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Dynamic characteristics of built heritage using ambient noise recordings

Sayed Hemeda[1,2*]

Abstract

The paper addresses the investigation of the dynamic characteristics of a case study, the Egyptian church of Abu serga. To this aim some in situ investigations have been conducted and related results are discussed. The paper presents interesting and innovative aspects, mainly related to the characteristics of the church investigated, covering a lack of knowledge in the scientific literature due to the typology of the church. The integrated geotechnical and geophysical investigation techniques assessed the level of seismic and other geo-environmental risks that Abu serga church suffers from. It suffers multiple Geo-environmental hazards. The main objectives of this pilot study are as follows: (1) Identifying the shear velocity Vs analysis profile of the subsoil and also the resonant frequency of soil and the historical building of Abu serga church using ambient noise recordings (microtremors) to assess the level of seismic and other geo-environmental hazards. (2) Understanding the damage to the historic building caused by the recent earthquakes. (3) Offering technical support and advice on intervention retrofitting for the historic damaged structure.

In this study, ambient noise recordings have been processed through horizontal to vertical spectral ratios to examine the main frequencies and to examine whether the building has its main frequency close to that of the soil in order to identify potential resonance phenomena. Numerous ambient noise recordings were recorded on the soil, in the basement, and at each floor of the buildings.

This study suggests moderate level of earthquake activity at Abu serga church and is in a good agreement with the fact that "Egypt is a part of the stable African Shield", but the existence of old structures such as the Abu serga church may reduce the ability to resist any earthquake shaking.

Keywords: SHA, PGA, Microtremor analysis, Natural frequency, Abu serga church-Cairo, Resonance, Geophysical campaign

Introduction

Microtremor has based on ambient noise recordings to determine site response parameters. Two methods that have used it are horizontal-to-vertical Fourier amplitude spectral ratio (HVSR), and the more advanced array technique. The ability of the HVSR technique to provide a reliable information related to site response has been repeatedly shown in the past. HVSR method for microtremor data analysis to be derived fundamental frequency of the sediment. The use of microtremor was later extended to the identification of the fundamental frequency of buildings and the soil-structure resonance. Damage enhancement and soil-structure resonance were recently studied using microtremors. The theory and interpretation of ambient vibration results for buildings are not so structured and straightforward as they are for the free-field case. When measuring inside a given building in a densely populated area, one of the main difficulties is to detect and eliminate the effects of fundamental frequencies of the nearby free-field and of other buildings in the vicinity. In addition, when an instrument is

*Correspondence: Sayed.hemeda@cu.edu.eg; Sayed.hemeda@ejust.edu.eg

[1] Architectural Conservation Department, Faculty of Archaeology, Cairo University, Giza, Egypt
Full list of author information is available at the end of the article

not positioned in the mass centre, the torsion frequencies can mask the results.

Monitoring seismic structural response is an essential issue in earthquake risk assessments and mitigation studies for monumental buildings in order to undertake earthquake disaster management.

Studies of earthquake damage after destructive earthquakes (Mexico City, 1985; Loma Prieta, 1989; Turkey, 1999; Athens, 1999; L'Aquila, 2009; and recently the Nepal earthquake, which occurred in April 2015) reveal the importance of local site effects and soil–structure interaction on earthquake damage distribution.

Seismic ambient noise recordings have been used as a tool to estimate the seismic dynamic response of buildings, their fundamental period, and possible resonance phenomena between the soil and structures.

From a conceptual point of view the dynamic behavior of the historic masonry structures may be studied using two different approaches: an analytical approach, in which starting from geometry, damping, distribution of mass and stiffness it is possible to calculate in a closed form the modal characteristics of the system; and an experimental approach, in which starting from the experimental structural response under a certain excitation it is possible to estimate the dynamic properties of a structure, such as frequencies, vibration modes, and damping by applying dynamic identification techniques, [1, 2].

The analytical approach, known as direct problem, requires the definition of a numerical model.

The experimental approach, also known as indirect problem since it starts from measurements data for estimating system properties, requires the availability of an equipment for monitoring structures. The first applications of dynamic structural identification were carried out in the 1970s for performing damage identification of aerospace structures and offshore platforms. Also, it should be mentioned the pioneer activity carried out by Ellis and BRE (1998), [3] in order to evaluate the integrity of 534 stone pinnacles on the Westminster Palace. Nowadays, this technique is widespread also for structural restoration of built heritage purposes, aiming at the evaluation of the structural behavior along the time, [4] also in the case of historical constructions (among the others), [5–11].

Usually churches are characterized by vibration modes have modal participating mass ratio less than 10%. As the participating mass ratio of each vibration mode is small, it is hence necessary to take into account a great number of 100 modes to describe the dynamic behavior of the Basilica, [12]. The dynamic excitation due to the seismic ground motion activates many vibration modes of the building structure, though all of them are characterised by small participation factors. In all the examined case studies, the base shear V ratio ranged between 20 and 30% of the church weight. The observation of damage and failures under real experimental actions, like real earthquakes, are a precious means for the advancement of knowledge in the field of seismic engineering, [13].

Heritage masonry buildings are particularly vulnerable to earthquakes because they are deteriorated and damaged, they were built with materials with low resistance, they are heavy and the connections between the various structural components are often insufficient, [14]. Approximately one-half of the churches composing the sample have the normalized simplified indexes lower than one, indicating the need of further investigations. For the Basilica of San Francesco the results of LA-2 level of analysis confirm the conclusions obtained with the more simplified procedures, while a criticism is highlighted with the LA-3 approach when the N2 method is adopted in combination with a pushover methodology of analysis, [15]. The hazard should be combined with the specific vulnerability of the structure to assess its seismic risk. Apart the numerical modelling approach, simplified index-based methods for this typology have been proposed in literature, the valuable information can be obtained from simplified methods, with respect to performing a first screening and to prioritizing further, deeper investigations. A new proposal is made regarding the combined usage of two of the indexes, [16].

When buildings are not designed and constructed to withstand these unpredictable and often violent ground motions and shaking, major structural damage, or outright collapse, can result, with grave risk to human life. Historic buildings are especially vulnerable to seismic events, particularly those built before seismic codes were adopted, which represents the different vulnerability of the construction Materials to ground shaking. Also, more and more communities continue to adopt higher standards for seismic retrofit of existing buildings, [17–20].

Seismic risk defines as a function of earthquake hazard and vulnerability. Assessing the seismic risk of a historic property is the first step to avoid the potential loss of life and injuries, damage and loss of property, or disruption of services. Seismic evaluations of historic buildings within areas of earthquake hazard should be conducted if they have not been previously performed.

This evaluation should identify both the potential structural deficiencies of the building (any structural component such as columns, beams, floors, etc., required to resist seismic forces), as well as the potential vulnerabilities of the nonstructural components of the building (all components that are not part of the structural system, which include exterior cladding, glazing, chimneys, interior partitions, ceilings, and other architectural features, as well as building systems, and equipment).

The purpose of this study is to examine the main frequencies of Abu Serga Church, using ambient noise recordings. Specifically, this study is aimed at identifying the resonant frequency of soil and a structure of the Church using ambient noise recordings considering the importance of assessing soil amplification effects occurring at frequencies comparable with those observed for building structures, which may cause a pronounced increase of damage during earthquake motion excitation. This study highlights the necessity of incorporating prone resonating buildings into urban planning for earthquake risk assessments and earthquake disaster management.

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 in the late 4th-early fifth century, [21]. Yet some, [22] consider that the present building, unaltered in its main features, dates back to the 6th or even the eighth century. Nowadays its floor level is about 4.5 m below that of, the main street of Mar Guirguis (Saint George) at the subway station, [23].

The Church is about 27 m long. 17 m wide and 15 m high and its floor level is about 1.5 m below the surrounding alleys. It has a typical Basilicas design with a narthex leading to the nave with two side aisles. These aisles are separated from the nave by twelve columns in two equal raw, with a mezzanine above the aisles. The nave leads to the choir (khoaros) then to three sanctuaries occupying the east side of the Church. In the north and south sanctuaries, there are two staircases leading down to the Crypt. Nowadays one would notice quite a change in the inner arrangement with no change in the structure of the Church. The walls of the church, in general, are built with dressed limestone blocks with brick layers in-between, [24, and 25]. The Church was built in the fourth century and was probably finished during the fifth century. It was burned during the fire of Fustat during the reign of Marwan II around 750. It was then restored during the eighth century, and has been rebuilt and restored constantly since medieval times; however, it is still considered to be a model of the early Coptic churches. Again, the most precious and ancient of the icons are on the southern wall. A vast central hall is divided into three naves by two rows of pilasters. Some of the columns contain images of saints. The icons represent scenes from the life of Christ, the Virgin Mary and the saints.

In the eastern part of the temple is a sanctuary separated from the main part by a higab, adorned with ebony and ivory, the oldest part of this sanctuary dates back to the thirteenth century. The wooden canopy on the altar of the sanctuary rests on four pillars and is adorned with biblical scenes, with the image of the Pantocrator and the Archangel Gabriel, among others. The apse behind the altar is adorned with marble mosaics.

The ceiling above the central altar, dedicated to the temple's holy holders, is shaped like a barrel vault. The lateral shrines, the one in the north dedicated to Archangel Gabriel and the one in the south dedicated to Archangel Michael, have shallow domes. In the northwest part is the church's baptistery.

In this church there was formerly the oldest altar in Egypt; It was transferred to the Coptic Museum belonging to the church. There are also fragments of the original wooden ambo.

The seismic design and risk assessment of Abu serga church 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 church and the design of the necessary remediation measures. In the present pare we present the results of the first phase.

Some other papers on AVT, especially applied to churches, could be taken into account, i.e. [26–30].

State of preservation

Abu serga Church, in Coptic Cairo is one of the oldest Coptic churches in Egypt. The Church was built in the fourth century and was probably finished during the fifth century.

Saints sergius and Bacchus Church is traditionally believed to have been built on the spot where the Holy Family, Joseph, Mary and the infant Jesus Christ, rested at the end of their journey into Egypt.

The church is of significant historical importance, and in fact, it is where many patriarchs of the Coptic Church were elected.

It was burned during the fire of Fustat during the reign of Marwan II around 750. It was then restored during the eighth century, and has been rebuilt and restored constantly since medieval times; however, it is still considered to be a model of the early Coptic churches. Again, the most precious and ancient of the icons are on the southern wall. A vast central hall is divided into three naves by two rows of pilasters, as shown in (Fig. 1a, b and c).

The subsurface profile, under the church's floor, consist of an upper filling cover of about 5 m thickness, under lied by soft then medium plastic silty clay layers mixed with variable percentages of sand. The fine to medium sand layers appear at depth 10–11 m below the church's floor level. The groundwater appears at 1.4 m depth.

Numerous local cracks and deformation patterns were observed and recorded mainly during the old fluctuations of the Nile before to the construction of the Aswan High Dam in 1968 (ancient dams that caused the loading and unloading of the underground layers under the historic building structures) and during the water removal project (Contract 102 in 2000) to reduce groundwater in the Old Cairo area.

Almost causes of structural deficiency and damage seem to be of the mechanical static and dynamic actions, affecting the superstructure of the church:

(A) Differential consolidation settlement due to the plane loading of the superstructure on the full saturated clay soil and expulsion of the pore water, also the differential settlement due the shear failure of the soil layer under the heavy loading and the poor geotechnical characteristics of the soft bearing clay layer, also the fluctuations of the subsurface water can reduce the bearing capacity of the bearing soil to 50%. The dewatering project in the old Cairo area in 2000 was one of the causes of soil settlement due to consolidation of the thick fully saturated clay layer.

The internal deformities of the two facades of the Abu serga church are clear. Settlement and the rotation and inclination of the structural marble columns and the different cracks in the arches inside the church are well observed; also the vertical cracks in the lintels inside synagogue are obvious.

(B) Seismic loading, according to historical facts the powerful earthquakes and the recent earthquakes in particularly the Dahshur earthquake 1992 and Aqaba earthquake 1995, that have stuck old Cairo area, caused medium damages to Ben Ezra synagogue. The investigated building is behaved in a global way, even if some local mechanisms not producing any wall collapse have been recorded. In addition, its seismic behaviour is conditioned by the interaction of the oratory with the remaining part of the building, which give rise to the so-called building aggregates, whose response towards earthquakes is not very simple to be understood, so that wide studies have been developed on this topic.

(C) Degradation of construction and building materials, moisture often plays the important and main role of the degradation of the building materials. The main source of the humidity is the subsurface water and high groundwater level for a long period of time.

The technical evaluation of the brick walls provided a general case of in and out of plane deformations.

Neither did the stone walls any great damage, although some irregularities were found in the stone walls of the synagogue structure. The protrusion was not great, which suggested that the seismic motion was not so large and that the land subsidence affected the structure. Cracks and disarrangement were seen in the stone walls and stairs. But ground subsidence made the entire differential settlement of the church structure, and it is presumed that the concentrated strain caused them.

Also, peeling was seen on some corners and coping stones, but it can be determined that this did not reduce the strength of the body. There was little damage on the stone surfaces. Where this damage was from the earthquakes was not evident, but surrounding land seemed to have subsided due to earthquakes and it was presumed that the damage came from the earthquakes.

Although damage was mainly due to the seismic loading, some of the damage was not earthquake-related. Damage assessment of the building indicated typical damage to unreinforced masonry structures (UMS).

Blistering, detachment, Peeling, scaling and flaking off of the surface of marble and granite columns in thin layers caused by expansion and contraction or weathering and moisture.

Detachment and wearing a way of the renders and plaster layers due to the crypto florescence of salt weathering and rising damp.

Rising damp, salt fretting, spalling, break off layers or peel away of brick. Efflorescence and erosion, wearing a way of the surface, edges and corners of masonry.

Complete break and failure of many walls and ceiling of the annex structures.

Seismic hazards

Historical seismicity

Globally, geophysical disasters—primarily earthquakes killed more people and destroyed many archaeological sites than any other type of natural hazard in the past 20 years.

Dealing with the earthquakes, Egypt is a country of low to moderate seismic hazard but earthquakes are active in the northern parts of the country and along the western side of the Red Sea.

The areas with relatively low seismic activity are covered by thick marine limestone of Cretaceous age lying above the Nubian sandstone in the larger part of the Western Desert. The basement rocks in the Eastern Desert have also low seismic activity. The Nile Valley and Delta areas are underlain by thick alluvial sequences that are likely to provide a much less secure

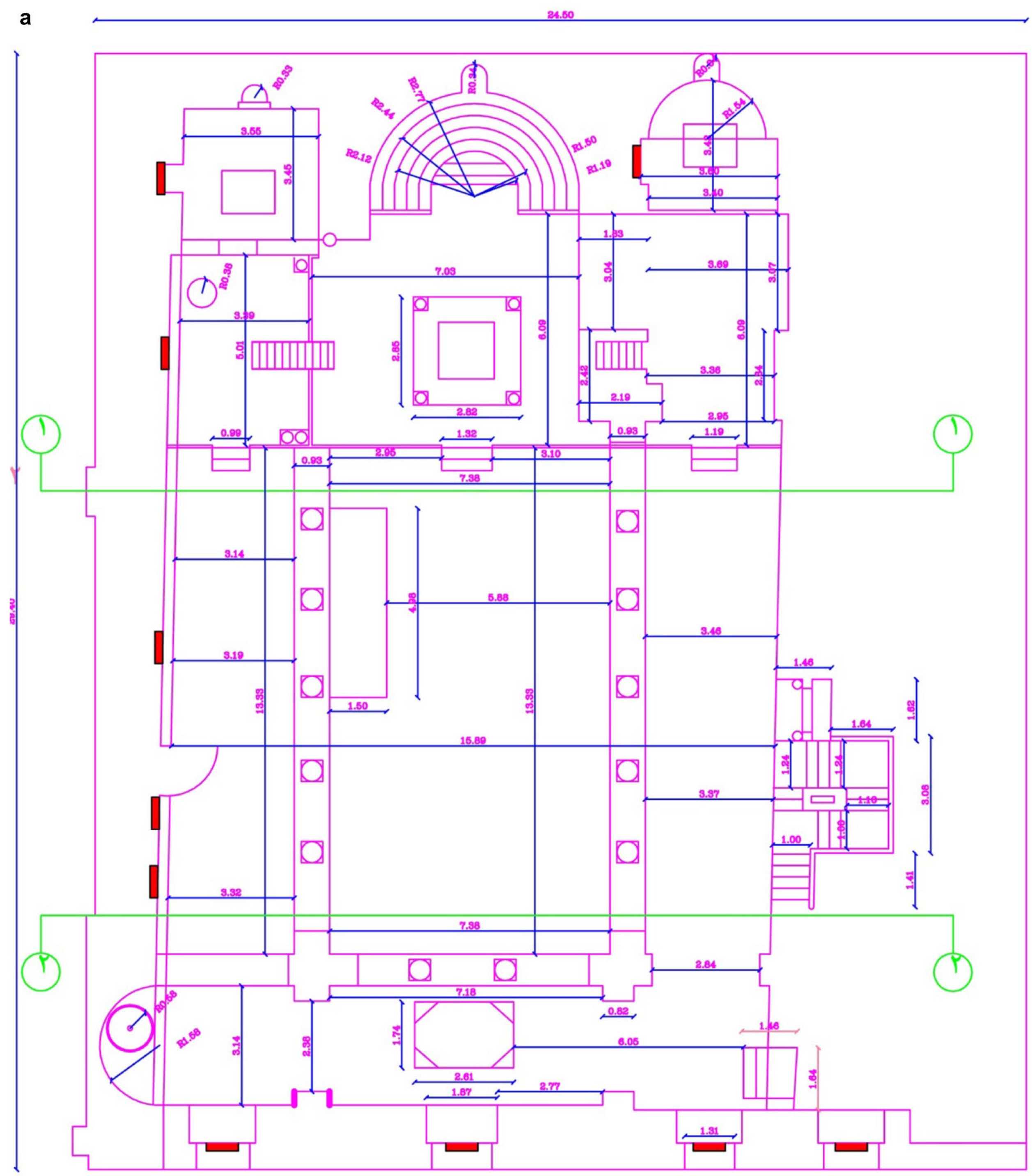

Fig. 1 **a** Layout of the basement of Abu Sega Church. **b** Layout of the first floor of Abu Sega Church. **c** Layout of the roof of Abu Sega Church. **d** General External over view of the Abu Sega Church

foundation during earthquakes than the crystalline bedrock in the Eastern Desert. Damage to buildings is related to clay thickness. Clays swell and slake in water leading to vulnerability of the buildings in areas with considerable clay thickness.

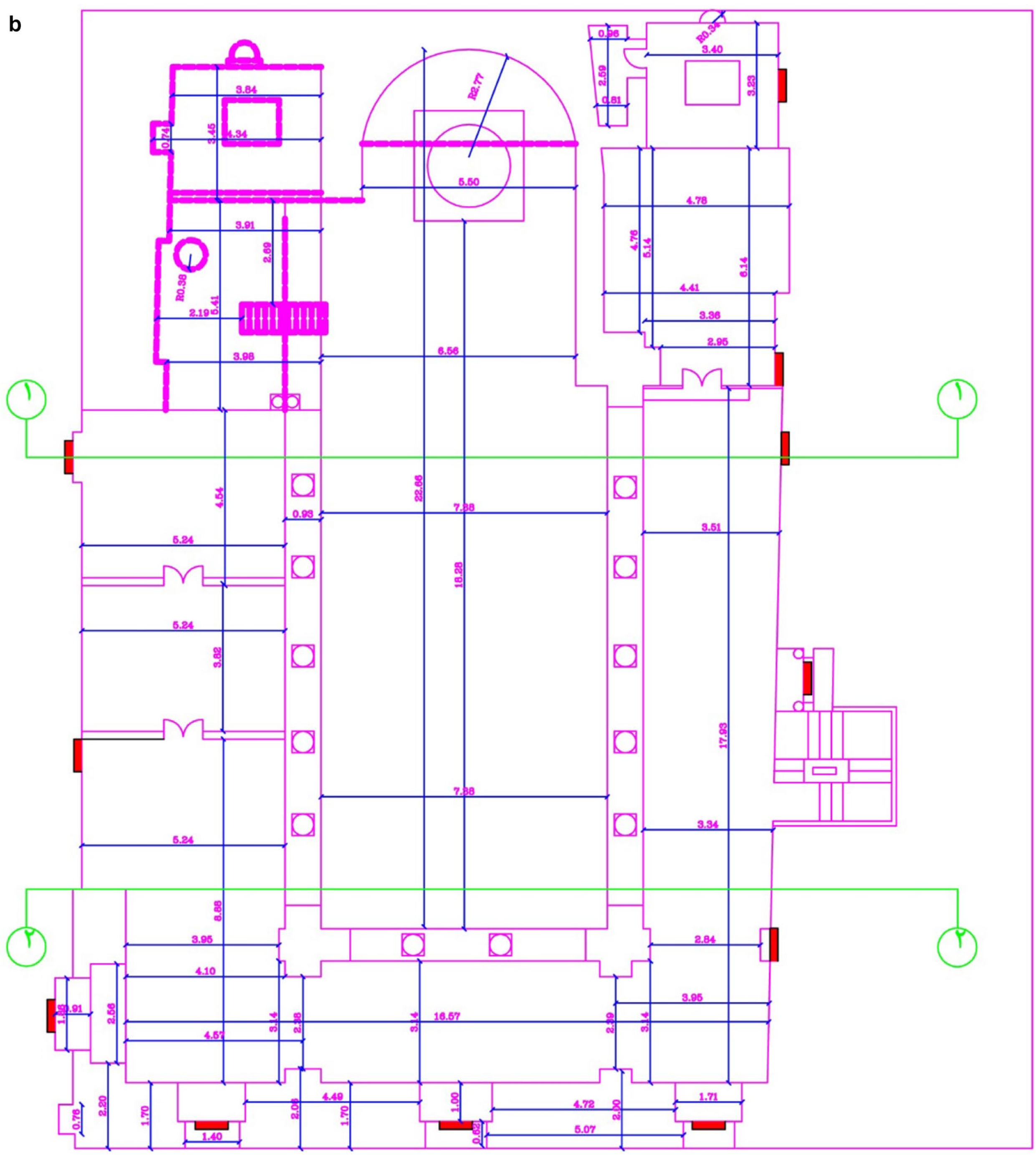

Fig. 1 continued

Fortunately Egypt possesses a great earthquake catalogue that goes as far as the ancient Egyptian times. The pharaohs left us a detailed description to earthquakes that we can put a seismicity maps for some earthquakes that goes to the 4000 years ago. From the most important historical seismicity around Abu serga church from 1900 to present, we can see that the Faiyum area as well as the Gulf of Suez is the most important earthquakes affecting Abu Serga church (Table 1).

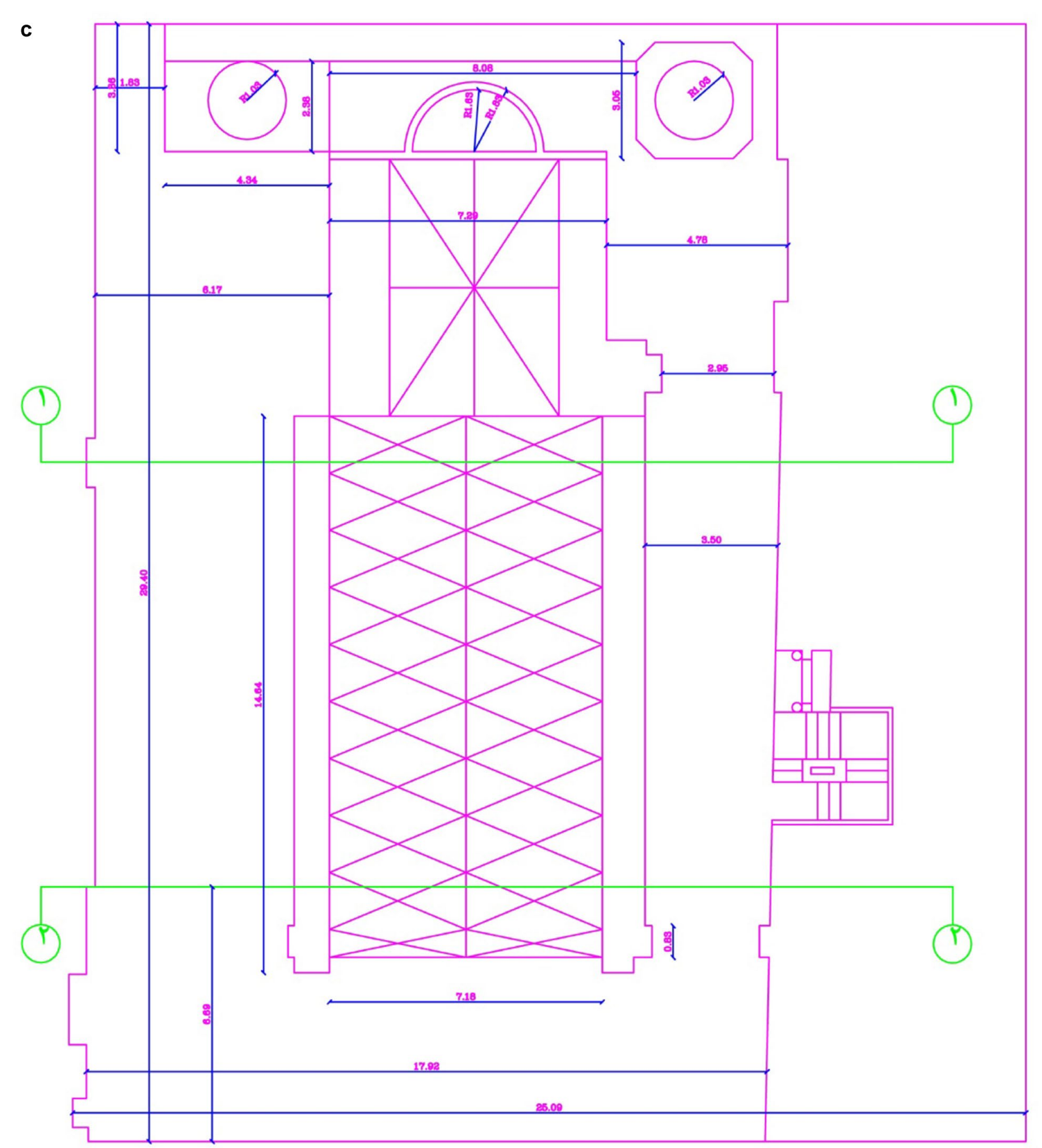

Fig. 1 continued

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 use 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 affected Abu serga church area. This

Fig. 1 continued

Table 1 The estimated return periods of earthquakes in the region per year

Magnitude	M ≥ 5	M ≥ 6	M ≥ 7
Return period/years	33	229	1550

was done using a cells value of equal area 0.1 lat. × 0.1 long. Figure 2 shows the Probabilistic Ground Shaking Hazards. G SHAP 10% in 50 years PGA for Cairo and surrounding area.. 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 was 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.

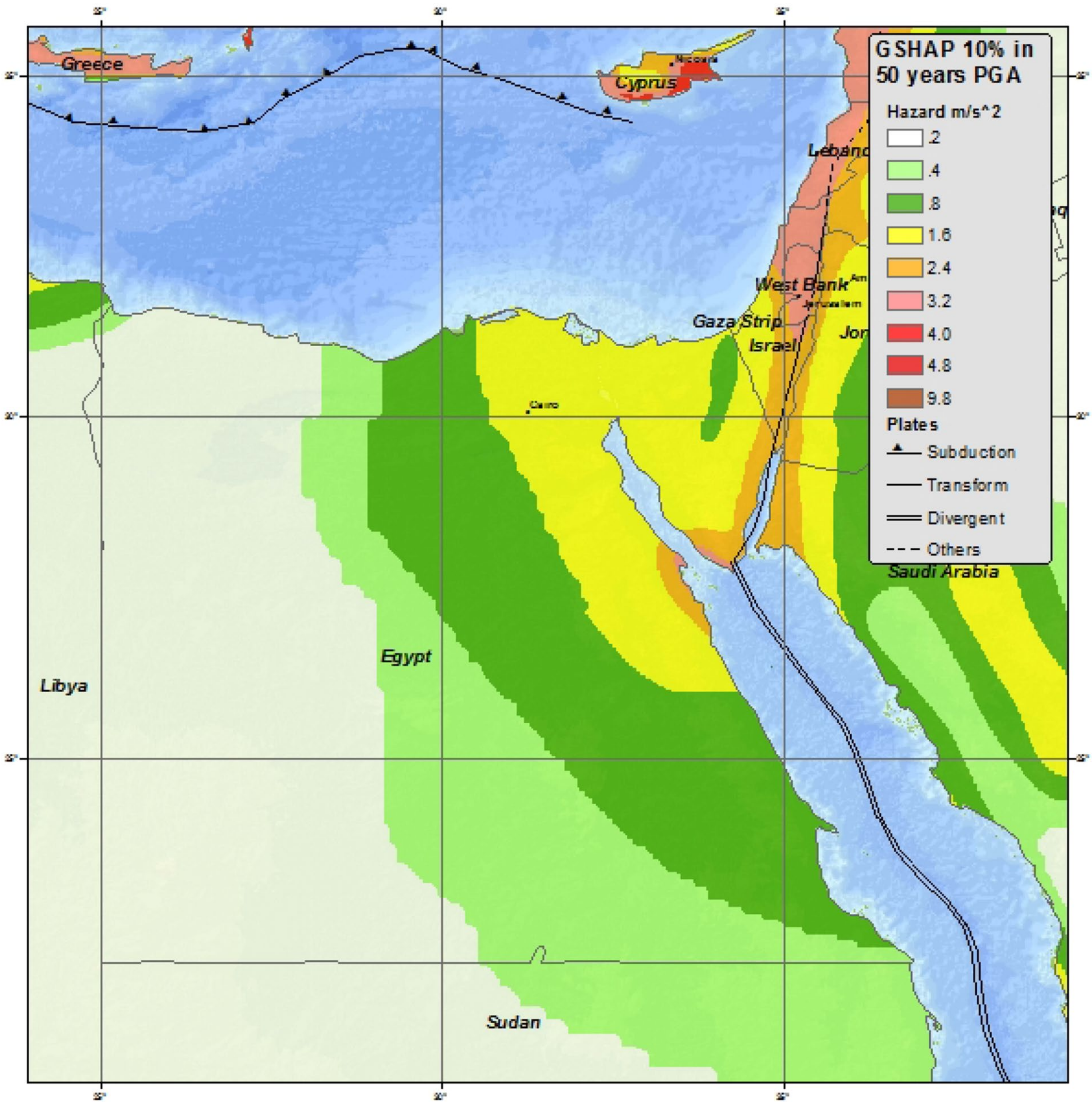

Fig. 2 Probabilistic Ground Shaking Hazards. G SHAP 10% in 50 years PGA for Cairo and surrounding area

Recurrence of earthquakes at Abu serga church

The recurrence of earthquakes is very important for determining the future plans for sensitive structures like the archeological sites. We have 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 was proposed. 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, suggest 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 no cooperation exist between agencies, we succeed to generate two important kinds of maps and these are the "Maximum Intensity Zonation Maps for Abu serga church and the "Iso-Acceleration Contour Maps for Abu serga church". To 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.

Probabilistic hazard assessment

The hazard maps 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, as shown in Fig. 3a, b. 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 hazard map 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 (GPA) in Gals With 10% Probability of Exceedance over 50 years:

144.8 cm/sec^2; (or 0.15 g) 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 0.20 g) 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.

Geophysical campaign

The main goal of this study is to investigate the dynamic properties of main lithotypes outcropping to evaluate the general features of the local seismic response through the combined use of geophysical methods based on Rayleigh waves and horizontal to vertical noise spectral ratios. These kinds of studies have unfortunately never been undertaken in Egypt and, therefore, no shear wave velocity values and fundamental frequency of outcropping lithotypes in historic sites have been published enough. The proposed preliminary results represent a valid set of data useful for evaluating seismic hazard and risk for the historic masonry structures. Even if the seismic activity around the Abu serga church is generally of low to

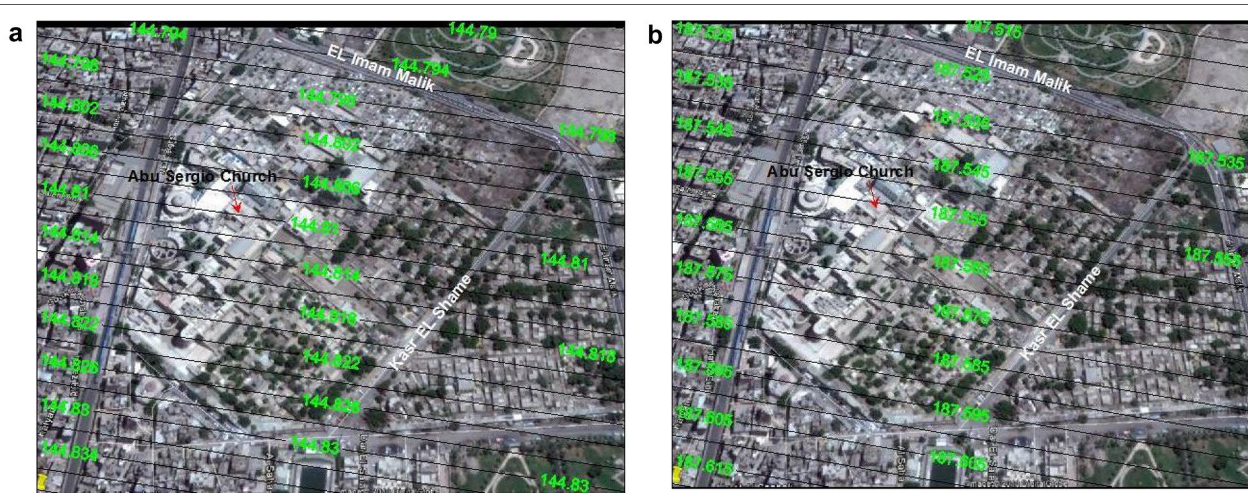

Fig. 3 **a** Peak Horizontal Acceleration in Gals (cm/sec2) with 10% Probability of Exceedance over 50 Years. **b** Peak Horizontal Acceleration in Gals (cm/sec2) With 10% Probability of Exceedance over 100 Years

moderate magnitude the old Cairo area in the past were struck by large events lie Dahshuor earthquake 1992, resulting in considerable damage.

Refraction—microtremor (ReMi method)

The microtremor survey method (MSM) has been established as a method to estimate shallow S-wave velocity profiles from passive seismic data (i.e., microtremors). In this method we use shear velocity analysis techniques (Vs). One of the important roles of shear waves is a measured parameter in determining the strength of earthquake shocks, soil amplification, and mapping for engineering needs. This method is able to get waves with shallow penetration (up to 30 m), so Vs30 is a shear wave velocity with penetration reaching a depth of 30 m from the surface. Vs30 value is used to determine rock classification or characteristics of subsurface structures to a depth of 30 m. Based on the vs30 values, the site can be defined by the NERHP classification.

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 equipment [31, 32].

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 Louie, 2001, 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 900 m/s for average depth of about 6.5 m. The results of data measurement from points analyzed by HVSR curve. Therefore, HVSR curve inverted using ellipticity curve method to gets shear wave (Vs) profile. The locations of the conduced Vs profiles are illustrated in Fig. (4). The results of HVSR inversion point 1 until 12 shown in (Figs. 5 through 6c), and the Vs30 calculated values of each site.

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 4–6 m at Abu Serga Church site (USGS, 1980 take S-wave velocity of > 765 m/s to be the velocity of the bedrock).

It can be seen that the value of Vs30 is obtained around (900–1000) m/s and land classification in the study area if referring to the NEHRP table, including the classification of land types E and D, including land soft and rigid soil. Shear wave velocity at a depth of 30 m is an important parameter in soil movement analysis basically the layer with low Vs has a low level of rigidity as well. The measurement point that has a low Vs is the thickness of the sediment in it is thicker than the site with a high Vs. Sediment thickness can also indicate the presence of bed rock, the thicker a layer of sediment is, the more in the presence of bed rock and otherwise, [33].

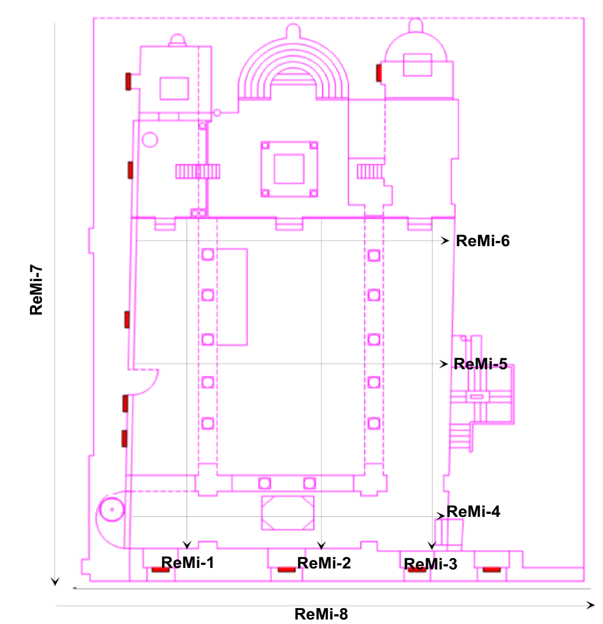

Fig. 4 basement floor of Abu Serga Church showing the location of 8-ReMi profiles (ReMi 9,10 11 are 30 away in front of Ben Ezra Synagogue)

Frequency characteristics of the soil and structure using microtremors

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. 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. 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 on going 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

Fig. 5 **a** A sample of ReMi profile conducted out side Abu Serga Church. **b** A sample of ReMi profile conducted inside Abu Serga Church

originated from farther distances [34], 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, [33–40].

Kanai 1957, [41], 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 [42–47].

Instrumentation and data acquisition

A high dynamic range Seismograph (Geometrics ES-3000 mobile station with triaxial force balance accelerometer (3 channels), orthogonally oriented was used. 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 we followed the following steps:

-Recording 10 min 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-minnoise at time domain.
-Subdivision of each 10-minsignal into fifteen 1 min sub-windows,
Each of these series was tapered with a 3 s 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 choose carefully in the site as deepest and calmest station in the basement floor with least soil response (usually we 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 [33].

Results

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, as shown in Fig. (7).

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.

Natural frequency of vibration for the basement floor is determined using the stations shown in Fig. (8a and b). The natural frequency of vibration for basement floor for Abu serga church is obtained. It can be seen that there is no or little resonance peaks and little or no amplification exist for the basement floor.

The natural frequency of vibration for floor No. 1 was determined using the stations. The fundamental natural frequency of vibration for the 1st floor is 5.5 Hz while

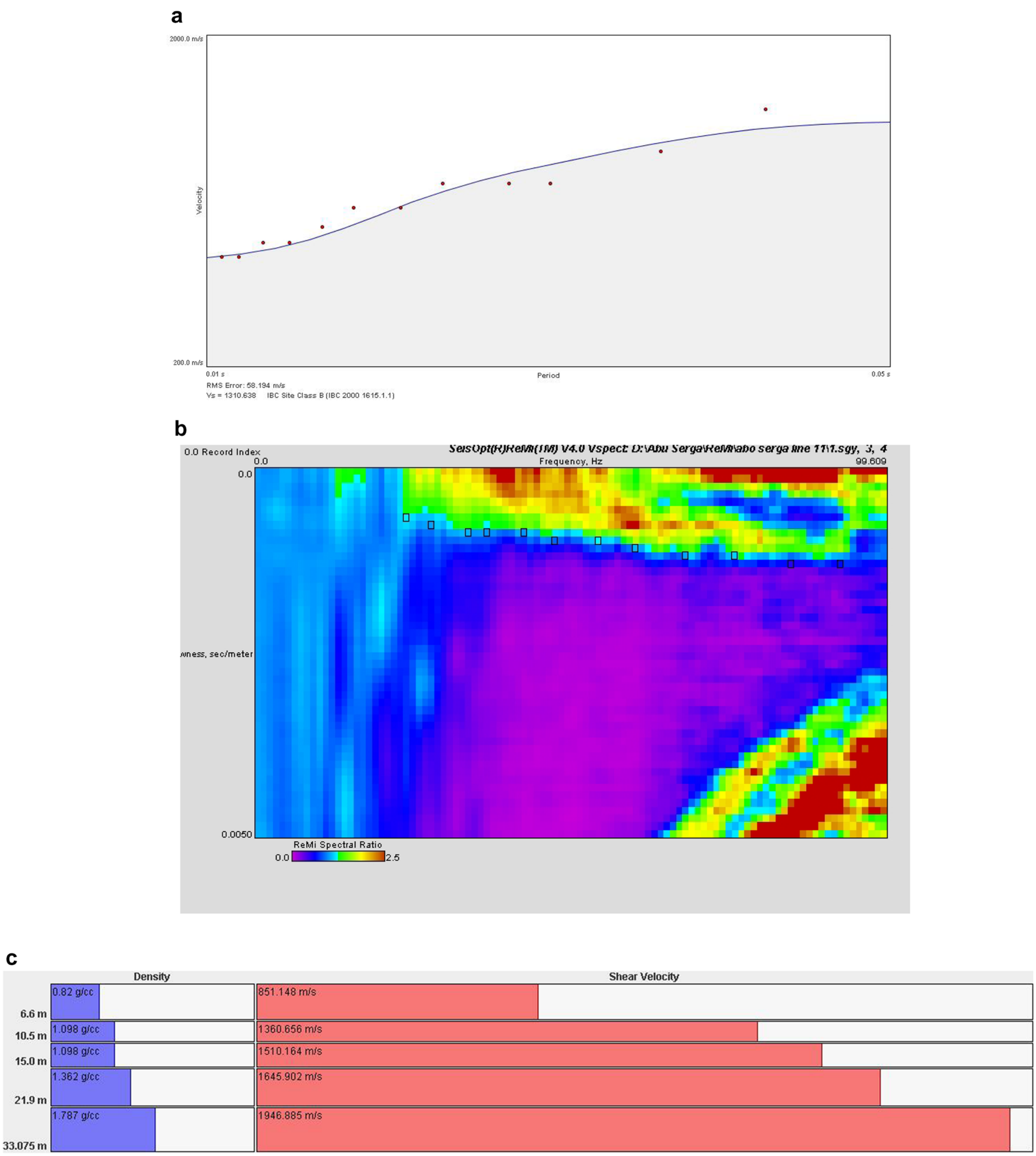

Fig. 6 **a** Dispersion Curve showing picks and fit for Profile ReMi-11. **b** P-F image with dispersion modeling picks for Profile ReMi-11. **c** Shear wave velocity model calculated for profile ReMi-11

the 2nd and third peaks exist at 7.7 Hz and 9.3 Hz and amplification factor 4–9 as shown in Fig. (9a and b).

The roofs stations are shown in Figs. (10a and b) while its resonance curves are found in (Fig. 11) station 4 to 6. The fundamental natural frequency of vibration 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 to 10 (Table 2).

Three stations were used to determine the natural frequency of vibration for underground Crypt found at Abu

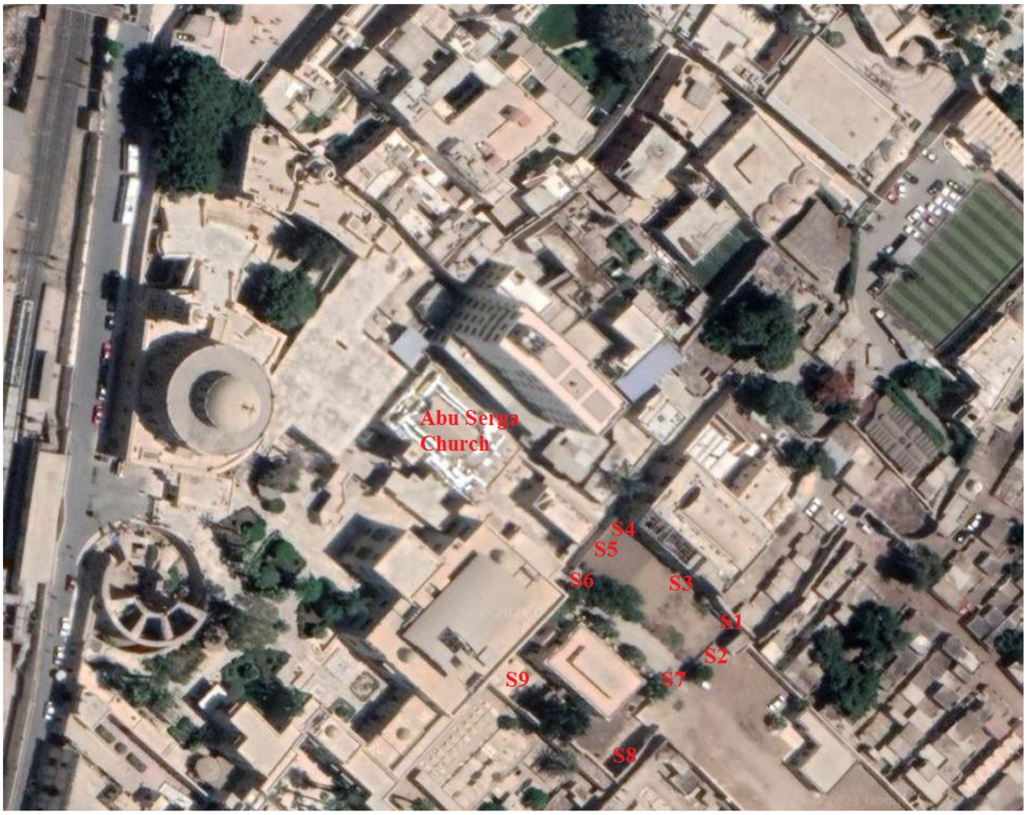

Fig. 7 Location map showing soil stations locations used to drive soil response for Abu Serga Church

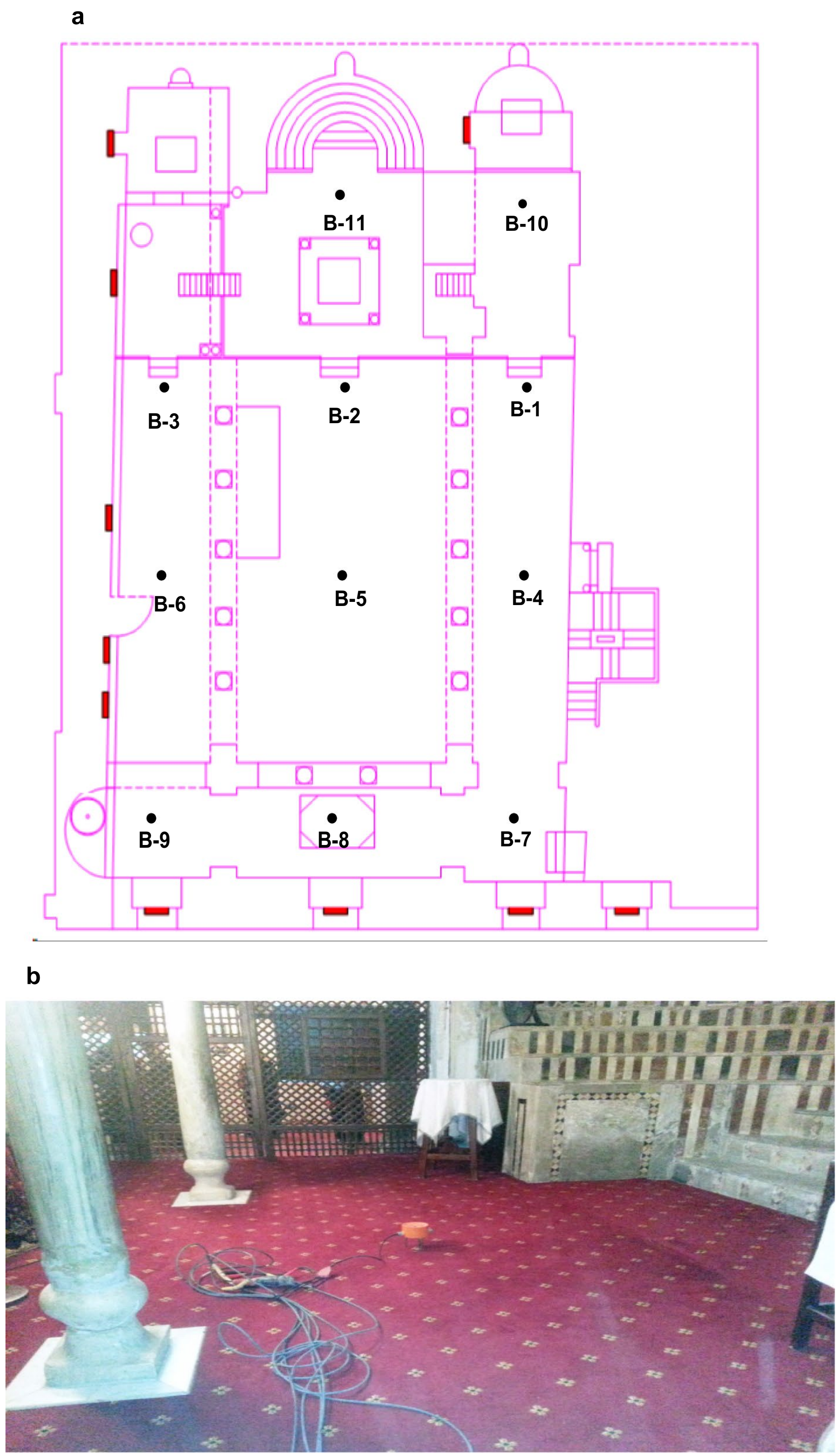

Fig. 8 **a**, **b** Locations used to drive the basement response for Abu Serga Church

Serga church. The Underground Crypt shows no fundamental peak of neither vibration nor amplification factors as shown in (Fig. 12).

The recurrence of earthquakes is very important for determining the future plans for sensitive structures like the archeological sites. We have calculated the return period for Magnitudes M ≥ 5, M ≥ 6 and M ≥ 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 was proposed. This introduces an important remark that if two active trends intersect at Abu Serga Church area the hazards and threats in Abu

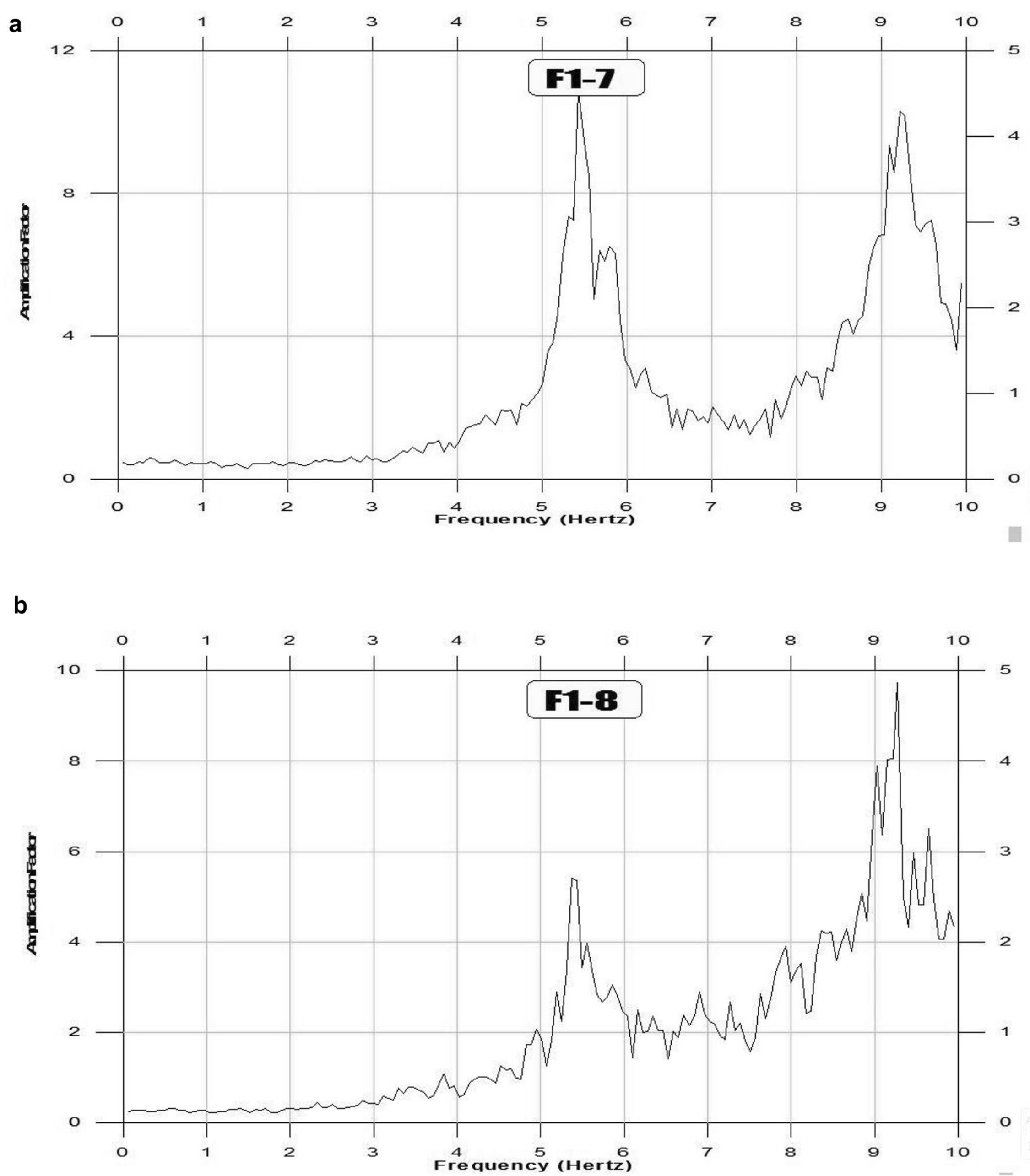

Fig. 9 **a** Natural frequency of vibration for the F1_7 for Abu Serga Church. **b** Natural frequency of vibration for the F1_8 for Abu Serga Church

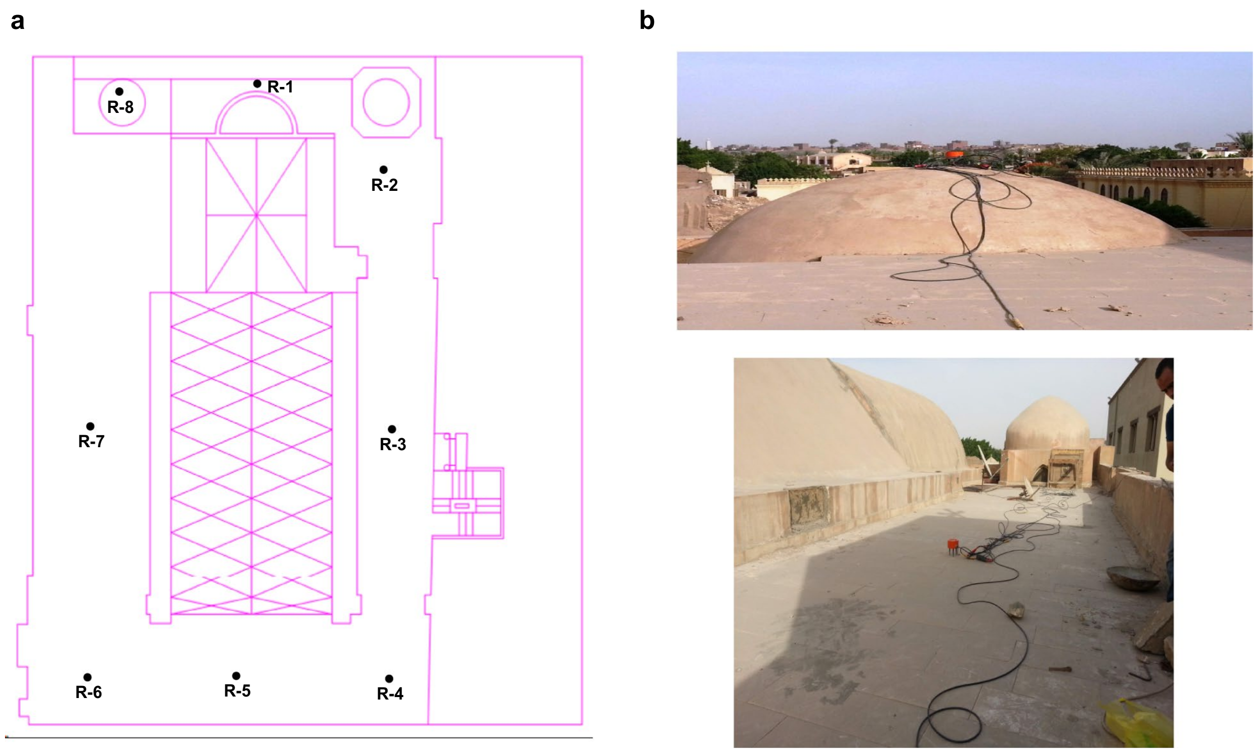

Fig. 10 **a**, **b** Locations used to drive the roof response for Abu Serga Church

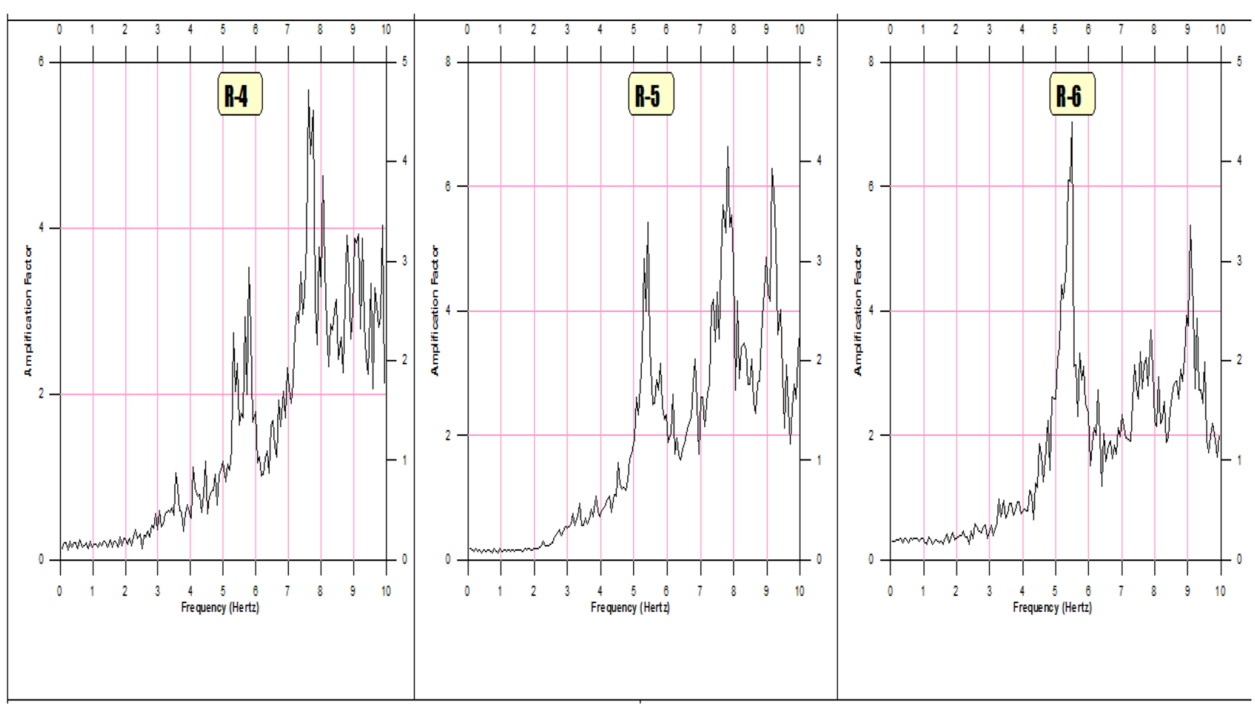

Fig. 11 Natural frequency of vibration for the roof of Abu Serga Church

Table 2 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	–	–

serga Church will be bigger. However no support is given to this from seismotectonics or seismic plate boundaries for these suggestions.

The hazard maps 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.

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 are 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 such as the 1st floor (5.5, 7.7 and 9.5 Hz) with amplification factor between 3 and 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 microtremors method used to show natural frequency of vibrations succeeded to show the resonance frequencies of vibration, however the amplification factor is affected by the level of the background noise. It is thus important to realize this in the design response spectrum.

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

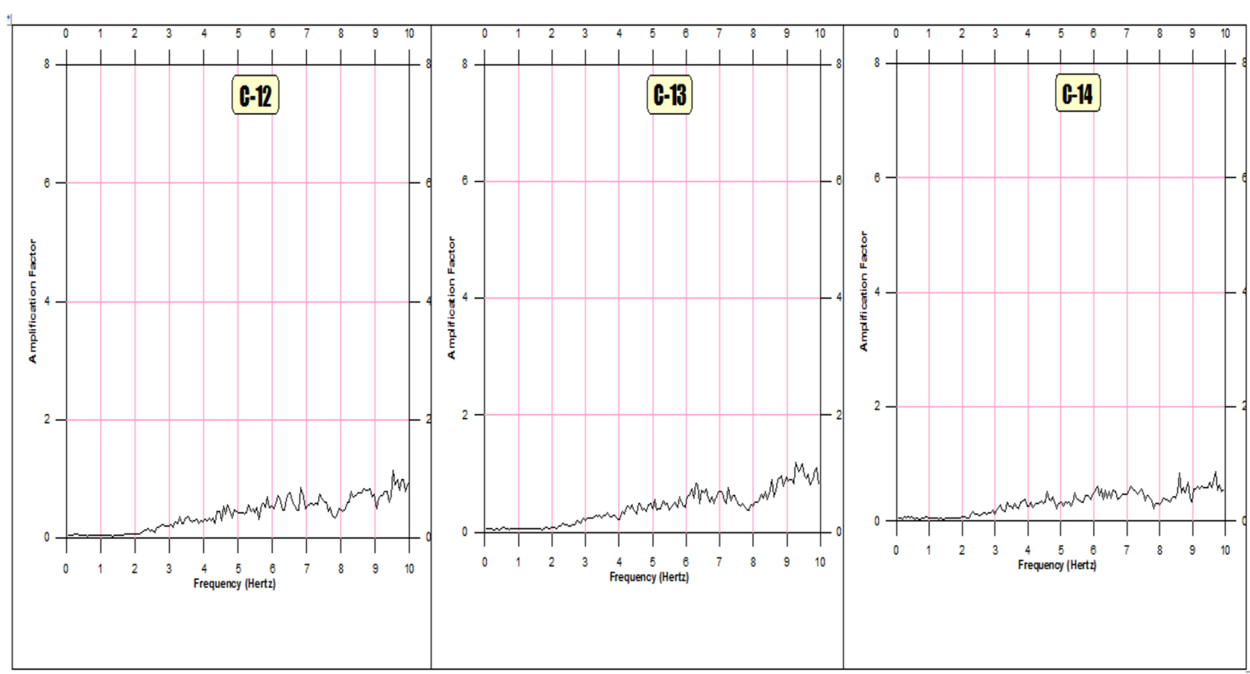

Fig. 12 Natural frequency of vibration for the Crypt of Abu Serga Church

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. Fortunately this earthquake is considered one of the most important earthquakes that affected Egypt in the last 100 years.

As normally expected the at higher frequencies > 10 HZ (short period 0.1 s) 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.

As damping increase, the response becomes less and the shape of the response spectrum becomes smoother. Response spectra, particularly at increased damping values, very much less.

The important notice that we should pay attention here is that the maximum acceleration response spectrum maintained for 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 occur (0.1 g), [33].

Soil-structure resonance

The determination of seismic hazard, oriented to seismic risk management in urban areas, particularly in Cairo, force us to know the resonance range between the dynamic behavior of ground and the building structures. Major damaging earthquake has occurred in site of Abu serga church in recent times, the presence of soil—structure interaction effects from observed damage pattern are available. In order to assess the soil-structure resonance for this site study, the microtremor measurements was applied.

Microtremor measurements were performed inside Abu serga church of various heights. The Horizontal-to-Vertical Spectral ratio (HVSR) analysis was applied in order to access the fundamental frequencies of the sediments, beside the longitudinal (EW) and transverse (NS) fundamental frequencies of each building determined from amplitude spectra and the Floor Spectral Ratio (FSR). When one of these frequencies is close to a nearby free field fundamental frequency, a potential soil-structure resonance is present. This study shows that the microtremor method could be used to make preliminary assessment of soil-structure resonance.

Measurement performed in Abu serga church confirmed that microtremors are an effective tool for identification of the main building frequencies. For all measurement, it was possible to identify the longitudinal and transverse frequencies. We used amplitude spectra of horizontal and standard spectral ratio (building spectral divided by free-field spectral).

The soil-structure resonance identify can be compared between frequencies of sediment and building structure. The amplitude of HVSR ranges are mainly in the range. The danger levels soil-structure resonance was chosen by applying the following criteria. First we select the building frequency that is closer to the free-field frequency and then we compute the ratio between them. The difference is within ± 15%, the danger of soil-structure resonance is high, if it is within 15–25%, it is medium, and if it is higher than ± 25%, then it is low.

Abu serga church, where a clear peak at frequency 5.5, 7.5, 9.3 Hz with amplitude 3–10 was obtained in free-field measurement. From microtremor measurements in the church, it was possible to identify the main building EW is a wide peak (5.18 − 9.73 Hz) centered around 7.6 Hz using spectral method and a clear peak at frequency 7.87 Hz for SFR method and NS is 73.29 Hz for spectral method and 7.97 Hz for SFR method were identified.

Soil-structure resonance is therefore very likely. This building can be medium–high damage cause of resonance free-field [48]. Differencing of result was caused by difference method analysis. Although the microtremor investigation have proved to be an effective tool for assessing the soil-structure resonance, microtremor measurements in a larger number of housed should be performed, including analysis of their dynamic behavior and of available information on the construction of individual buildings. In addition investigation should be enhanced to identify the area study of possible soil-structure resonance.

Conclusions

In the paper integrated geotechnical and geophysical investigation techniques were done to assess the seismic—geo-environmental risk of the Abu serga church using ambient noise recordings (microtremor). This activity was used to evaluate the historic building damages caused by the recent earthquakes, so to offer technical support and advice for retrofitting interventions. The manuscript reports on a study on an old church in Egypt. The paper presents the results of integrated geophysical techniques in order to assess the level of geo-environmental hazards and risk of the Abu serga church.

The study presents the results of integrated geophysical techniques in order to assess the level of geo-environmental hazards and risk at the Abu serga church.

Refraction microtremors 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 Louie, 2001, a total of six tests inside the church and another 5 tests outside the church were used to detect the average s-wave velocity within the Abu serga Church.

The conducted 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 900 m/s for average depth of about 6.5 m. This is most probably due to the change in level of the ground which is higher outside the church with about 2–4 m.

The bedrock velocity is thus 4–6 m at Abu serga Church site (USGS, 1980 take S-wave velocity of > 765 m/s to be the velocity of the bedrock).

Highlights and novelty of the study can be included as follow:

The Vs profile of the subsoil and the resonant frequency of soil and structure of Abu serga church have been identified. The seismic damage suffered by Abu serga church is illustrated. The experimental analysis is performed for evaluating the vulnerability of churches. The analysis results are compared with the seismic damage of the church. The existence of old structure such as the Abu serga church may reduce the ability to resist any earthquake shaking. Furthermore, evaluation of strength church able to use damping ratio, natural frequency and vulnerability index of church was estimated by microtremor data.

Abbreviations
Vs: Shear wave velocity; Vp: Prime wave velocity; ReMi: Refraction microtemors; HVSR: Horizontal-to- vertical spectral ratio; FSR: Floor spectral ratio; f: Frequency; GPA: Peak ground acceleration; φ: Friction angle of the fracture; x τ: Shear stress in resin annulus; σ b: Applied stress; α: Decay coefficient 1/ in which depends on the stiffness of the system; β: Reduction coefficient of dilation angle; σ c: Uniaxial compressive strength of soil; U: The shear displacement at each step of loading; σ n: Normal force; b u: Shear displacement; N p: Normal force at failure; Qp: Shear force at failure; Ei: Modulus of elasticity of intact rock; Qcf: Shear force; Lcp: Reaction length; UMS: Unreinforced masonry structures.

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Declarations

Competing interests
The author declare that they have no competing interests.

Author details
[1]Architectural Conservation Department, Faculty of Archaeology, Cairo University, Giza, Egypt. [2]Liberal Art and Culture Centre (LACC), Egypt-Japan University of Science and Technology (E-JUST), New Borg El-Arab city, Alexandria 21934, Egypt.

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