Seismic Hazard Analysis for Architecture Heritage Preservation in Egypt: The Case of the Cairo's Oldest, Abu Serga Church

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***Abstract*-The present integrated geophysical techniques were done to access the amount of hazards at Abu Serga Church in Cairo. The present work helps understanding the amount of hazards that Abu Serga Church suffers. Abu Serga Church is located within Cairo city and is considered one of the oldest Churches found in Egypt. The Church suffers moderate hazard but high risk in terms of seismic, geotechnical and environmental hazards.**

In the present research, the author tries to know how the most ancient church in Egypt should respeond in event of earthquakes. For this, besides the deterministic characterization of acceleration and seismic intensity, the author had conducted spectral studies of the soil and the structure itself with respect to seismic hazard.

The aim of Geotechnical and geophysical field and laboratory tests is to define the physical, mechanical and dynamic properties of the building and the soil materials of the site where the church is founded.

All these results together with the seismic hazard analysis will be used for the seismic analysis of the church response in the framework of the rehabilitation and strengthening works foreseen in a second stage. The author present herein the most important results of the field campaign and the definition of the design input motion.

Keywords*- *SHA; PGA; Microtremors; Natural Frequency; Abu Serga Church- Cairo; Geotechnical; Geophysical Campaign

I. INTRODUCTION

Abu-Serga church stands among the three most prestigious churches in Egypt. The other two are the suspended (El-Muallaka) church, built on top of the south entrance of Babylon Fortress, and the Holy Virgin church at Haret Zewaila. This church gained its high prestige from the fact that it was built on top of the Crypt. It is believed that the church was built between the late 4th and early 5th century. Yet some, [1] consider that the present building, unaltered in its main features, dates back to the 6th or even the 8th century. Nowadays its floor level is about 4.5 meters below that of, the main street of Mar Guirguis (Saint George) at the subway station (Figs. 1-3).

Fig. 1 Exterior and interior views of Abu Sega Church, Cairo

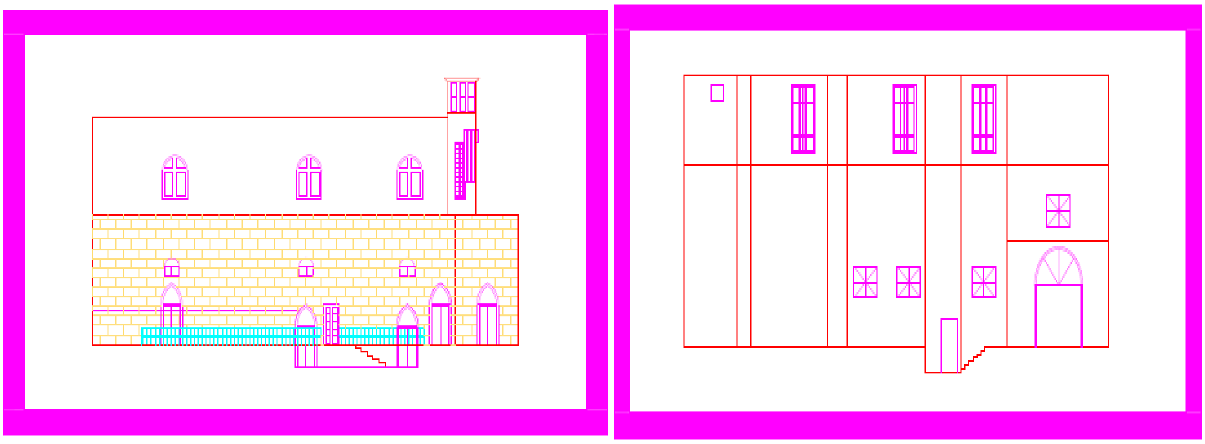

Fig. 2 Northern and western façade of Abu Sega Church

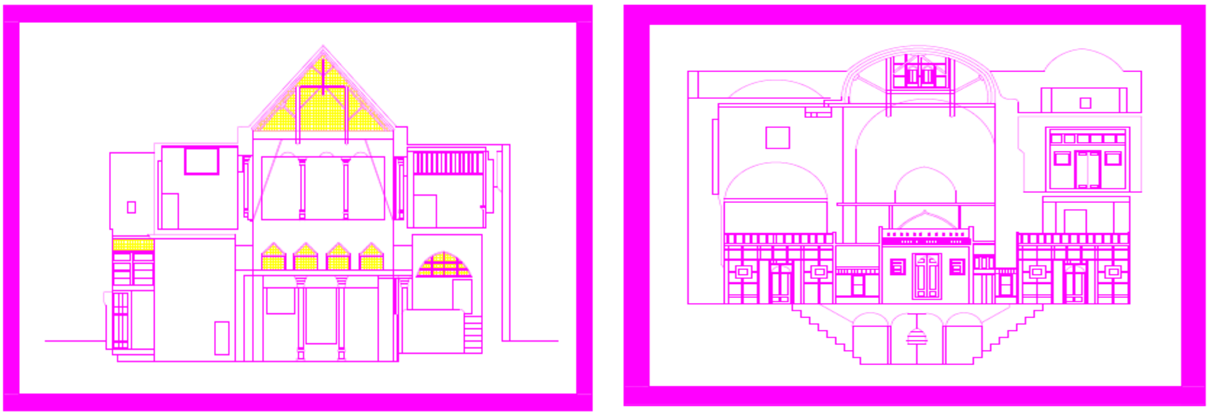

Fig. 3 Cross sections of Abu Sega Church, Cairo

The resonance study held at Abu Serga Church, shows the soil is of nearly a bedrock nature with little or no natural frequency of vibration especially for the basement floor. The fundamental natural frequency of vibration for the 1st floor is 5.5 Hz. The other two peaks, 7.7 and 9.3 Hz, are considered the second and third mode of vibrations. Although the fundamental natural frequency of vibration inserts the biggest energy inside the structure during earthquake excitation, the other two peaks will contribute to add more energy from earthquake vibrations.

The roof is showing nearly the same natural frequencies of vibration as the 1st floor (5.5, 7.7 and 9.5 Hz) with amplification factor between 3-9 times, while the underground Crypt is showing nearly the bedrock effect with little or no amplification factor. The 1st floor is thus the most important floor that may suffer from earthquake shaking.

The seismic design and risk assessment of Abu Serga Church is performed in two steps. In the first one, the author 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. The second phase comprises the detailed analysis of the church and the design of the necessary remediation measures.

II. THE SUBSURFACE CONDITION

The subsurface profile, outside the church, (4.5 m above the church's floor) consists of an upper filling cover of about 5 m thickness, under lied by soft then medium consolidated plastic silty clay layers mixed with variable percentages of sand. The fine to medium compacted sand layers appears at depth 10-11 m below the church's floor level. The groundwater appears at 1.4 m depth.

III. SEISMIC HAZARD

A. *Historical Seismicity*

Fortunately Egypt possesses a great earthquake catalogue that goes as far as the ancient Egyptian times. The pharos left us a detailed description to earthquakes that the author can put a seismicity maps for some earthquakes that goes to the 4000 years ago. Fig. 4 shows the historical and recent Seismicity in the Period 2200 B.C. - 2006 AD and around Abu Serga Church area, the seismic sources regionalization using 37 seismic sources zone adopted for Egypt and surrounding area. The author can see that the Faiyum area as well as the Gulf of Suez is the most important earthquakes affecting Abu Serga Church.

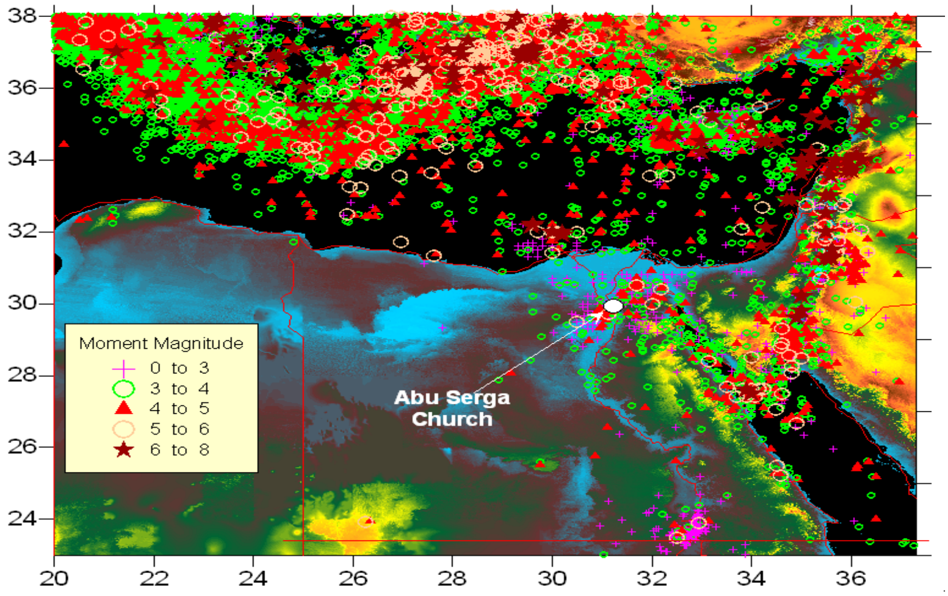

Fig. 4 Historical and recent Seismicity in the Period 2200 B.C - 2006 AD in and around Abu Serga Church area

B. Maximum Intensity

In studying the hazard from earthquakes at Abu Serga Church area, it is usual practice to assume that the likelihood of future occurrences can be predicted from the history of past seismicity. Isoseismal map for all available historical and recent earthquakes were used to generate maximum intensity that affected Abu Serga Church area. All available isoseimal maps in and around Abu Serga Church area were digitized and recontoured to determine maximum intensity affecting the Abu Serga Church area. This was done using a cells value of equal area 0.1 lat. × 0.1 long. It is clear that utilizing maximum intensity value VII is good for Abu Serga Church area.

In this study, the seismic source regionalization methodology utilized in these maps has been assumed that in the future the location of major seismic activity will be limited to the boundary and intraplate tectonics of the micro-plates as it has been over the course of the recorded history, regardless of the times at which these boundaries were locked for considerable periods.

The peak ground acceleration attenuation relationships used in this study is for mean maximum horizontal accelerations on bedrock. With soil deposits of soft-and-medium-stiff sands and clays of appreciable depth the ground accelerations will be considerably modified and should be taken into consideration.

Although the variability of the attenuation relations, maximum magnitude, recurrence relationships and even the border of the seismic source zones should certainly be considered for the site-specific seismic hazard assessment of very sensitive structures such as Abu Serga Church area, it is not thoroughly accounted for in such general regional seismic hazard assessments.

The maximum magnitudes assigned to each seismic source zone have been based only on the historical recordings within each source zone. It should be noted that higher maximum magnitudes can affect the iso-acceleration contours of these maps.

The recurrence of earthquakes is very important for determining the future plans for sensitive structures like the archeological sites. The author has calculated the return period for Magnitudes $M \geq 5$, $M \geq 6$ and $M \geq 7$ for most affecting zones at Abu Serga Church: The Southern pelusium zone.

The return period in years for the southern Pelusim Zone is as follows: The clustering and distribution of earthquakes in and around Abu Serga Church have introduced the idea that two intersected active seismic trends intersect at Abu Serga Church. This introduces an important remark that if two active trends intersect at Abu Serga Church area the hazards and threats in Abu Serga Church will be bigger. However no support is given to this from seismotectonics or seismic plate boundaries for these suggestions.

This study suggests moderate level of earthquake activity at Abu Serga Church and this is in a good agreement with the fact that “Egypt is a part of the stable African Shield”, but the existence of old structure such as the Abu Serga Church may reduce the ability to resist any earthquake shaking.

Although it was difficult to get and gather the kind of data needed to construct hazard maps in Egypt because of lack of data and cooperation between agencies, the author succeed to generate two important kinds of maps and they are the “Maximum Intensity Zonation Maps for Abu Serga Church” and the “Iso-Acceleration Contour Maps for Abu Serga Church”.

To some great extent, these maps succeed in forming a general picture for the amount of hazard that Abu Serga Church is subjected to.

Among the important points that are worth mentioning is that most archeological sites such as Abu Serga Church is not seismically assessed in Egypt, no seismic hazard assessment studies were applied for these important archeological sites nor any reinforcements.

C. Probabilistic Hazard Assessment

The hazard maps (Fig. 5) in Abu Serga Church based on peak horizontal acceleration in Gals (cm/sec^2) and 10 % Probability of Exceedance over 50 and 100 years, shows relatively moderate rate of hazards 0.15 g and 0.20 g, respectively. This PGA level (PGA> 10%g) is of significance to engineers, as it is the common threshold for taking seismic safety measures for normal structures and should be taken into consideration. Also the hazard map in Abu Serga Church based on Maximum Intensity value affected the area collected from instrumental and historical seismicity, shows maximum intensity VII.

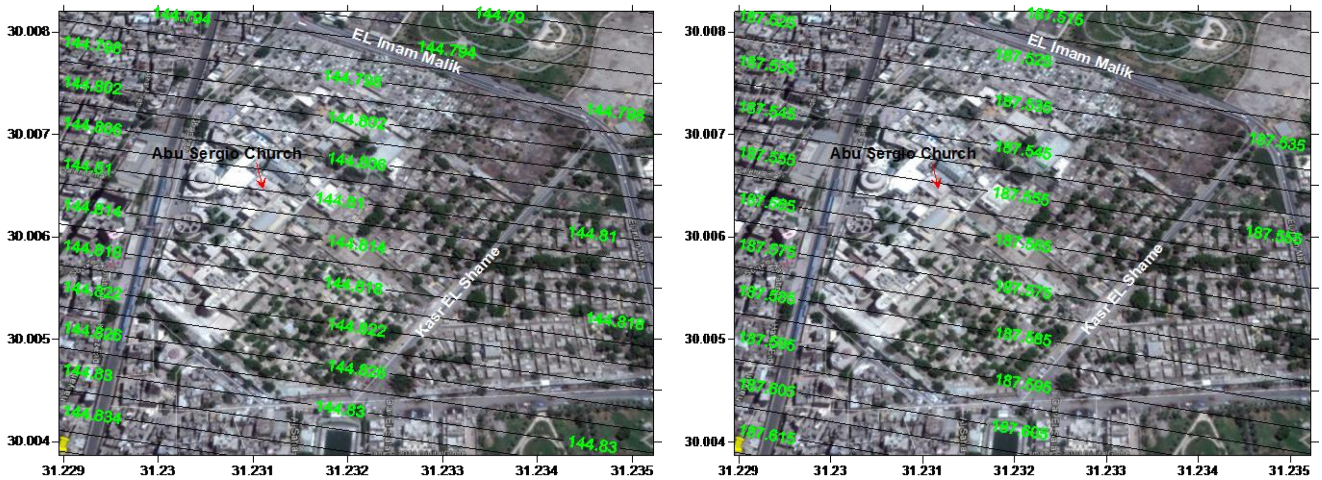

Fig. 5 Peak Horizontal Acceleration in Gals (cm/sec^2) with 10 % Probability of Exceedance over 50 and 100 Years

The hazard maps represented in this study constitute a rational attempt to estimate the probabilistic PGA hazard in Egypt and are intended to serve as a reference for more elaborated studies; it is, therefore, open for suggestions regenerated based on different data bases, assumptions and the inputs in order to evaluate seismic risk which aid in defining true seismic zoning or seismic building code for Egypt. The later is very helpful in the design of well-constructed buildings and for engineering facilities that resist earthquake hazards.

The expected PGA over the bedrock at Abu Serga Church is as follows:

-Peak Horizontal Acceleration in Gals With 10 % Probability of Exceedance over 50 years:

144.8 cm/sec^2 or 0.15g, where g is the acceleration of gravity.

-Peak Horizontal Acceleration in Gals With 10 % Probability of Exceedance over 100 Years:

187.6 cm/sec^2 or 0.20g, where g is the acceleration of gravity.

It should be noted that these values are above the bedrock and should be corrected for the local site conditions and soil at Abu Serga Church.

IV. GEOPHYSICAL CAMPAIGN

A. Refraction- Microtremor (ReMi Method)

-Refraction microtremors test was applied to 11 tests in and around the Abu Serga Church to detect the shear strength in terms of S-wave velocity and detect the average depth of the bedrock.

-The test was done using normal p-wave geophones and normal refraction equipments.

-The test was done using 30 records of 20, seconds each cultural noises coming from culture disturbances inside sand bags and leveled 14 Hertz p-wave geophones.

-Using multichannel analysis of surface waves (MASW) using Refraction Microtremors technique described by [2], a total of six tests inside the inside the church and another 5 tests outside the church were used to detect the average s-wave velocity within the Abu Serga Church.

-ReMi profiles ReMi-1 to ReMi-6 inside the church, show shear-wave velocity of about 1000 m/s for average depth of about 3.5 m. While outside Abu Serga Church, the S-wave velocity detected is about 852 m/s for average depth of about 6.5 m (Fig. 6).

-This is most probably due to the change in level of soil which is higher outside the church with about 2-4 m.

-The bedrock velocity is thus 14-16 m at Abu Serga Church site (USGS, 1980 take S-wave velocity of > 765 m/s to be the velocity of the bedrock).

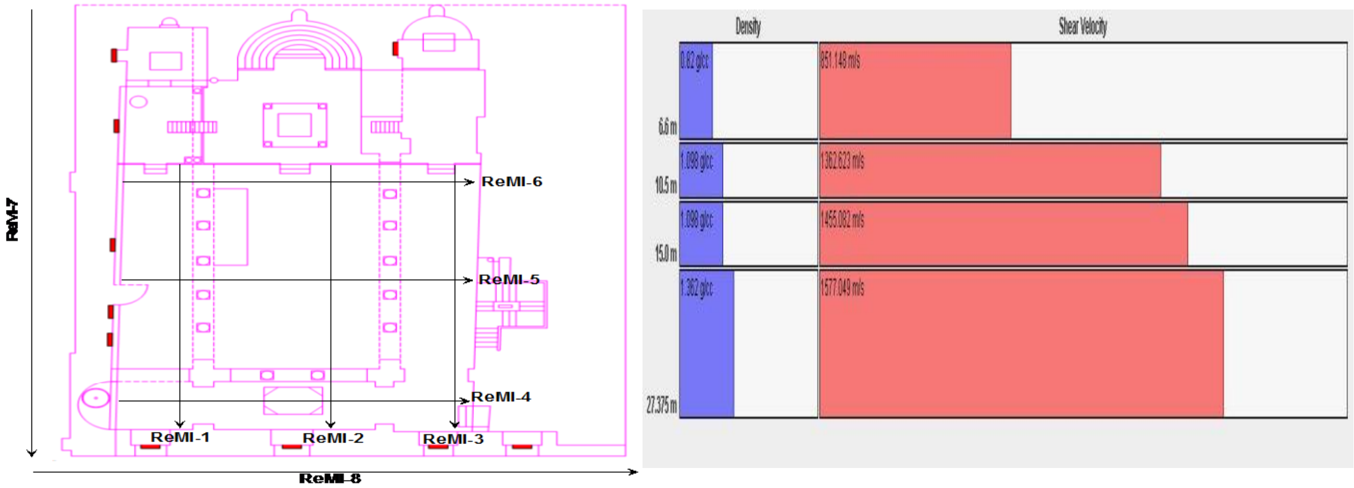

Fig. 6 Shear wave velocity model calculated for profile ReMi-1

V. FREQUENCY CHARACTERISTICS OF THE SOIL AND THE BUILDING USING MICROTREMRS

The aim of the study is to determine the natural frequency of vibration of the soil present at Abu Serga and the Natural frequency of vibration of the Church itself. It is also to determine the amplification factor for the church to be able to deal with the PGA emerging from the bedrock.

It may be considered to compose of any of seismic wave types. The author has 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 an ongoing debate 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 [3], 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 [4-6].

Reference [7] 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 [8-14].

A. Instrumentation and Data Acquisition

Eight soil resonance stations were used to drive site response at Abu Serga Church. Soil resonance stations used to drive the soil response, are distributed over the nearest exposed soils beside the church (Fig. 7).

A high dynamic range Seismograph (Geometrics ES-3000 see Fig. 8) mobile station with tri-axial force balance accelerometer (3 channels), orthogonally oriented was used (Fig. 8).

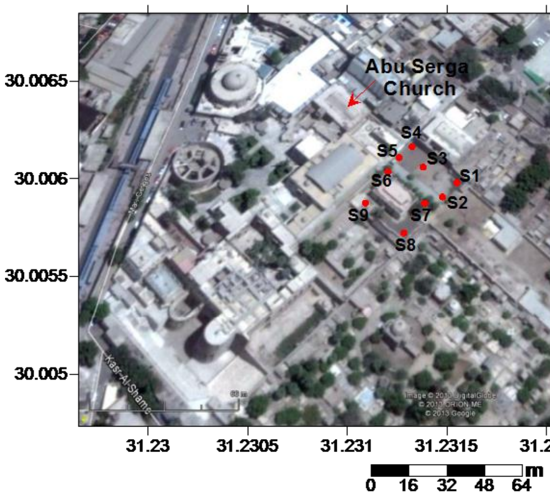

Fig. 7 Location map showing soil stations locations used to drive soil response for Abu Serga Church

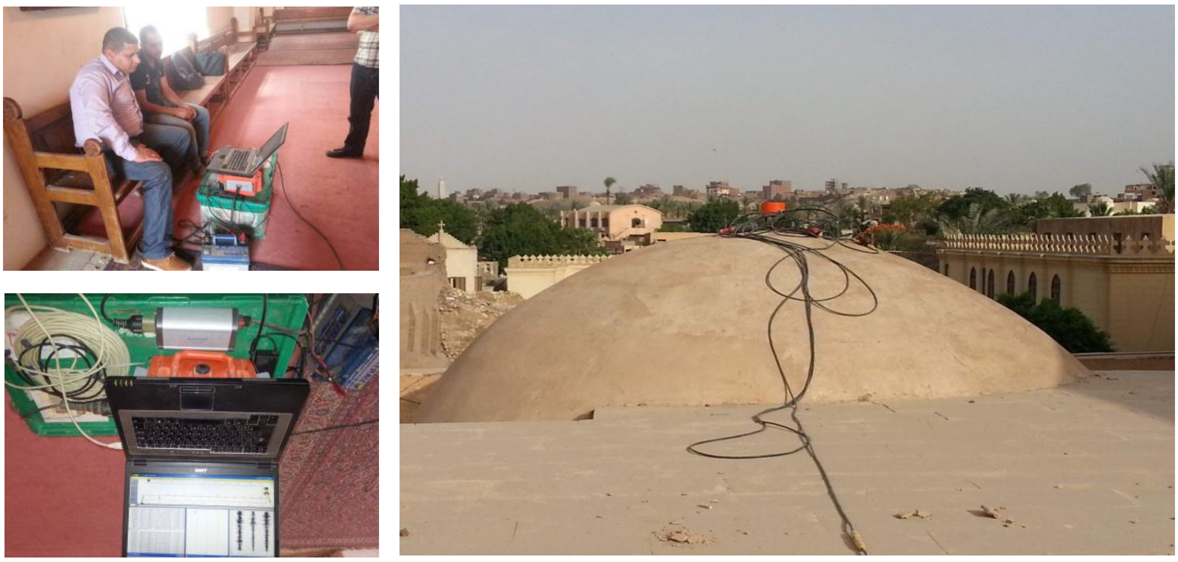

Fig. 8 High dynamic range ES-3000 Geometrics mobile station and triaxial geophone used 4 Hz to drive soil and structure response of Abu Serga Church

The station was used with 4 Hz sensors to record the horizontal components in longitudinal and transverse directions in addition to the vertical components. For the data acquisition and processing the author followed the following steps:

-Recording 10 minutes of ambient noise data using a mobile station moving among variable soil stations or Abu Serga Church 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.

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 deepest and calmest station in the basement floor with least soil response (usually the author choose a certain basement floor location with least soil response to be used as reference site).

-Smoothing the final response curves by running average filter for better viewing. A complete description of the methodology can be found in.

B. Results

The soil response found at Abu Serga Church is almost flatty shape with no specific natural frequency of vibration or significant amplification. This effect is most probably due to the nearness of the bedrock found at this area or the buried archaeological units (Fig. 9). Natural frequency of vibration for the basement floor is determined using the stations. It can be seen that there is no or little resonance peaks and little or no amplification exists for the basement floor (Fig. 10). The natural frequency of vibration for floor No. 1 was determined using the stations shown in (Fig. 11). The fundamental natural frequency of vibration for the 1st floor is 5.5 Hz while the 2nd and third peaks exist at 7.7 Hz and 9.3 Hz and amplification factor 4-9.

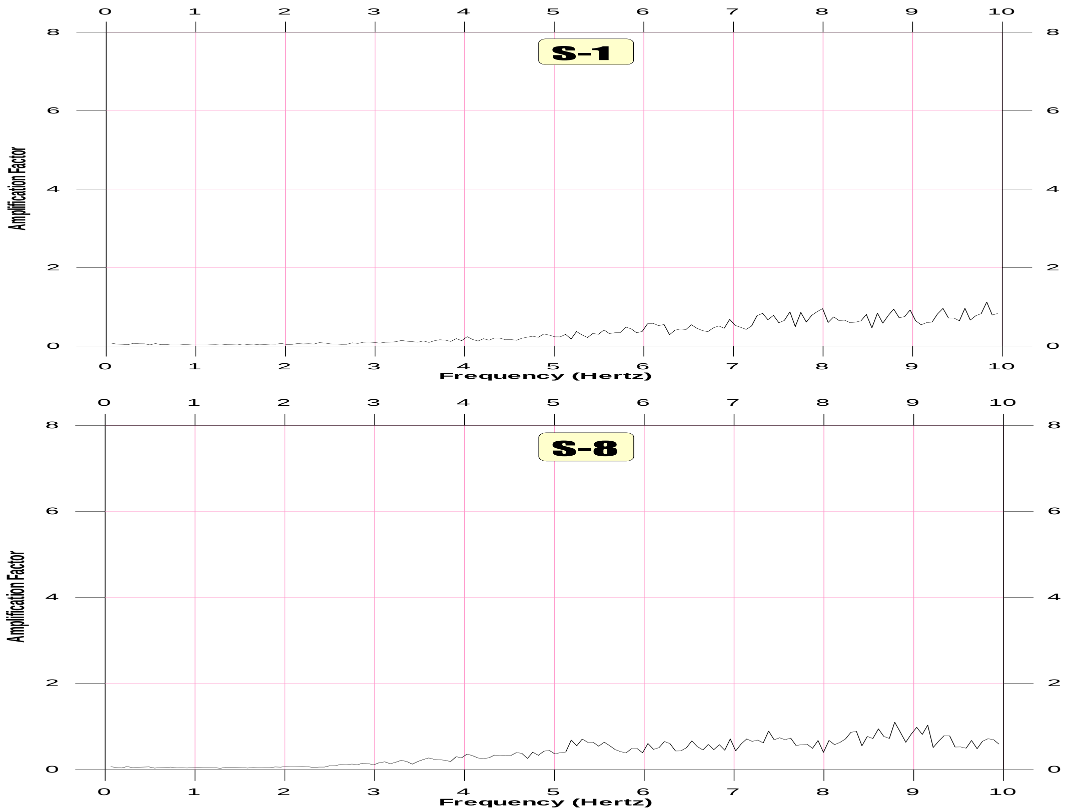

Fig. 9 Natural frequency of vibration for the soil around Abu Serga Church

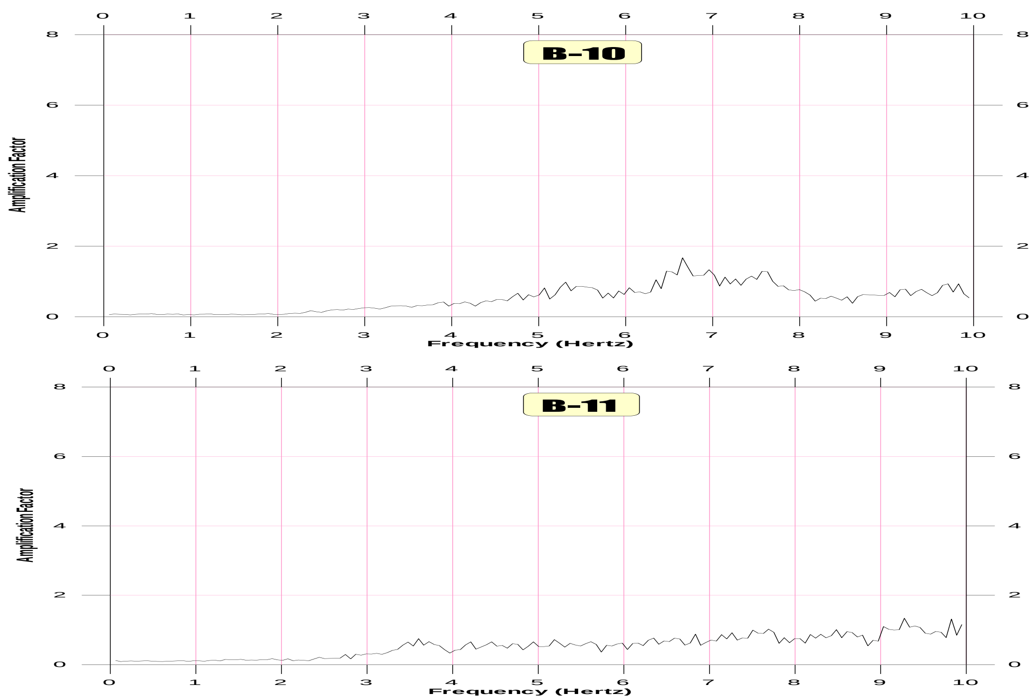

Fig. 10 Natural frequency of vibration for basement floor for Abu Serga Church

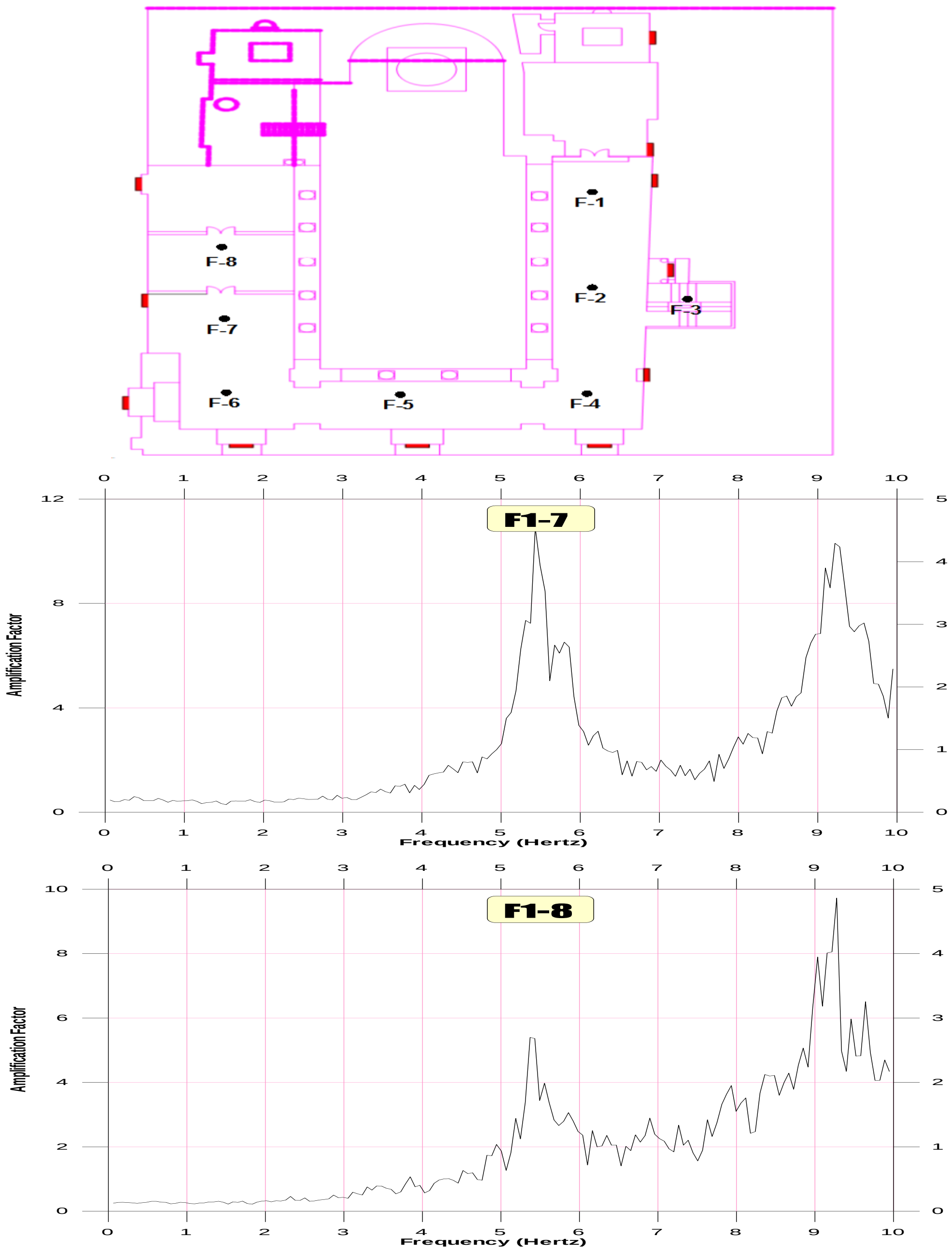

Fig. 11 Natural frequency of vibration for the 1st floor for Abu Serga Church

The fundamental natural frequency of vibration for the roof is 5.5 Hz while the second and third peaks are found at 7.7 and 9.3 Hz. The amplification factor determined from this method for the roof is between 3 and 10.

Three stations were used to determine the natural frequency of vibration for underground Crypt found at Abu Serga Church. The Underground Crypt, shows no fundamental peak of vibration nor amplification factors (Table 1).

TABLE 1 NATURAL FREQUENCY OF VIBRATION FOR ABU SEGA CHURCH STRUCTURE

Floor	**Fundamental resonance frequency (HZ)**	**Amplification Factor**
Basement	----------	----------
1st Floor	5.5, 7.5-8, 9.3	3-9
Roof	5.5, 7.5-8, 9.3	3-10
Underground Crypt	-------------	----------

VI. DESIGN RESPONSE SPECTRUM FOR ABU SERGA CHURCH

The response spectra for Faiyum earthquake, was selected as the best earthquake for most effective zone near Abu Serga Church to construct the design response spectrum for the church. The original acceleration time history was recorded 10 km away from Abu Serga Church over the bedrock of Cairo city at Mokattam area (about 10 km from Abu Serga Church). The original acceleration time history was recorded 10 km away from Abu Serga Church over the bedrock of Cairo city at Mokattam area (about 10 km from Abu Serga Church).This is considered to be the first response spectrum done for all earthquakes that ever affected Egypt (Fig. 12). Fortunately this earthquake is considered one of the most important earthquakes that affected Egypt in the past 100 years.

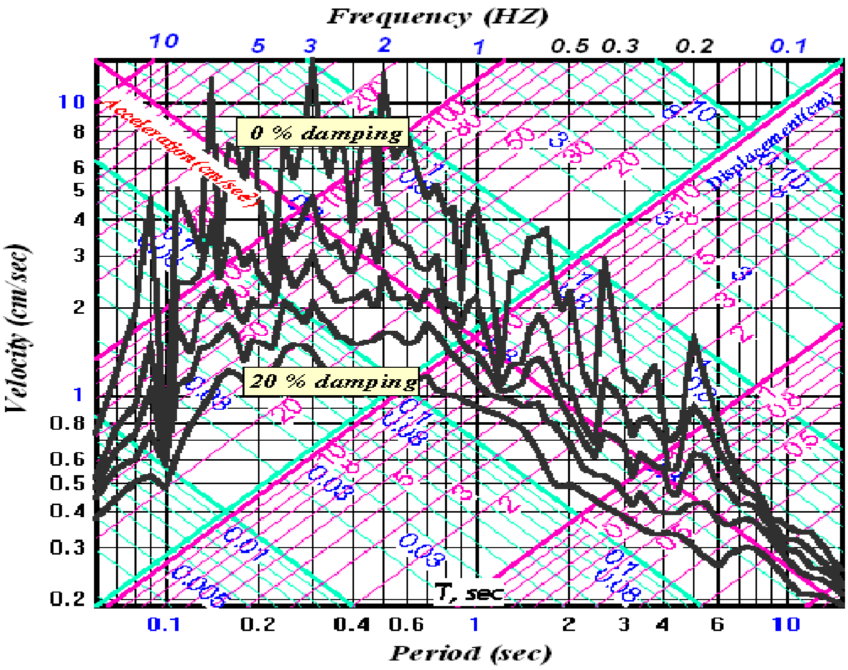

Fig. 12 Design response spectra for different damping (0%,2%,5%, 10% and 20%) determined from, Faiyum, 12/10/1992 earthquake 10 km away from Abu Serga Church

As normally expected the at higher frequencies >10 HZ (short period 0.1 sec) acceleration response is approaching the peak acceleration (40 cm/sec^2) in the original time history while at low frequencies < 0.1 HZ (long period) the displacement response is approaching the maximum recorded displacement in the originally recorded time history.

Seen from (Fig. 12) as damping increase, the response becomes less and the shape of the response spectrum becomes smoother. Response spectra, particularly at increased damping values, becomes very much less.

The important notice that the author should pay attention to here is that the maximum acceleration response spectrum maintained for Abu Serga Church is maintained for the fundamental resonance frequency of the church which is 5.5 Hz, is about 100 cm/sec^2 for 5% damping soil. As for the other resonance peaks for the 2nd floor and the 3rd floor nearly the same spectral acceleration occurs (0.1 g).

VII. CONCLUSIONS

Abu Serga Church is an important monument and the oldest church in Egypt. The author 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 Abu Serga Church site is VII. This study, suggests moderate level of earthquake activity at Abu Serga Church and this is in a good agreement with the fact that “Egypt is a part of the stable African Shield”, but the existence of old structure such as the Abu Serga Church may reduce the ability to resist any earthquake shaking.

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The hazard maps in Abu Serga Church based on peak horizontal acceleration in Gals (cm/sec2) and 10 % Probability of Exceedance over 50 and 100 years, shows relatively moderate rate of hazards 0.15 g and 0.20 g, respectively. This PGA level (PGA> 10% g) is of significance to engineers, as it is the common threshold for taking seismic safety measures for normal structures and should be taken into consideration. Also the hazard map in Abu Serga Church based on Maximum Intensity value affected the area collected from instrumental and historical seismicity, shows maximum intensity VII.

The conducted ReMi profiles ReMi-1 to ReMi-6 inside the church, show shear-wave velocity of about 852 m/s for average depth of about 6.6 m. This is most probably due to the change in level of the ground which is higher outside the church with about 4 m.

The maximum acceleration response spectrum maintained for Abu Serga Church for the fundamental resonance frequency of the church which is 5.5 Hz, is about 100 cm/sec^2 for 5% damping soil. As for the other resonance peaks for the 1^{st} floor and for the roof nearly the same spectral acceleration occur (0.1g). This is in a good agreement with the probabilistic PGA calculated for exposure time 50 and 100 years (0.15g-0.2g).

REFERENCES

[1] A.J. Butler and A. J., "Ancient Coptic Churches of Egypt," vol. 1&2, London: Oxford at The Clarendon Press,1884.

[2] J.N. Louie, "Faster, Better: Shear-wave velocity to 100 meters depth from refraction microtremors arrays," *Bulletin of the Seismological Society of America*, vol. 91, pp. 347-364, 2001.

[3] M. Gamal and A. Noufal A., "A Neotectonics model AND seismic hazard assessment for Egypt," 8th international conference on geology of the Arab world, Cairo university Egypt, 2006.

[4] P. Apostolidis., D. Raptakis, Z. Roumelioti, and K. Pitilakis, "Determination of S-Wave velocity structure using microtremors and SPAC method applied in Thessaloniki (Greece)," *Soil Dynamics & Earthquake Engineering*, vol. 24, no. 1, pp. 49-67, 2004.

[5] M. Manakou, D. Raptakis, P. Apostolidis, F.J. Chávez-García, and K. Pitilakis K., "3d soil structure of the Mygdonian basin for site response analysis," *Soil Dynamics and Earthquake Engineering*, vol. 30, pp. 1198-1211, 2010.

[6] S. Hemeda, M. Gamal, and K. Pitilakis, "Seismic hazard and Geophysical Investigations for architectural heritage preservation in Egypt: The Case of Habib Sakakini palace," 7th International Conference on Case Histories in Geotechnical Engineering. Chicago, Illinois. USA, 2013.

[7] K. Kanai, "The requisite conditions for predominant vibration of ground," *Bull. Earthq. Res. Inst.*, Tokyo University, vol. 31, pp. 457, 1957.

[8] K. Kanai, "On the spectrum of strong earthquake motions," Primeras J. *Argentinas Ing. Antisismica*, vol. 24, no. 1, 1962.

[9] K. Kanai and Tanaka, "On microtremors," VII, *Bull. Earthq. Res. Inst.*, Tokyo Univ., vol. 39, pp. 97-115, 1961.

[10] H. Kagami, C. M. Duke, G. C. Liang, and Y. Ohta, "Observation of 1-5 second microtremors and their application to earthquake engineering. Part II. Evaluation of site effect uppon seismic wave amplification due to extremely deep soils," *Bull. Seism. Soc Am.*, vol. 72, pp. 987-998, 1982.

[11] R.D. Miller, C.B. Park, J.M. Ivanov, J. Xia, D.R. Laflen, and C. Gratton, "MASW to investigate anomalous near-surface materials at the Indian Refinery in Lawrenceville, Illinois," Kansas Geol. Surv., Open-File Rept. 2000-4, Lawrence, Kansas, 48 pp, 2000.

[12] J. Lermo, M. Rodriguez, and S. K. Singh, "The Mexico Earthquake of September 19, 1985: Natural periods of sites in the valley of mexico from microtremor smeasurments and from strong motion data," *Earthquake Spectra*, vol. 4, pp. 805-814, 1988.

[13] J. Lermo and F. J. Chavez-Garcia, "Site effect evaluation using spectral ratios with only one station," *Bull. Seism. Soc. Am.*, vol. 83, pp. 1574-1594, 1993.

[14] R.K. McGuire, "FORTRAN computer program for seismic risk analysis," U.S. Geol. Surv., 1993.