pitilakis, 2011., Apostolidis et al., 2004., Manakou et al, 2010., Mucciarelli, 1998).

Kanai 1957, first introduced the use of microtremors, or ambient seismic noise, to estimate the earthquake site response (soil amplification). After that lots of people followed this work but from the point of soil amplification of earthquake energy for different frequencies (e.g. Kanai and Tanaka 1961 and Kanai 1962, Kagami et al, 1982 and 1986; Rogers et al., 1984; Lermo et al., 1988; Celebi et al. 1987).

### 5.1. Instrumentation and data acquisition

A high dynamic range Seismograph (Geometrics ES-3000 see Figure 13) mobile station with triaxial force balance accelerometer (3 channels), orthogonally oriented was used. The station was used with 4Hz sensors to record the horizontal components in longitudinal and transverse directions in addition to the vertical components. For the data acquisition and processing we followed the following steps:

- Recording 10-min of ambient noise data using a mobile station moving among variable soil stations or El Sakakini building floors/
- Zero correction to the total 10-min noise at time domain
- Subdivision of each 10-min signal into fifteen 1-min sub-windows,



**Figure 13.** High dynamic range ES-3000 Geometrics mobile station and triaxial geophone used 4 Hz to drive soil response of El-Sakakini Palace.

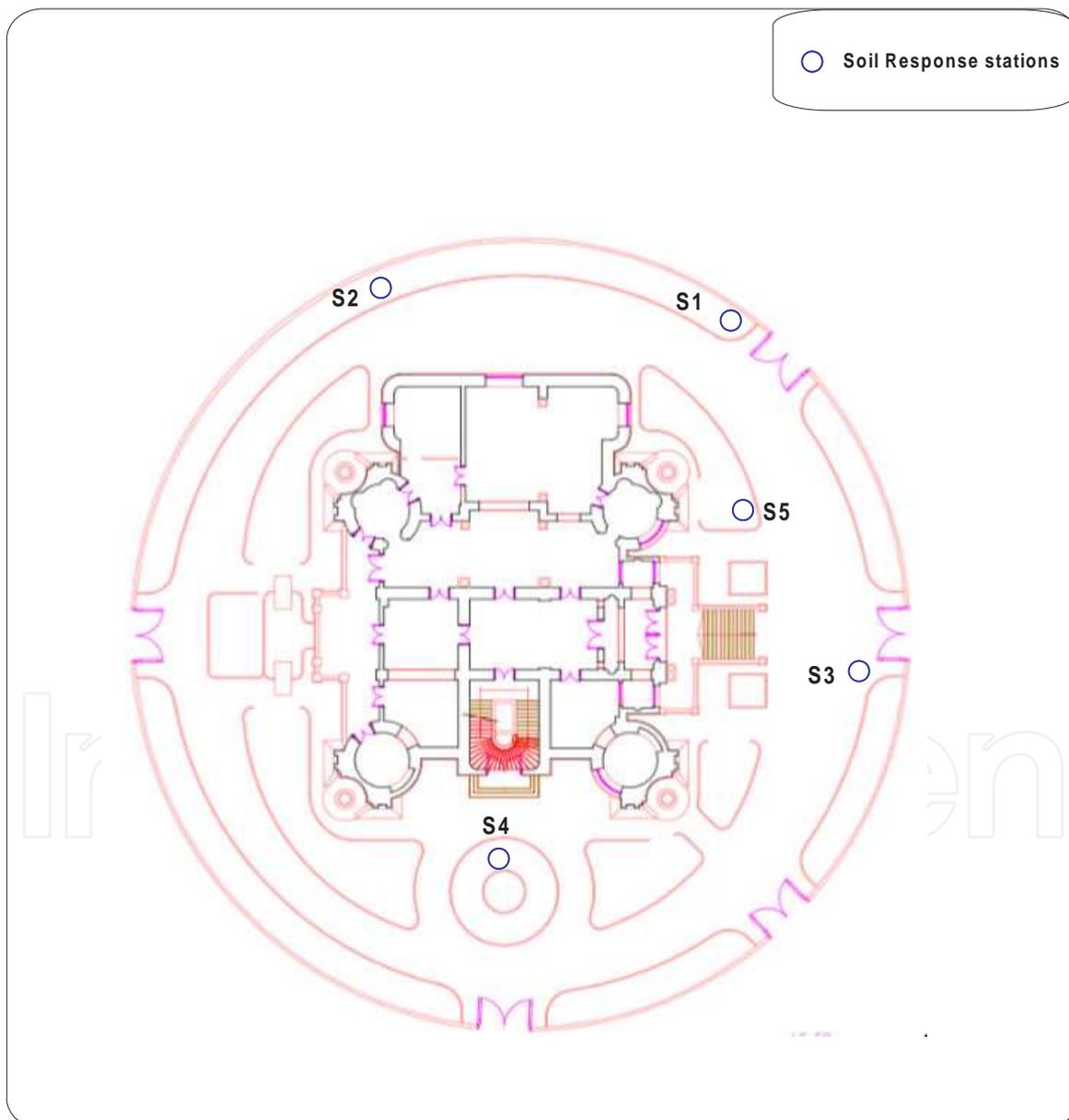
Each of these series was tapered with a 3-sec hanning taper and converted to the frequency domain using a Fast Fourier transform,

- Smoothing the amplitude spectrum by convolution with 0.2-Hz boxcar window,
- Site response spectrum for a given soil site (or certain floor) is given by dividing the average spectrum of this site over the spectrum of the reference site. The reference site is chosen carefully in the site as the deepest and calmest station in the basement floor with the least soil response (usually we choose a certain basement floor location with the least soil response to be used as the reference site).

- Smoothing the final response curves by running average filter for better viewing. A complete description of the methodology can be found in Gamal and Ghoneim, (2004).

## 5.2. Ground response

Figure 14 shows the locations of microtremors stations used to determine the ground response at EL Sakakini Palace area. The predominant frequency of the ground at EL Sakakini Palace is about 3 Hz (see Figure 15 & Table 1), a value almost identical to the theoretical estimation according to Kennett and Kerry (1979) (Figure 16 & Table 4). The amplification factor is about 2, which is relatively low.



**Figure 14.** Ambient noise measurement locations

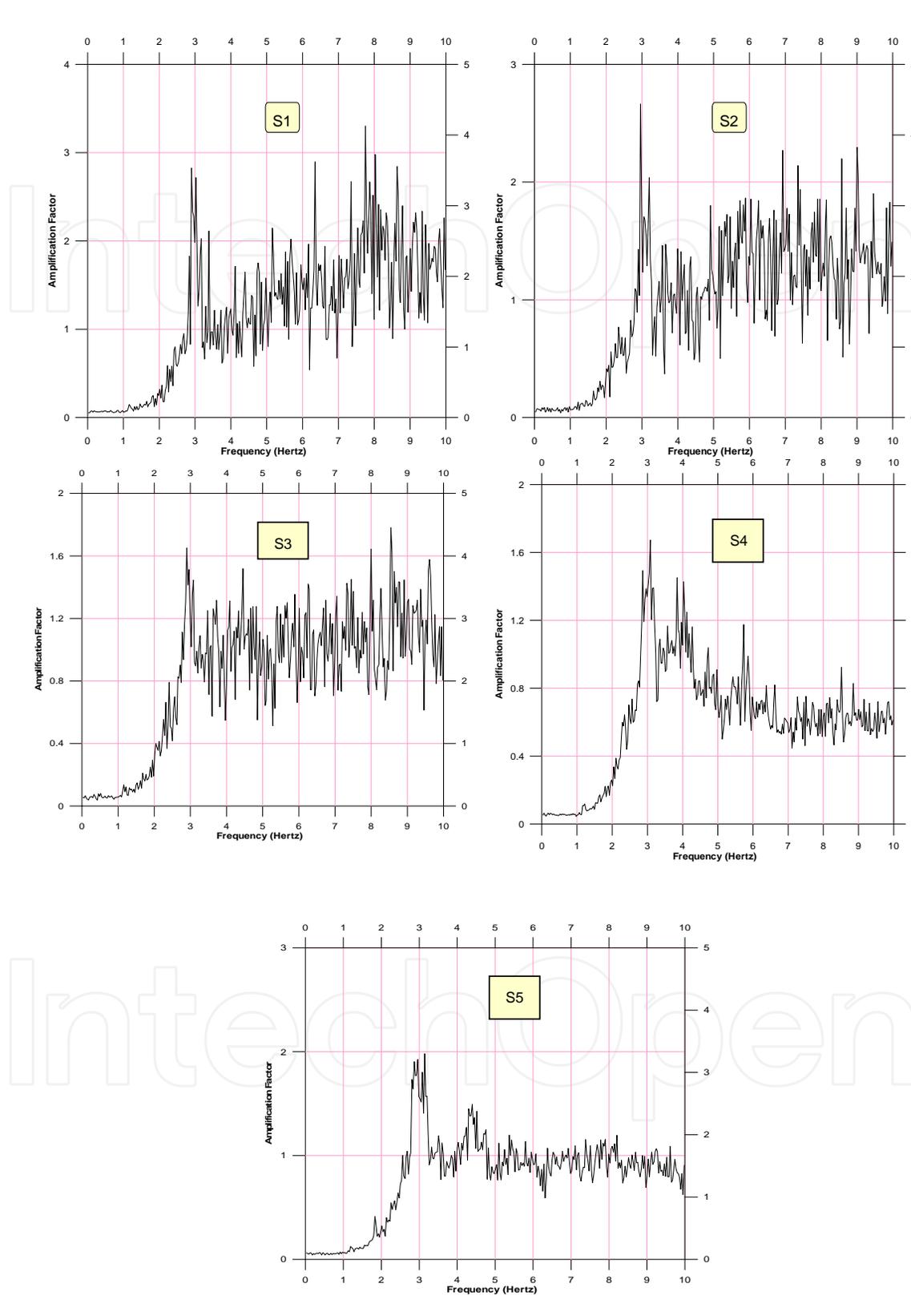


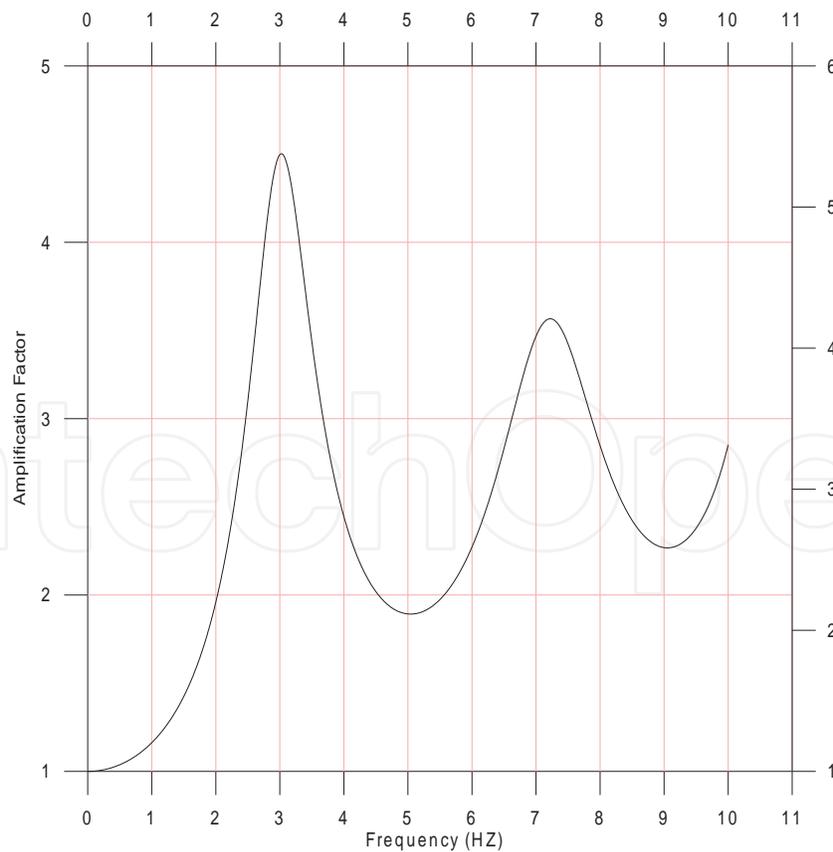
Figure 15. Microtremors soil response for El Sakakini Palace Sites S1 to S5.

Site	Fundamental frequency (Hz)	Amplification Factor
S1	3	2.5
S2	3.2	2
S3	3	1.6
S4	3	1.6
S5	3	2

**Table 3.** Fundamental frequencies and amplification factors at five locations

Thickness	P-wave velocity (m/s)	S-wave velocity (m/s)	Dry Density (gm/c.c)	Quality factor Qs
10	1300	315 (350?)	1.6	7
25	1300	500	1.7	15
>10.5	2000	700	2	100
	3000	1200	2.5	200

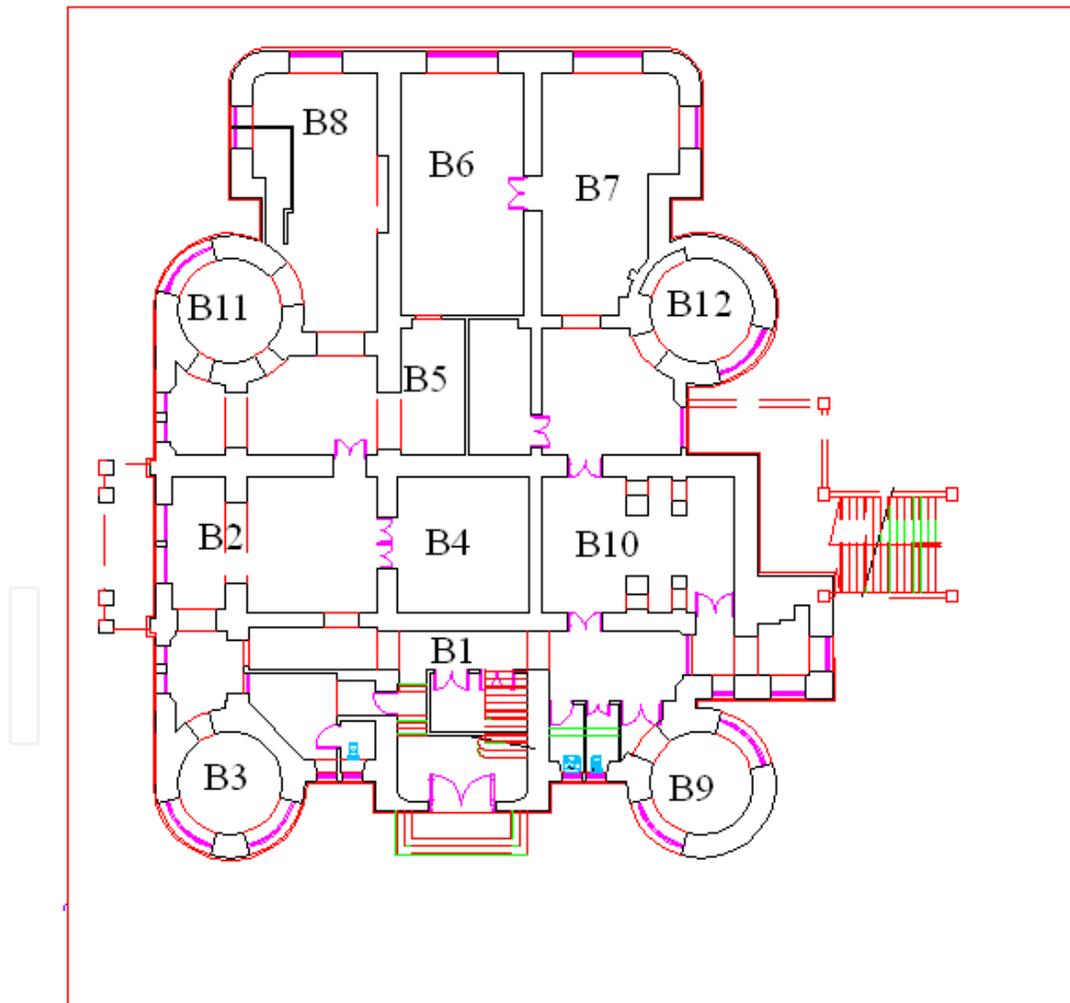
**Table 4.** Parameters used for the Kennett and Kerry method (1979)



**Figure 16.** Theoretical ground response analysis at EL Sakakini Palace using Kennett at al. (1979) method.

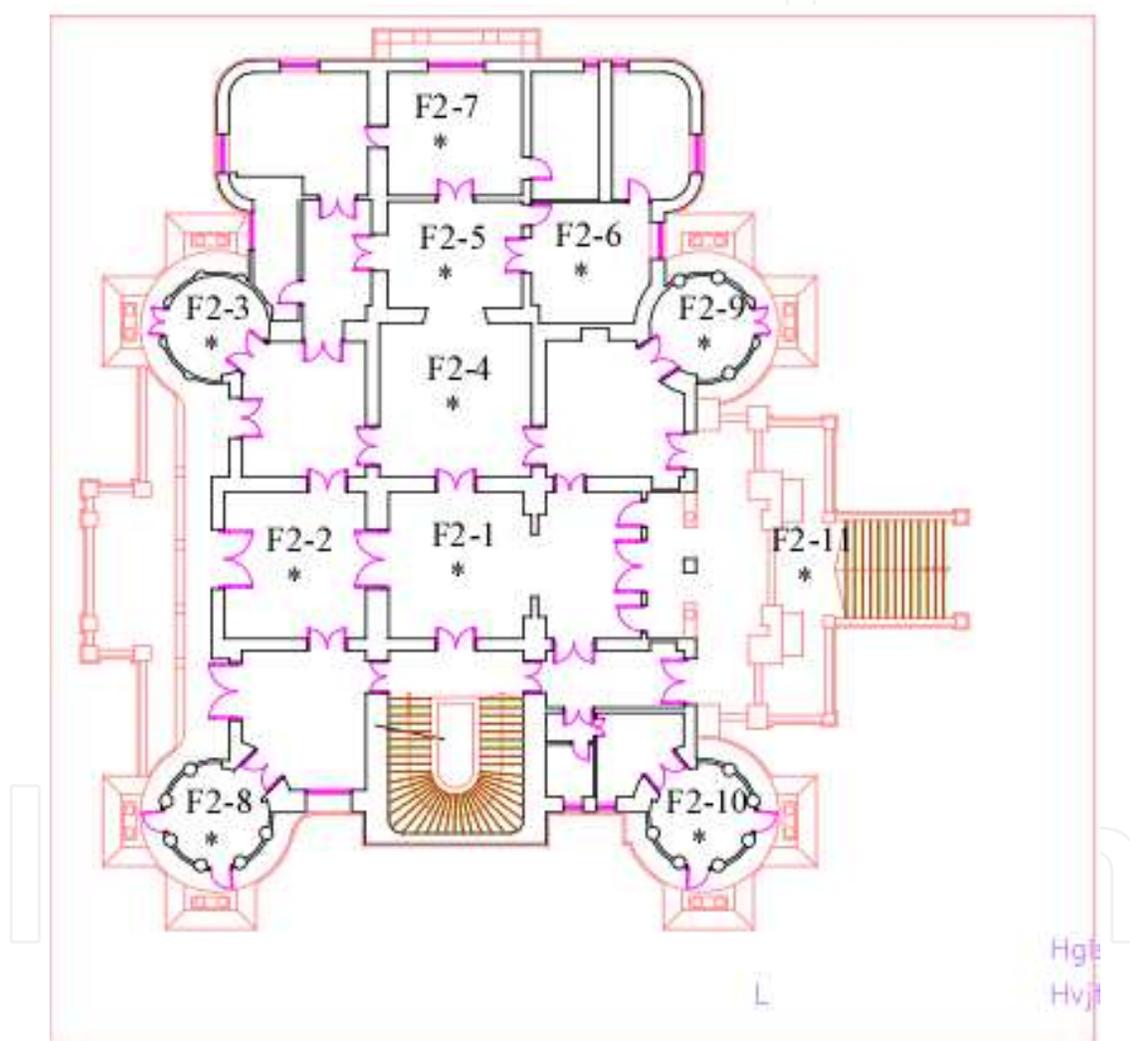
### 5.3. Building response

The El Sakakini building is composed of a basement and five floors the upper two being wooden. Figures 17 to 19 show the locations of recording stations used to drive El Sakakini building response. Figures 21 to 26 and Table 5 show the recorded natural frequency of vibration for each floor. All floors show nearly the same resonance frequency with the soil (3-4 HZ). The wooden floors (Figure 25 & 26) show very high amplification and multi peak as fundamental and other harmonics. The fundamental natural frequency of vibration is always the most important frequency that insert the maximum earthquake vibration energy into structure. However when we find other mode of vibrations with big amplification factors we consider this as a warning that this structure may suffer from vibration. This could be very good warning for its unstable performance during vibration.



**Figure 17.** Location of stations at the basement of EL-Sakakini Palace.

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**Figure 18.** Location of stations at 2nd floor of EL-Sakakini Palace.

IntechOpen

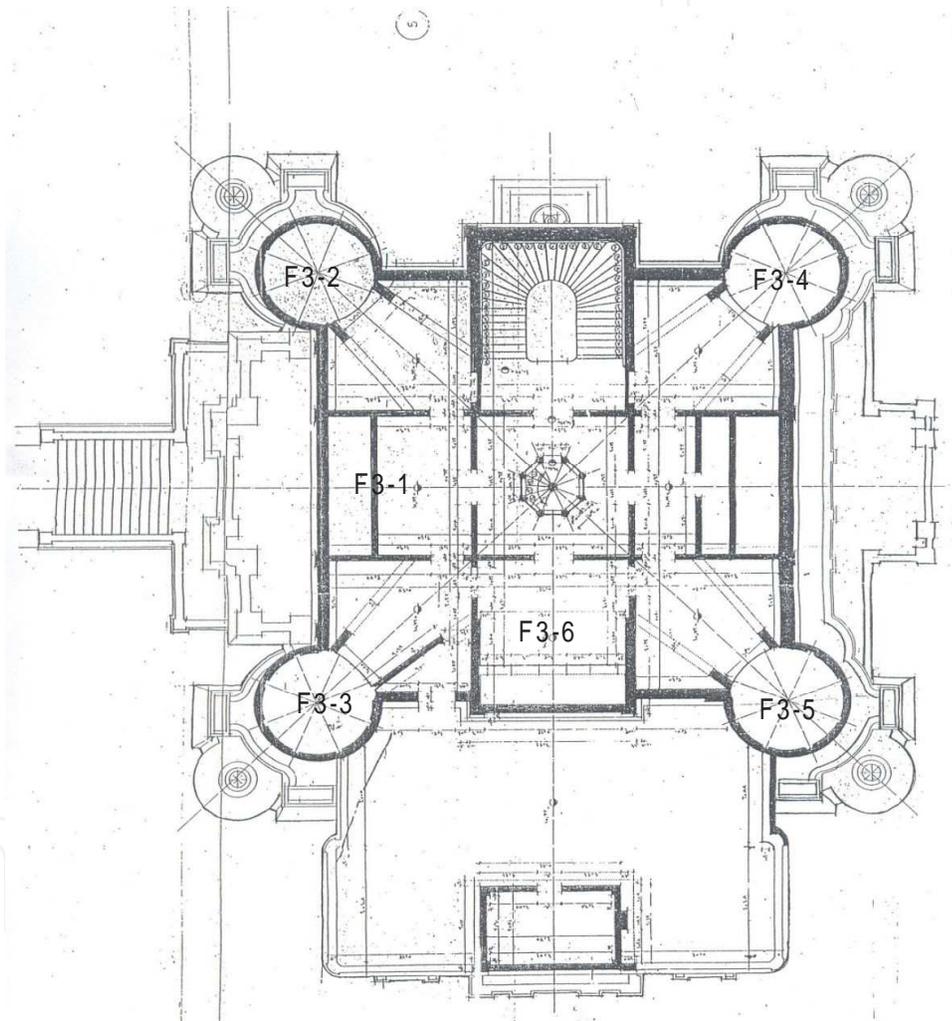


Figure 19. Location of stations at the 3<sup>rd</sup> floor.



**Figure 20.** High dynamic range ES-3000 Geometrics mobile station and triaxial geophone used 4 Hz to drive structure response of El-Sakakini Palace.

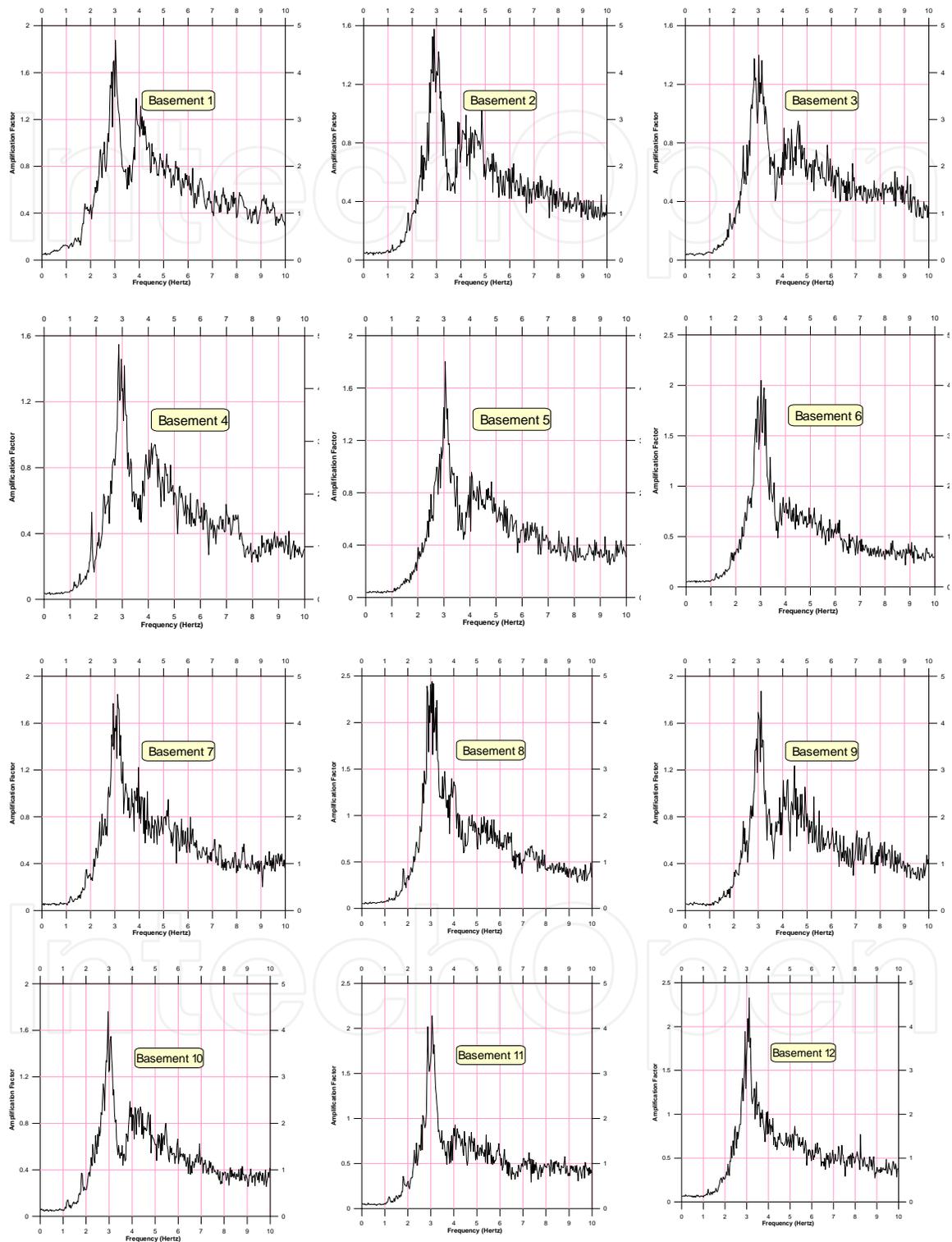


Figure 21. Natural frequency of vibration for basement floor.

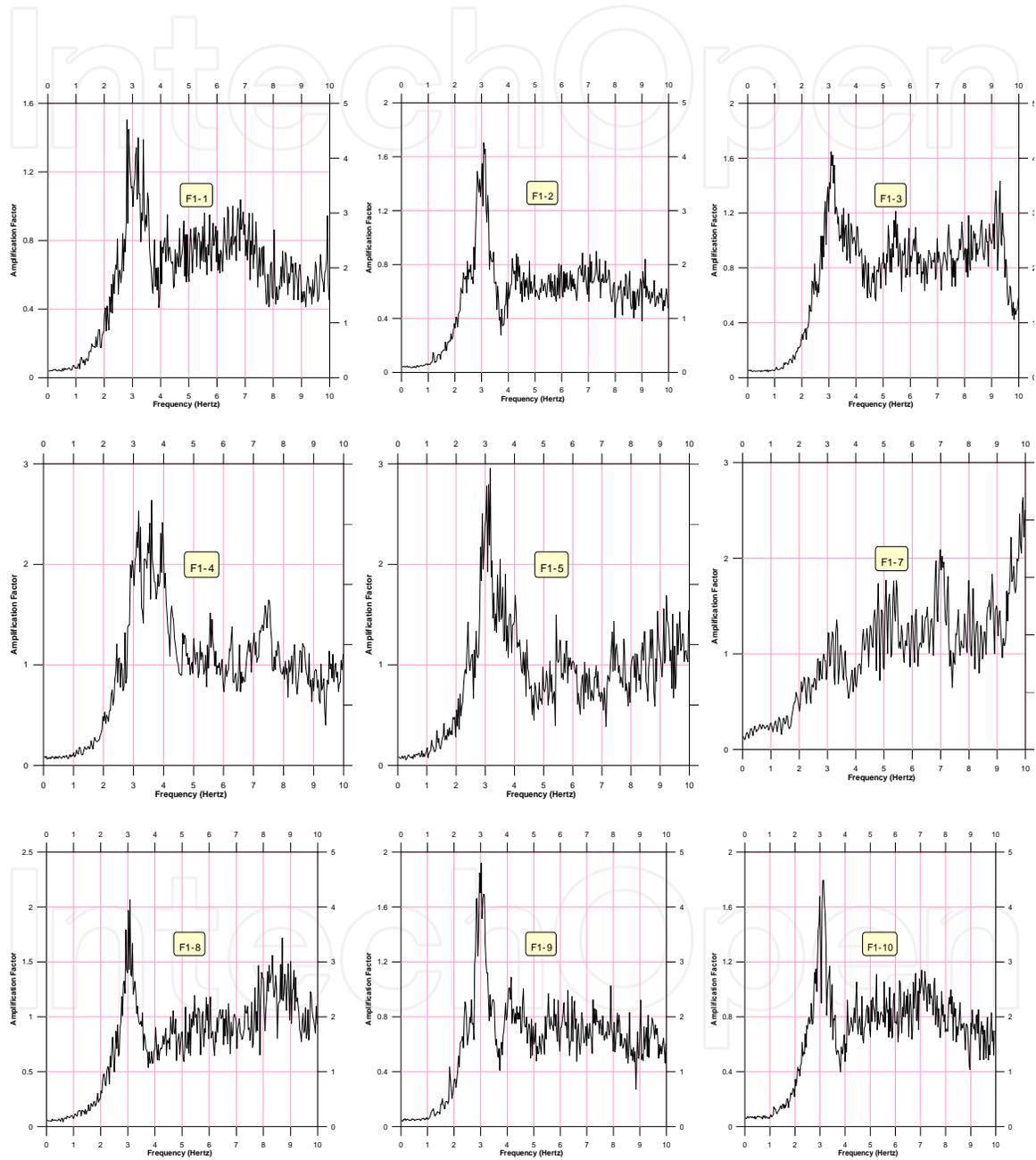


Figure 22. Natural frequency of vibration for the 1<sup>st</sup> floor.

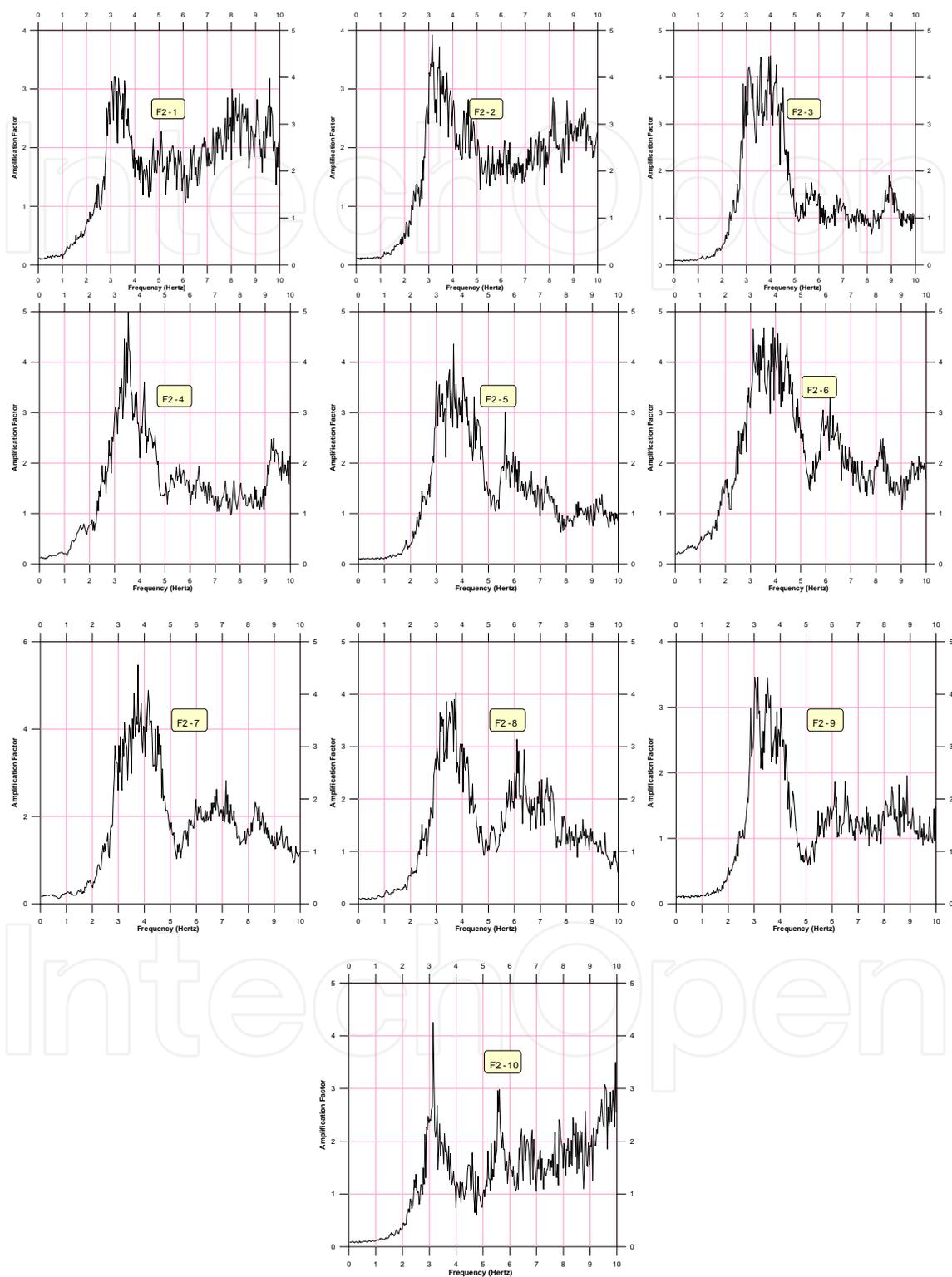


Figure 23. Natural frequency of vibration for the 2nd floor.

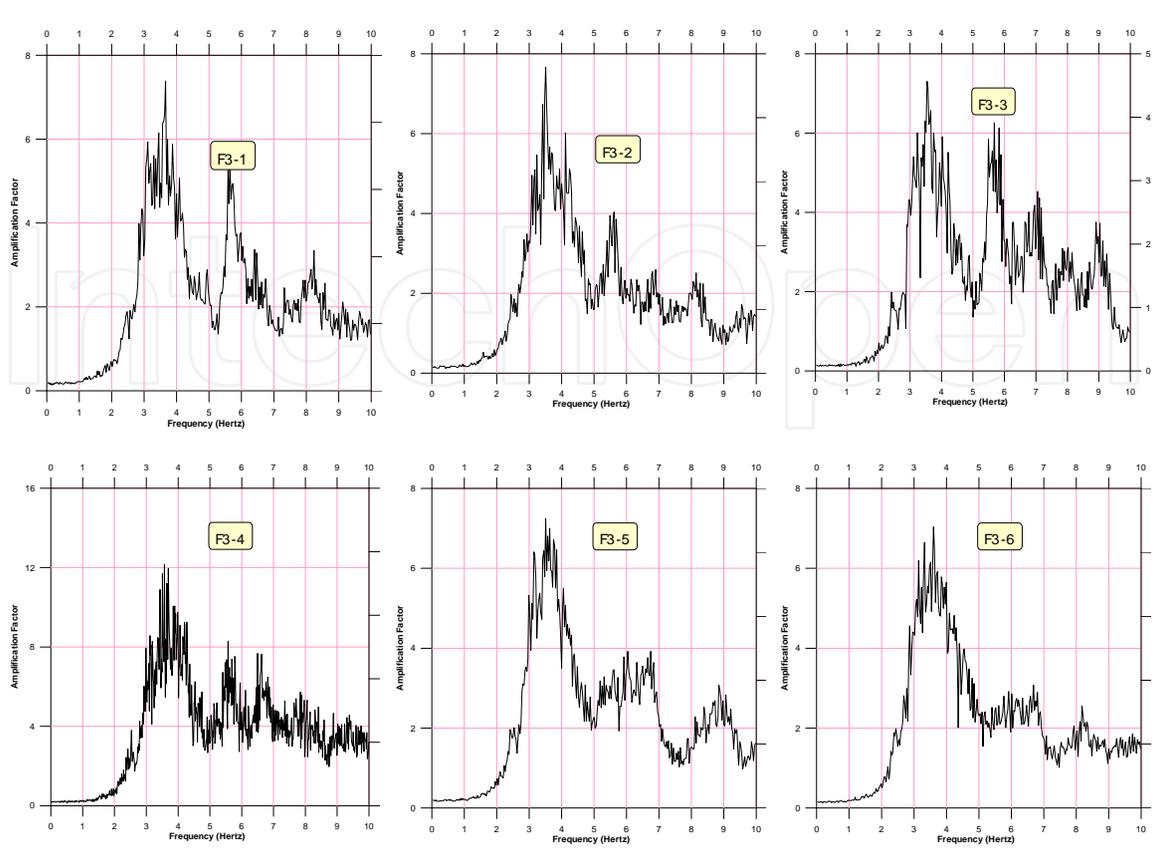


Figure 24. Natural frequency of vibration for the 3<sup>rd</sup> floor.

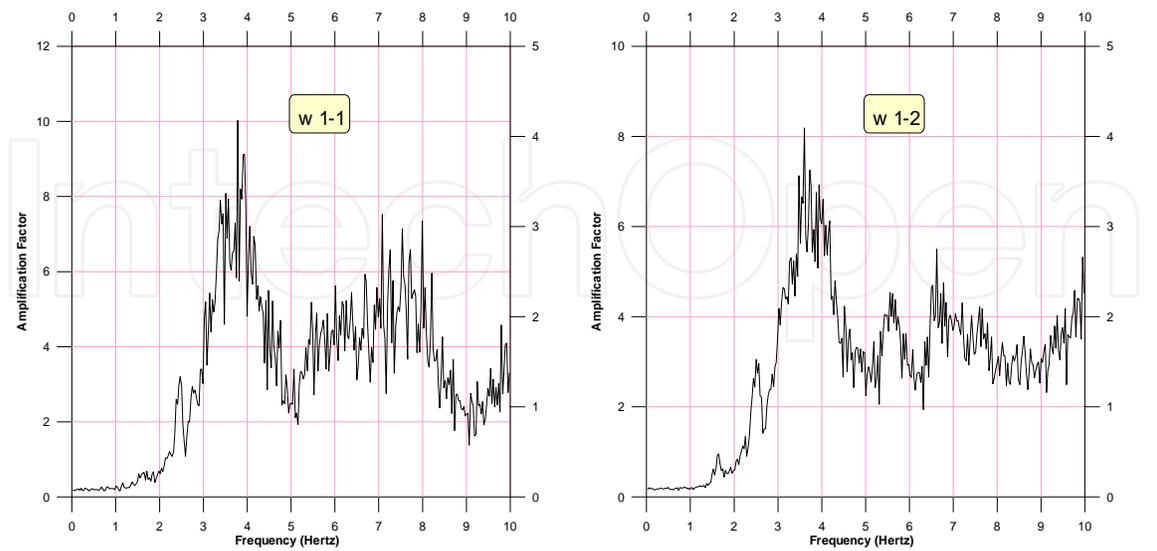
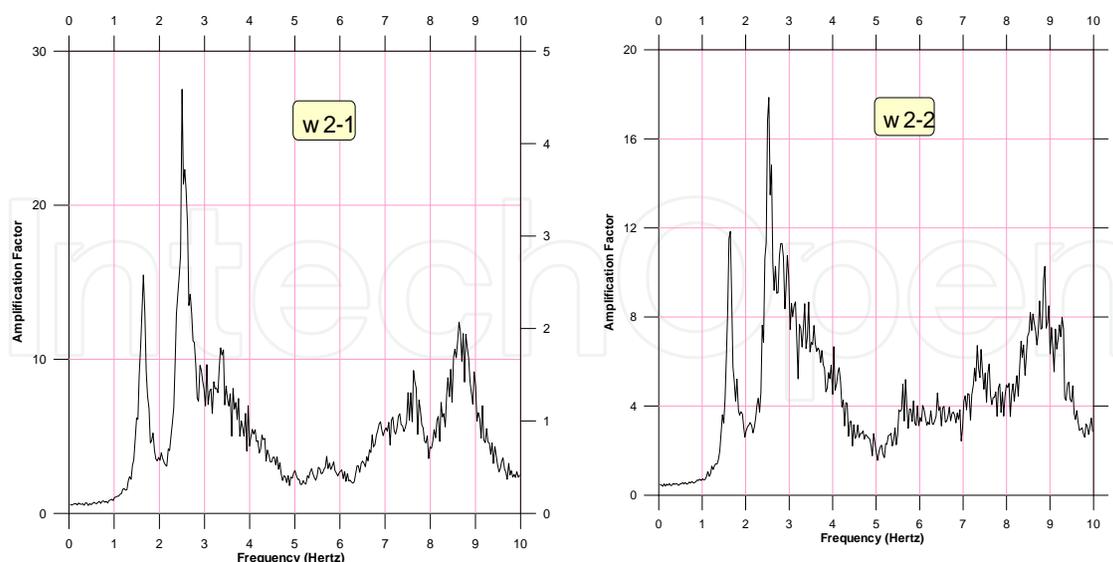


Figure 25. Natural frequency of vibration of the 4<sup>th</sup> floor (wooden).



**Figure 26.** Natural frequency of vibration of the 5<sup>th</sup> floor (wooden).

Floor	Fundamental resonance frequency (HZ)	Amplification Factor
Basement	3	1.3-2
1 <sup>st</sup> Floor	3-3.5	1.4-2.8
2 <sup>nd</sup> Floor	3-4	3-4.5
3 <sup>rd</sup> Floor	3-4.3	5.5-8
4 <sup>th</sup> wood Floor	3-4.5	7.5-8
5 <sup>th</sup> wood Floor	2.5	12-20

**Table 5.** Natural frequencies of vibration of El Sakakini Palace.

## 6. Conclusions

ElSakakini Palace is an important monument in Egypt. We presented the main results of the seismic hazard analysis and the geophysical campaign to estimate the main characteristics of the ground response and the structure. Based on the available maximum intensity maps for historical earthquakes (>2200BC) the maximum Mercalli Intensity expected at ElSakakini Palace site is VII.

The peak horizontal acceleration at the seismic rock basement found at -35m approximately, and for 10% probability of exceedance in 50 years is 144 cm/sec<sup>2</sup> (0.147g), while for 100 years is 186 (cm/sec<sup>2</sup>) (0.19 g). We determined the average soil profile using different geophysical campaigns. It is found that the upper layer has an average shear wave velocity lower than

300m/s and a thickness of 5 to 10 meters. It is a man made fill material in rather loose conditions. Below there is a clayey material with average  $V_s$  velocity equal to 400-600m/s. At -35m in average we found saturated compacted sand and gravels with  $V_s$  velocity exceeding 700m/s. It is considered as the seismic bedrock for the foreseen detailed site-specific analysis of the ground response.

Based on the ambient noise campaign the fundamental frequency of the ground is of the order of 3.0 to 3.5sec very close to the fundamental frequency of the palace. Resonance phenomena should be expected and considered seriously in the detailed analysis of the structure. There are strong evidences that the upper two stories with wooden floors, which are presenting high amplification factors, are subjected to several damages and degradation of their bearing capacity.

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