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Multidisciplinary Approach of Proactive Preservation of the Religions Complex in Old Cairo—Part 1: Geoscience Aspects

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Abstract: Old Cairo is a unique site in the world because of its historical, cultural, and religious values. Old Cairo, a UNESCO World Heritage site, represents a rich tapestry of history and culture. Its significance lies in its role as a center of Coptic and Islamic civilizations and its preservation of numerous historical monuments. Today, the conservation of cultural heritage demands a proactive approach that integrates a robust multidisciplinary strategy. This approach must consider the unique characteristics of the heritage itself and the extensive research and efforts devoted to various scientific fields and avenues. As a case study, the focus is on the Religions Complex, the target of the "Particular Relevance" bilateral Italy–Egypt "CoReng" project. The historic Religions Complex in Old Cairo, a UNESCO World Heritage site, faces significant seismic hazards, threatening its irreplaceable Coptic and Islamic heritage. This research contribution focuses on reviewing and assessing aspects of geological and seismic hazards. This assessment serves as a crucial foundation for future vulnerability analyses and the development of effective retrofitting strategies for the Complex's historic structures. The current work identifies critical vulnerabilities related to sub-surface geology and geotechnical conditions, various deterioration driving forces, rising groundwater levels, and earthquake ground shaking of the complex site to mitigate these risks and ensure the long-term preservation of this invaluable cultural heritage. In addition, attention is given to missing/weak characterization aspects and the proposal of possible future solutions and research developments.

Keywords: multi-hazard; Old Cairo; Religions Complex; vulnerability assessment

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1. Introduction

The Religions Complex in Old Cairo is a testament to the city's rich and diverse history, encompassing places of worship for the three Abrahamic faiths: Islam, Christianity, and Judaism (Figure 1). This unique juxtaposition of religious traditions highlights the site's profound cultural significance and importance as a symbol of interfaith co-existence. Within the Complex's boundaries lie architectural treasures such as the Babylon Fortress, the Greek Orthodox Church of Saint George, the Abu Serga Church (dedicated to Saint Sergius), the Ben Ezra Synagogue, and the Mosque of Amr ibn al-As.

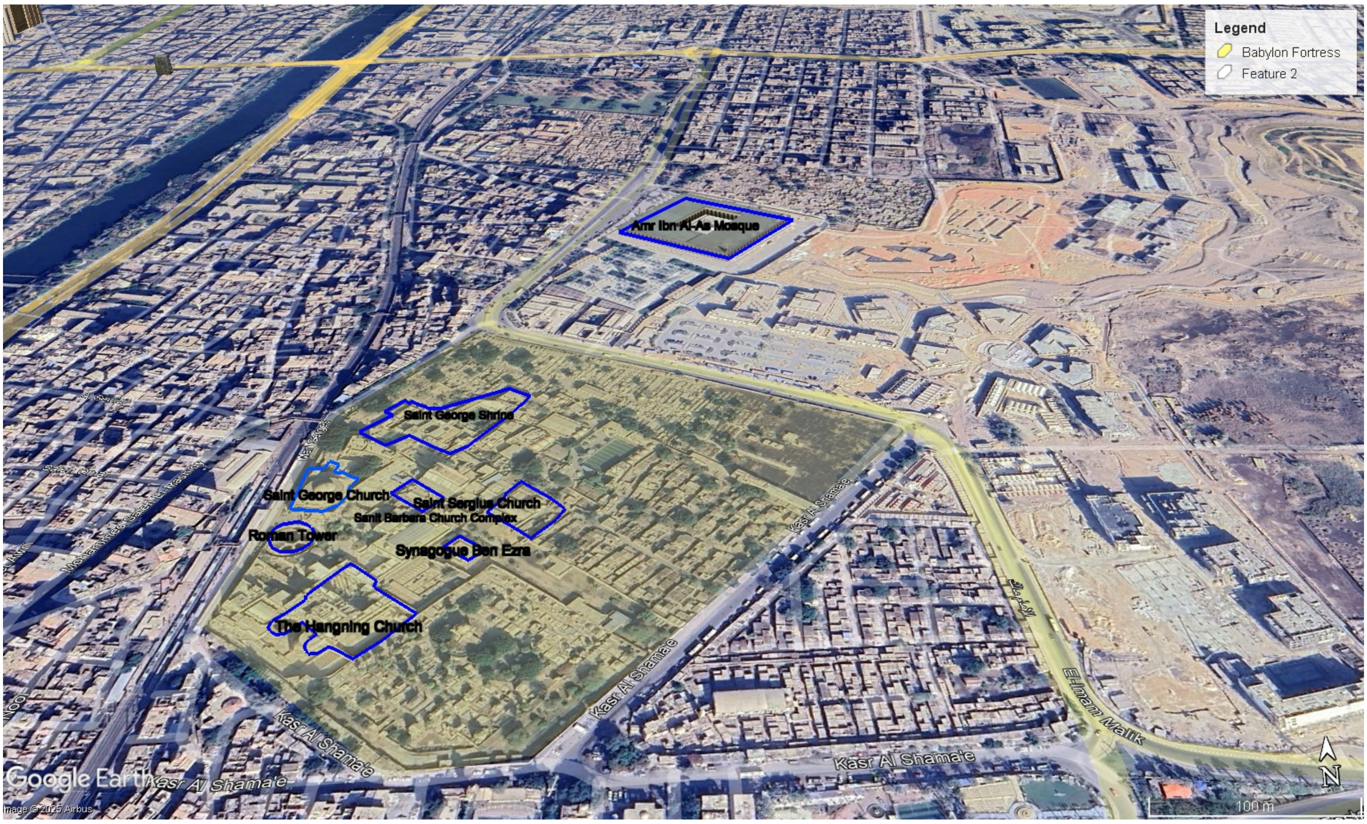


Figure 1. The Religions Complex in Old Cairo, highlighted in shaded color.

The Religions Complex holds the singular distinction of being the only location worldwide where places of worship for all three Abrahamic faiths exist in such proximity. Cultural heritage sites like this possess immense moral, historical, and economic value, serving as sources of national pride and generating substantial revenue through tourism. Indeed, the antiquities and heritage sector are crucial to Egypt's economy, contributing significantly to the nation's GDP. Recognizing this importance, preserving cultural heritage is a cornerstone of Egypt's 2030 national strategy.

Many historical monuments in the Old Cairo area include mosques, madrasas, hammams, sabils, and fountains. Presently, the condition of many of these monuments is progressively deteriorating due to natural and anthropic factors. Several factors may combine and create a complicated and irreparable situation for some monuments (i.e., groundwater, weak building conditions, limited seismic resistance, absence of maintenance, protection, and preservation policies). Consequently, even modest earthquakes could cause major damage to Old Cairo monuments. For example, an earthquake measuring Mw 5.9 in 1992 in Cairo caused damage to approximately 212 of the 560 monuments [1]. Despite its moderate magnitude, the earthquake caused widespread damage to historic structures throughout the city, including monuments within the Complex [1]. It is also worth reporting that some of the Complex's monuments had damage with severity from light to severe (i.e., the Hanging and the Abu Serga churches), as reported in [1]. Hence, the Religions Complex faces a growing threat from seismic hazards. The 1992 Cairo earthquake (Mw 5.9) is a stark reminder of this vulnerability. This event underscored the urgent need for comprehensive risk assessment and mitigation strategies to protect these irreplaceable cultural assets.

Significant advancements have been made in archeological site conservation and restoration in recent years. However, further progress can be achieved by leveraging the latest scientific knowledge and integrating cutting-edge technologies. In this context, the ongoing bilateral Italy–Egypt project, about the "Conservation of the Religions Complex in Old Cairo through the integration of geosciences and earthquake engineering" (CoReng), seeks to develop a multidisciplinary and integrated methodology for preserving the Complex. This project recognizes that effective conservation requires a holistic approach and a deep understanding of the site's geological context, potential hazards, and vulnerabilities.

Preserving Cairo's Religions Complex structures is a national obligation and a shared global responsibility to safeguard the collective cultural heritage. Through this research endeavor, we aim to formulate a comprehensive review and creation of a site-specific inventory for multidisciplinary studies that can assist in raising the current knowledge and define the gaps to be filled in the following studies. The proper preservation requires a comprehensive understanding of the current situation at Old Cairo and complex site scales, joining available geoscientific and engineering knowledge and design work that could fill the existing gaps to achieve proper risk assessment and the adoption of effective mitigation strategies. This study contributes to the CoReng project by conducting a comprehensive evaluation of the Religions Complex, starting with its geological foundation and extending to identifying potential hazards and conservation challenges. This multi-faceted analysis provides a crucial framework for assessing the structural condition and vulnerability of the cultural heritage assets. Furthermore, it facilitates the integration of new technologies and culminates in creating a detailed inventory and technical document. This document will be valuable for guiding future research and practical conservation efforts.

This review seeks to thoroughly evaluate historical sites, starting from the soil/rock on which they have been founded and then passing through hazards and challenges for conservation tasks. All these steps represent a major background for the final assessment of the structural condition and vulnerability of cultural heritage, as well as for the integration of new technologies and for the final elaboration of a sort of inventory and technical document that could be used as a guide in case of future studies and practical works. In particular, a literature analysis of available information about surface sub-surface geology, geotechnical issues, environmental hazards, geologic structures, earthquake activity and hazard, past earthquakes, and vulnerability studies is presented.

2. Site Geological Composition

2.1. Geological Setting of Old Cairo: Surface and Sub-Surface

Old Cairo's geological characteristics have significantly influenced its development over history. Old Cairo is located on a terrace formed by the Nile River, which represents an ancient floodplain, indicating the river's fluctuations over time. To the east of Old Cairo, the Mokattam Plateau rises abruptly. This plateau is composed of Eocene limestone and provides a dramatic contrast to the flat plains of the Nile Valley.

The abundance of Eocene limestone was significant in the city's architectural style. This durable stone was used to build many of Old Cairo's historic structures, including mosques, churches, and fortifications. The softer Quaternary alluvium was often used for foundations and filling in low-lying areas, providing an easy implementation for the base of buildings and nearby fresh water and agricultural activities. The region's geology has influenced the location and preservation of many historical sites, including the Citadel of Cairo, the Islamic and Coptic Cairo. These sites have played a crucial role in shaping Old Cairo's cultural and religious identity. The bedrock of Old Cairo is predominantly composed of Eocene limestone, a sedimentary rock formed from the fossilized remains of marine organisms (Figure 2, after [2,3]). This limestone is characterized by its light color and relatively porous structure. Overlying the limestone is a layer of Quaternary alluvium, consisting of the sand, silt, and clay deposited by the Nile River. This relatively young layer has significantly shaped the region's topography [4–7]. Nile alluvial deposits, aeolian sands, artificial fill, and rubbish deposits cover the more significant part of Cairo City and are also reported from the sub-surface. Given the results of drilling performed for groundwater and construction purposes, much is learned about the geographical distribution, the lithology, and the thickness variation in such deposits.

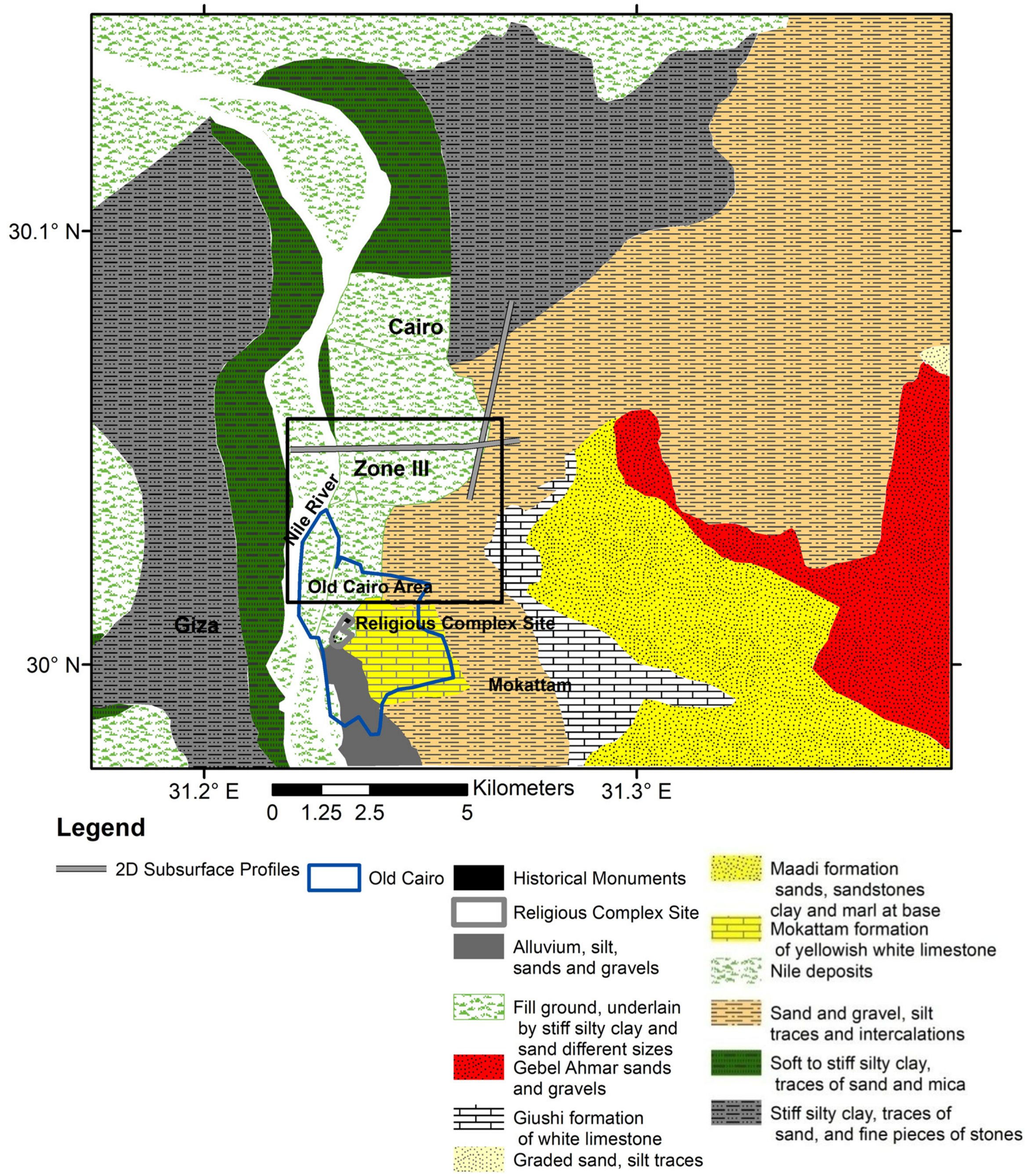
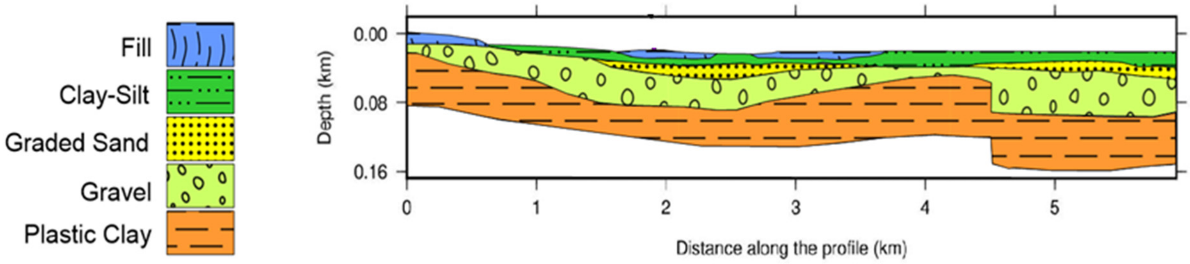


Figure 2. Geological map of the Mokattam area and Old Cairo (after EGSMA 1983).

The sub-surface geology of the Cairo area can be studied from the boreholes and vertical profiles given by [4,5]; see Figure 3. It can be used for site-specific seismic hazard analysis for Cairo in general, and specifically for the site of interest. Also, it can help study site amplifications to identify structural damage related to geotechnical problems. Hence, understanding sub-surface geology's vertical and horizontal characteristics can lead to forecasting future potential damage zones. Starting with the top layer, it varies in thickness and is composed of different materials. In the site of Fustat city, which is located in the

South of the Complex site (and was the first capital of Egypt under Muslim rule), ashes and ruins have been identified as the location, since the year 1200, of a huge heap of rubbish that extends parallel to Mokattam edge, towards North-East [4]. Borehole data indicate that below this fill are a Nile's deposits of stiff massive clay (clay–silt member). Then, there is a vast mass of interbedded graded sands, whose upper layers are frequently as fine as ground pepper, with the coarser-grained varieties beneath, and from which an inexhaustible water supply can be drawn. Also, many boreholes that penetrated deep enough encountered a unit of plastic clay that probably had unconformable relationships with the overlying sands and gravel members.



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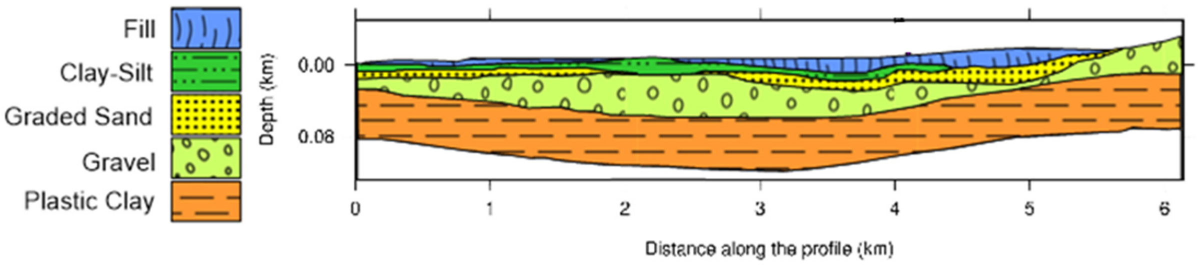

(**b**)

Figure 3. Two laterally heterogeneous profiles go through East-West (**a**) and North-South (**b**) directions compiled from borehole data and express the local conditions (Source: adapted from [8], licensed under © 2020 Elsevier B.V.) and shown in Figure 2 as gray lines.

The sub-surface geology of the Nile Valley at Cairo, as given in [4], is based upon the study of 217 boreholes (orange-filled circles in Figure 4) that cover a large part of Cairo and have an unequal distribution. Said [4] gives the location of these boreholes and the number of boreholes used in this study in each of the one square kilometre quadrangles of the city. Several wells or boreholes (purple-filled circles in Figure 4) have been dug in schools in Cairo after the 1992 earthquake, and several projects have been aimed at improving the structural safety of school buildings. This information can be combined to develop a multi-purpose soil map for Cairo (Figure 4).

According to Figure 3, in particular, the sub-surface geology of Old Cairo is mainly composed of the following layers (from top down): (a) Man-Made fill layer; (b) Holocene clay–silt member; (c) Pleistocene-graded sand–gravel member; (d) plastic clay Layer.

A substantial portion of Cairo is constructed on the Man-Made fill layer, composed mainly of construction debris and refuse, which may include remnants of decayed or collapsed structures that have been compacted over time. Historical maps from the 14th century indicate that canals, residual river channels, and ponds were filled with the materials above [4]. The thickness of this layer varies markedly across different locations, ranging from a few metres to as much as 40 m, with an average thickness of 15 m. Most of medieval Cairo has a bed of fill made up of remains of old buildings that had decayed one after the other, fallen, and been trodden underfoot till the original ground levels were entirely obliterated and artificial hills appeared. Virgin clay is seldom met within the surface except in the outlying portions of the city. Said [4] gives the outline and thickness of the fill in the different town boreholes; with the newly developed database, higher-resolution maps can be produced. The boreholes near the Religions Complex site indicate that the fill layer dominates the site surface.

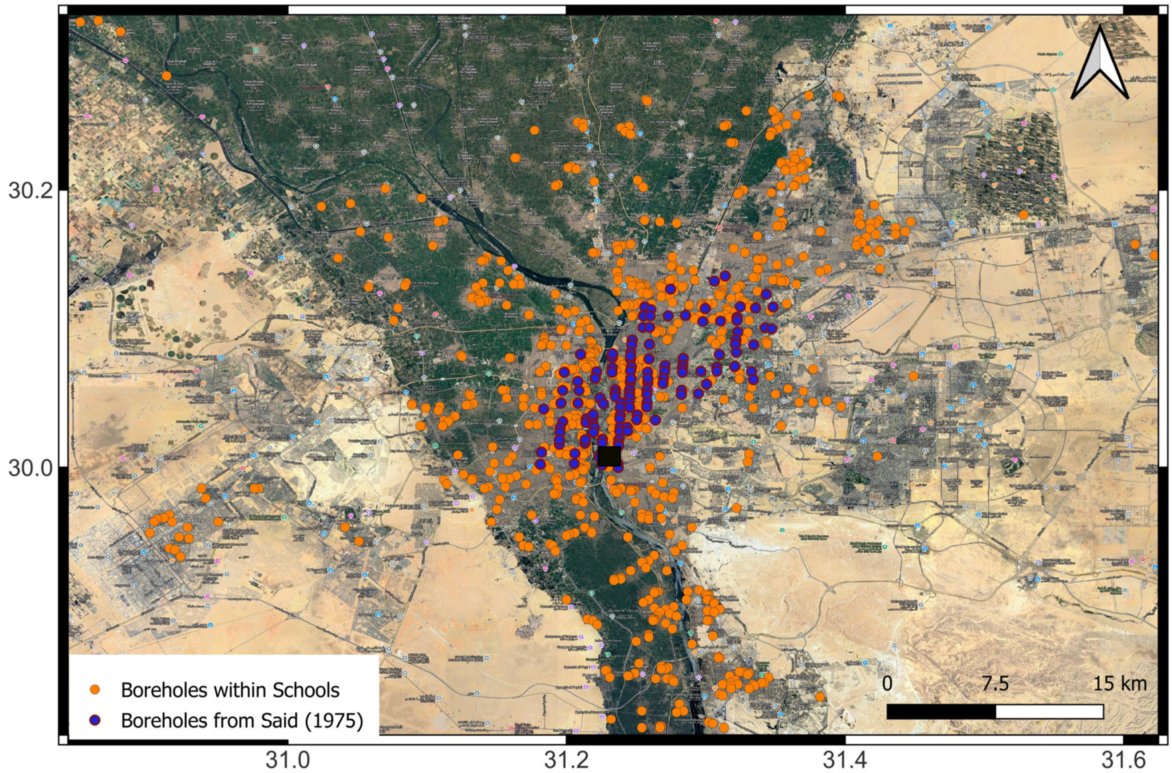

Figure 4. Spatial distribution of boreholes located in Great Cairo (compiled in this work).

The Holocene clay–silt member consists of contemporary sediment derived from the Nile, displaying a primarily uniform thickness of 8 to 10 m across available boreholes in Cairo. The sediment is characterized by dark grey to brown mud containing clay and sandy clay components. The Pleistocene-graded sand–gravel member has been identified in nearly all wells throughout the city. Its composition is likely similar to the gravel deposits visible along the Nile River's eastern and western banks. The isopach contour map indicates that the thickness of this layer increases progressively northward, with the maximum recorded thickness of 90 m found in the Zaitun basin. In contrast, the minimum thickness has been observed in the Nile River's eastern side boreholes.

The plastic clay layer comprises two distinct units: the upper unit consists of silts and clays, while the lower is characterized by clays containing microfossils indicative of salty water. Positioned at a depth of approximately 100 m, in Cairo, it serves as the foundation for the valley sediments. It sits atop the Oligocene gravel and sand of the Gebel Ahmar formation. The thickness of this layer varies, ranging from a few metres to 90 m. In certain areas, plastic clays can also be found at shallower depths and may exhibit shrink–swell behavior in response to significant fluctuations in groundwater levels. In the historical regions of Cairo, this unit typically measures between 20 and 40 m thick. This layer could be one of the main factors of groundwater raising as it is characterized by low permeability, making it act as a confined or semi-confined aquifer.

According to the above discussion, it is clear that the local site conditions in the historic area of Cairo can exhibit notable variations from one location to another, which are influenced by factors such as geological formations, soil and rock layer properties, bedrock depth, water table levels, and both surface and underground topography. These discrepancies are crucial as they significantly impact the ground's response to seismic load. Utilizing surface and sub-surface geology and site condition data from the existing literature, several laterally heterogeneous profiles of local site conditions could be constructed similarly to those in Figure 3. For example, the cross-sections by [4] could be combined with geophysical surveys to create high-resolution 3D sub-surfaces and velocity models for Old Cairo at a large scale and for the Religions Complex site in particular. Velocity models for Cairo and Religions Complex sites have yet to be investigated, and future surveys should be designed for proper site characterization to estimate the expected seismic input correctly.

Presently, the literature collects few research studies that specifically pay attention to combined geosciences and engineering/architectural tasks and issues that have a primary interconnection and correlation for the conservation of cultural heritage.

2.2. Geological Structure

Cairo City and its environs are cut by many faults, which follow two general trends: the North-West/South-East (Clysmic trend) and the East-West (Mediterranean trend). Faulting, as evidenced underneath the floodplain, is the most important structural feature in the area. The faults occur almost daily, with steep planes, and constitute a portion of a graben and horst complex [6,7]; see Figure 5.

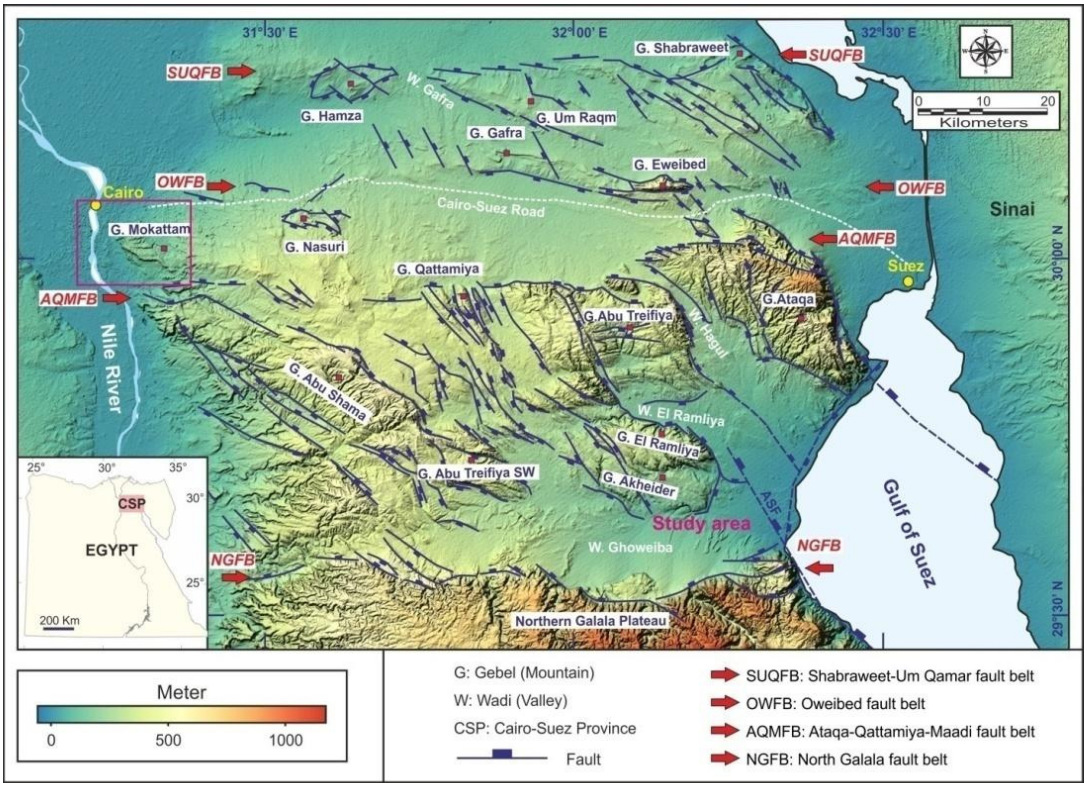

Figure 5. Shaded relief map (SRTM DEM) showing geologic faults and structural blocks along CSP (developed in this work).

Minor folding, primarily associated with faulting, is witnessed in the Gebel Mokattam area and east of Heliopolis. Proper folding is a common structural feature in the Abu Roash area north of the Giza Pyramids. The Abu Roash structure forms a part of the Syrian Arc System, a system of folds crossing the unstable shelf area of Northern Egypt. This system is believed to be due to compression in a northwest direction. As the Abu Roash structure lies on top of a significant subcrustal feature, for which there is seismic evidence and has the same southwest direction as folding, the surface structure may be a mechanical expression of this deep-seated faulting. In the Abu Roash area, some evidence of diapirism may be seen, with the subsequent development of overthrusting in some local folds with the axis running parallel to the fold axis.

3. Site Hydrology

Cairo lies in the arid belt of Egypt and is characterized by very low rainfall intensity and very high evaporation rates. The mean annual rainfall amounts to 21.4 mm, and the mean yearly evaporation amounts to 4.0 mm. In the Cairo area, the annual rainfall volume has been estimated as 39.3 million m^3, mainly in winter. This amount is almost all lost to evaporation. In rare cases, however, this area is affected by torrential winter and monsoon rains (roughly every seven or ten years), and the desert drainage lines (wadis), particularly those dissecting the Mokattam Plateau on the eastern side, become suddenly flooded. The runoff water contributes to the supply of the Nile surface water.

In the River Nile, which crosses Cairo city from South to North, the principal large volume flows of water are derived from the heavy rainfall of the Ethiopian and the Equatorial plateaux, which lie far to the south of Egypt. Artificial canals distribute this river water over the narrow strips of cultivated land on either side of the Nile.

The Late Pleistocene's coarse, massive sand and gravel unit constitutes the principal aquifer in Cairo city and its environs. With a maximum reported thickness of about 70 m, this unit occupies almost the entire area below the Nile floodplain and portions of the adjacent slightly elevated plains. The groundwater exists under semi-confined and under unconfined free water conditions. This water is found at depths varying between less than one metre below the ground surface in the northern portions and 19 m below the ground surface in the southern portions. The isopiezometric levels show a gradual decrease in the northward and westward directions. The Pleistocene aquifer in the Cairo area is of infinite areal extent, as it is connected hydraulically with the same aquifer in the Nile Valley in the southward direction and the delta in the northward direction [9]. The regional flow pattern in this aquifer is northward. However, a local anomalous flow pattern is noticed within the Cairo area between Heliopolis and the Pyramids and is either related to fault structure or to fold structures.

4. Site Geotechnical Characteristics

Knowledge of the geotechnical properties of subsoil sites, such as the stiffness of the shallow layers, is essential in various civil and earthquake engineering projects. Several different methods can be applied to estimate the stiffness of soils. Among those are drilling techniques such as down-hole and cross-hole seismic surveys. In these methods, soil resistance to penetration is measured using the standard penetration test (SPT), the cone penetration test (CPT), and surface wave analysis methods. The sub-surface geology section demonstrates the following engineering geological units in Cairo City: Although relatively little information is available about the geotechnical characteristics of such units, based on early studies [4,5], we found that most of Old Cairo, including some of Religions Complex structures, are built on the top of artificial fill layer, named Zone III (Figure 2). According to [5], Zone III occupies the central portion of east Cairo City, which extends to the foot of the Citadel and is dominantly underlain by artificial fill deposits and floodplain silt and clay. The relationship between these two units and the underlying plastic clay unit is complicated.

Data released about the laboratory testing of representative samples and geophysical surveys for different sites, respectively, from the engineering mentioned above units are so few that it is difficult to evaluate the geotechnical characteristics properly. Therefore, the characterization of this surface layer using multi-geophysical techniques is necessary, particularly at the site of interest. Artificial fill and Pliocene plastic clays are not commonly used as foundation layers in modern construction but are foundation layers for many historical sites. Hence, there needs to be more knowledge about laboratory tests.

5. Geological Hazard

Old Cairo is situated in an area that is prone to geological hazards. While it is impossible to eliminate these risks, several measures could be taken to mitigate their impact on built facilities. By identifying, understanding, and addressing these geological hazards, it is, thus, possible to protect the cultural heritage and ensure the safety of its residents.

5.1. Groundwater Rising

The rising groundwater surface is among the geological constraints that characterize the major portion of Cairo. This phenomenon is particularly manifested in the portion lying east of the River Nile, where there are indications that, since the nineteen-seventies, groundwater has risen on the order of two metres. This is principally linked to extensive urban development with the subsequent rapid increase in population. Rising groundwater has become a natural phenomenon resulting from leakage from the water supply and sewage systems, which exceeds 35% [5].

Two solutions are herein proposed to remedy the rising groundwater conditions:

- Reduction in the rate of leakage from sewage and water systems: This improvement in efficiency can be achieved only if the old pipes and connections are replaced (such an ambitious project is now underway for Greater Cairo).
- Pumped withdrawal of excess groundwater quantities by an area-wide system of relief wells: To avoid the adverse effect of ground settlement on the buildings, a maximum reduction of 1 m below the 1980 water level is proposed.

5.2. Seismicity and Seismotectonic Setting

Egypt is generally regarded as a region with low to moderate seismic activity. The geographic distribution of earthquake epicenters (Figure 6) reveals that the country has been affected by earthquakes in nearby and distant seismogenic sources. Most seismic activities are concentrated in Northern Egypt, particularly along the boundaries of the Sinai subplate, which includes the northern Red Sea and its two branches: the Suez Rift and the Aqaba–Dead Sea transform fault. Sporadic seismic activities exist even in areas away from this relatively active seismic zone [10,11].

From data available about earthquakes within about 200 km of Cairo City from 2200 BC till the end of 1978 (Figure 6), the following summarizes the general magnitude, frequency, and engineering aspects [12]: Cairo is located at a considerable distance from any significant tectonic plate boundaries, with the nearest major geological source being the Suez Rift [13]. This rift is a part of the larger Suez trend, characterized by normal faults that run parallel to the rift itself. The coastal faulting trend, identified by [14], encompasses a seismically active area along Egypt's Mediterranean coast. The authors linked the seismic activity in this region to the continental shelf and the likely presence of deep faults that align parallel to the coastline. This seismic trend is an extension of the subduction processes occurring to the north, particularly at the Hellenic and Cyprus arcs. Earthquake events associated with this trend have historically impacted Egypt, especially Alexandria. Significant recent seismic activity that has impacted Cairo include the mb5.8 earthquake of 1847 [15] and the mb5.8 Dahshour earthquake that occurred in October 1992 [16,17]. Both earthquakes originated from a seismically active region about 20 km southwest of the center of Cairo.

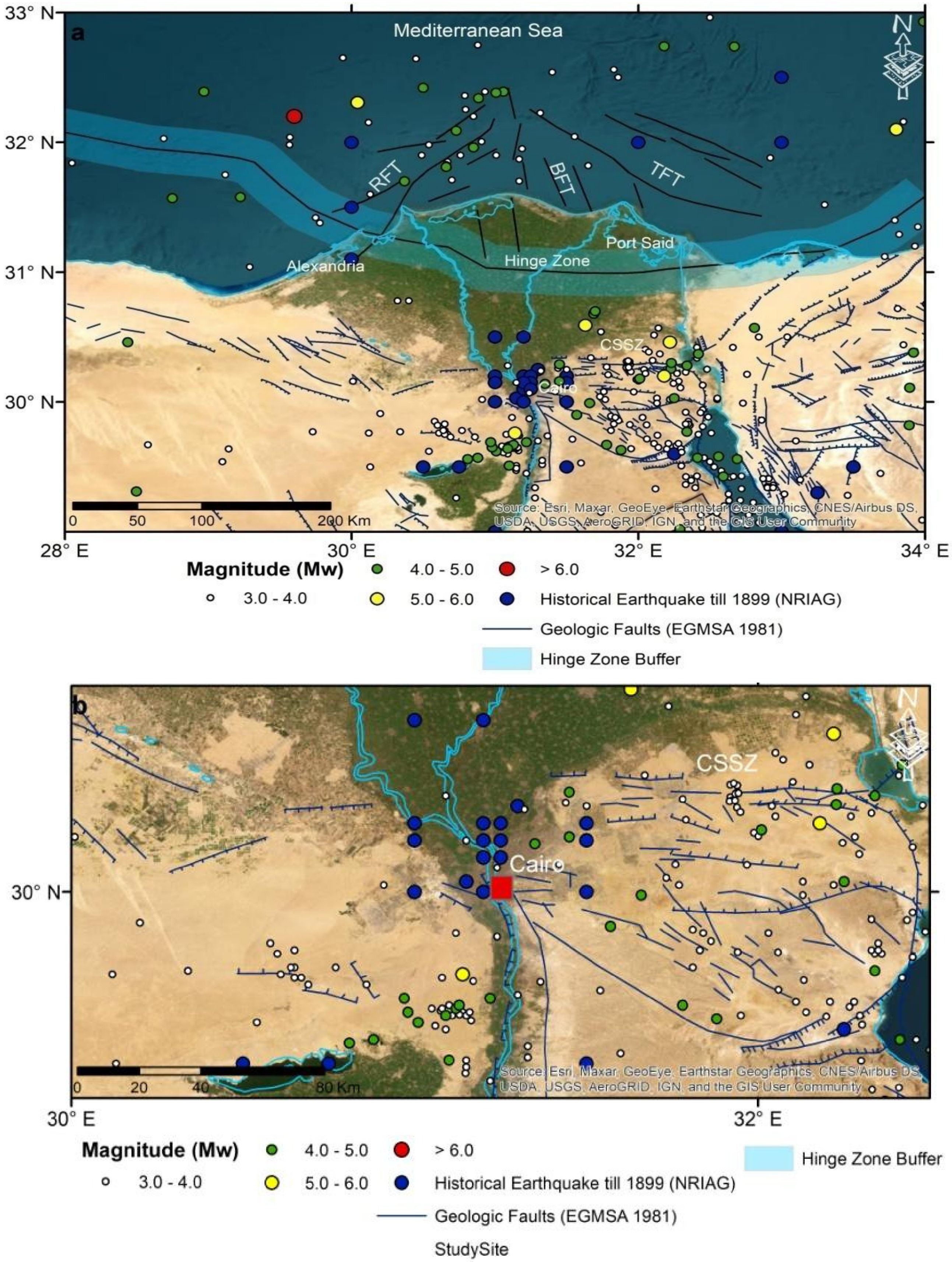

Figure 6. Regional and local seismicity maps for Cairo and its surroundings (developed in this work).

Stronger earthquakes are anticipated from the seismogenic sources located to the north and east. However, their considerable distances suggest that the shaking of the ground in

Old Cairo is unlikely to have significant consequences. Another potential contributor to earthquake tremors is the occurrence of major events in the Hellenic arc, particularly if we see a recurrence of the earthquake that struck on October 12, 1856 (Figure 6). Sieberg [18] noted that this event had an intensity of VII–VIII in Cairo. The isoseismal map created by Sieberg for this particular earthquake has been reproduced in [19], which highlights a distinct anomaly: it shows significantly higher intensity levels around Cairo compared to other areas along the North African coast, even at locations closer to the earthquake epicenter. In contrast to Sieberg's assessment, Ambraseys et al. [15] did not assign this earthquake a specific magnitude. They reported a lower impact, noting only 20 buildings collapsed in the Egyptian capital, along with an additional 200 that sustained damage.

Earthquake hazard analysis performed for Cairo suggests moderate seismic hazard [20,21] with peak ground acceleration (PGA) ranging from 0.15 to 0.3 g. However, due to the poor construction quality of buildings, the vulnerability of historical monuments, and the variable soil conditions, it is reasonable to assume that some urban areas could experience a relatively high seismic risk. A tailored multi-scenario seismic input, encompassing ground motion time histories and response spectra, has been generated for Old Cairo, taking into account the local site effect [8]. The seismic input was established through a three-step process: a first regional scale analysis, followed by a site-specific evaluation, and finally, the integration of the computed ground motion scenarios. In a later study, Hassan et al. [22] also assessed the seismic vulnerability of a well-preserved cultural heritage structure, specifically the minaret of the Madrasa of the Princess Tatar al-Higaziya in Cairo.

Moustafa and Abd-Allah [23] attributed the northern termination of the Suez Rift to the northwestward as a transfer of throw from the northern part of the rift into the Cairo–Suez Shear Zone (CSSZ) via East–West oriented pre-rift faults. They also indicated an ending of the NNW-SSE faults along western Sinai against the East–West themed fault. The CSSZ geographically extends over the northern part of the Eastern Desert of Egypt and covers the area from the northern end of the Suez Rift to the Nile Valley. This zone is affected by the late Oligocene–early Miocene deformation related to the opening of the Gulf of Suez in response to ENE-WSW-oriented extension. Meanwhile, it is probable that a part of this deformation is transferred to the land and led to the rejuvenation of the deep-seated pre-existing E-W-oriented faults by dextral transition (oblique-slip movement) in addition to NW-SE striking faults [23]. This produced E-W elongated belts of left-stepped en-echelon normal faults of about 20 km width, which overlie the pre-existing deep-seated faults of right-lateral strike-slip movement [24,25]. The CSSZ, on this basis, is characterized by several E-W elongated belts of E-W to WNW normal faults having left the stepped arrangement.

The Dahshour seismic source is located in the northern part of the Western Desert, forming an unstable shelf [4] further west of the CSSZ. The predominant structural features in this zone are faults. Abou Elenean et al. [26] indicated that this area is seismically active, as evidenced by small to moderate earthquakes. Notably, this zone's strongest instrumentally recorded earthquake occurred on 12 October 1992. The spatial distribution of earthquakes reveals that their epicenters align along a north–south direction. Abu El Nader [27] studied the focal mechanism solutions for several earthquakes in this zone and concluded that the solutions vary from pure dip-slip to pure strike-slip.

6. Seismic Vulnerability

6.1. Site Response and Amplification

Studies and reports after destructive earthquakes proved how important soil structure interaction and site effects are in determining earthquake damage distribution. Recent destructive earthquakes in the region include the 2020 Aegean Sea earthquake, the 2023

Turkey–Syria earthquakes, and the 2023 Morocco earthquake. Even when two sites have the same distance and directivity angle from an earthquake's epicenter, the intensity of the ground shaking at each location varies due to local site conditions [28,29]. As seismic waves travel from bedrock to the ground surface, their amplitude and frequency content change, passing through soil deposits due to the topography and sub-surface geology effect [28,30].

Structures built on soft sediments or artificial fill layers experienced a significant amplification of the ground motion caused by earthquakes in Cairo after the 1992 Cairo earthquake [31,32]. According to UNESCO [33], most of the historical structures in Cairo were constructed on the ruins of earlier homes and palaces. While rocky soil is more common near Mokattam Mountain, clay is more common in the lowlands [33]. Furthermore, according to [34], surface topography significantly impacts how the structure responds to seismic activity.

6.2. Evidence from Past Earthquakes

Many of Cairo's historic monuments have experienced the effects of moderate earthquakes on several occasions. It remains to be seen whether comprehensive records documenting the damage to historic landmarks and the insights gained from past experiences exist anywhere in Egypt. Historical reports typically indicate that mosques have suffered damage and destruction in earlier earthquakes. Research by [1,35,36] notes that the minarets of al-Hakim Bi-Amrillāh and al-Mansūr Qala'ūn mosques were affected during the 1303 earthquake, leading to the reconstruction of al-Hakim Bi-Amrillāh's minaret using its remaining base while al-Mansūr Qala'ūn's minaret underwent repairs. Many of the historical monuments in Cairo exhibit cracks or other signs of past seismic activity that have struck Cairo; see Table 1.

Table 1. Summary of some destructive earthquakes that struck Cairo.

Date	Impact of the Earthquake
11/885 (1,2)	It killed about 1000 people and collapsed many houses and mosques.
950 07 25 (1)	Several houses and some mosques were destroyed in historic Cairo.
26/05/1111 (1,3,4)	Many places were ruined in Cairo. The Church on the Ruda island was destroyed.
20/02/1264 (1)	Destroyed many houses in Cairo.
08/1303 (3)	The 1303 Fayum earthquake severely damaged Cairo's minarets and mosques as the minarets of al-Hakim Bi-Amrillāh and al-MansūrQala'ūn mosques.
10/1754 (5)	About 40,000 fatalities and damage to roughly 2/3 of structures.
12/10/1856 (5,6)	Occurred in the Hellenic Arc. Struck some Islamic monuments in Cairo. For instance, it caused damage to the minaret of Abu al-Ila minaret's top that fell, killing four people.
1847 (5)	Fayum was struck by another earthquake of 6.8 magnitude, which resulted in approximately 212 fatalities, 1000 injuries, and the destruction of over 42 mosques and 3000 homes.
1863 (5)	Caused damage in old Cairo to some mosques, for example, not limited to al-Mu'ayyad Shaykh minarets.
24/06/1870 (3)	Struck in Cairo and some of the Nile Delta villages.
12/09/1955 (3,7)	About 89 injuries, 18 fatalities, 40 houses were destroyed and ruined about 420 houses.
12/10/1992 (3)	Killed about 500 people, more than 6500 injuries, and about 8300 buildings suffered from damage.

(1) [37]; (2) [15]; (3) [1]; (4) [38]; (5) [39]; (6) [40]; (7) [41].

On 12 October 1992, the earthquake that struck near Cairo, Egypt, resulted in the tragic loss of approximately 540 lives, with around 6500 individuals injured and 8300 buildings either damaged or destroyed. Despite its moderate magnitude and distance from Cairo, the earthquake significantly destroyed historical monuments.

According to [42], the focal mechanism analysis reveals normal faulting and a strike-slip component. The two nodal planes are struck at N 113° E and N 175° E. Observations of the aftershock distribution indicate an NW-SE trend, suggesting that the fault plane associated with the main shock likely strikes at N 113° E with a dip of 50°. Additionally, the focal mechanism of the largest aftershock confirms a normal faulting pattern that includes a strike-slip component, with the NW-directed fault plane presumed to be the focal point. This orientation aligns with the Red Sea trend, a prevalent characteristic in the epicentral region. Badawy and Mónus [42] employed a circular rupture model based on Brune's approach, and analyzing the P-wave displacement spectra, the dynamic source parameters for the examined earthquake have been determined: stress drop = 11 bar, seismic moment = 0.04×10^{25} dyn.cm, and relative displacement = 16.5 cm at a fault length = 6.01 km. A more extended discussion of evidence from past earthquakes on historic monumental buildings for Old Cairo can be found in "Part 2" of the present study [43].

6.3. Seismic Hazard and Risk Assessment

One significant point is that only some archeological sites in Cairo have undergone seismic hazard assessments. Abd El-Aal [44] combined a deterministic seismic hazard assessment with a stochastic simulation of peak ground acceleration (PGA). He assessed site amplification, pseudo-acceleration, and fundamental frequency for the northeastern region of Greater Cairo, drawing data from three distinct seismic zones within the area of interest (Figure 7). This analysis pertains to the earthquakes that struck Cairo in 1992, 1999, and 2002. The estimated seismic motions are based on adjustments made to recordings from the main shock on 24 August 2002, located 7.7 km from the study area, to reflect the relative site response of different sites. Shear wave velocities were derived from standard penetration tests (SPTs) performed on boreholes at various schools in the vicinity, and damping values were estimated through analyses of the noise measurements taken at the investigated sites for the site response evaluation.

Abd El-Aal's findings, see [44], clearly illustrate the impact of local site conditions on the anticipated ground motion. The spatial distribution of PGA reveals that the most significant accelerations are primarily located in areas with soft soil, influenced by seismic sources at the epicentral distances of 13.2 km, 7.7 km, and 46.2 km. Models relying on natural noise measurements and lithological characteristics were examined across the investigated site and the site where the instrumental records were. Notably, from a seismic response standpoint, the two sites display similar conditions below a depth of 15 m. However, it can be inferred that ground motion levels were likely higher at the investigated sites compared to the recorded site (hard rock conditions), particularly in the frequency range of 1 Hz to 10 Hz, which is primarily attributed to the softer sediments and higher shear wave slowness present within the upper 15 m of the investigated areas. Typically, amplifications in the simulations conducted at the rock sites are about 1. In the areas under investigation, seismic motions experience amplification due to fractured geological structures and thin weathered layers. Amplification values for the sites examined range from approximately 3.45 to 6.5 Hz, with noticeable de-amplification occurring at higher frequencies due to significant near-surface attenuation effects.

Hemeda [45] studied the site of ElSakakini Palace, which is a significant historical monument in Cairo. Geophysical investigations and seismic hazard analysis were conducted to assess the characteristics of the ground response and the structure itself. According to historical earthquake intensity maps dating back to over 2200 BC, he predicts that the maximum Mercalli Intensity at the site of ElSakakini Palace will reach VII. The PGA at the rock basement, located approximately 35 m below ground, is estimated to be 144 cm/s^2 (0.147 g) with a 10% probability of exceedance over a 50-year timeframe and 186 cm/s^2 (0.19 g) over 100 years. An average velocity soil profile through various geophysical investigations was established in this study. The uppermost layer consists of artificial fill material with a shear wave velocity averaging below 300 m/s and a thickness ranging from 5 to 10 m, exhibiting relatively loose conditions. Below this layer, a clayey material has shear wave velocities between 400 and 600 m/s. At a depth of approximately 35 m, saturated, compacted sands and gravels with shear wave velocities exceeding 700 m/s were found. It is classified as the seismic bedrock for the subsequent detailed site-specific ground response analyses.

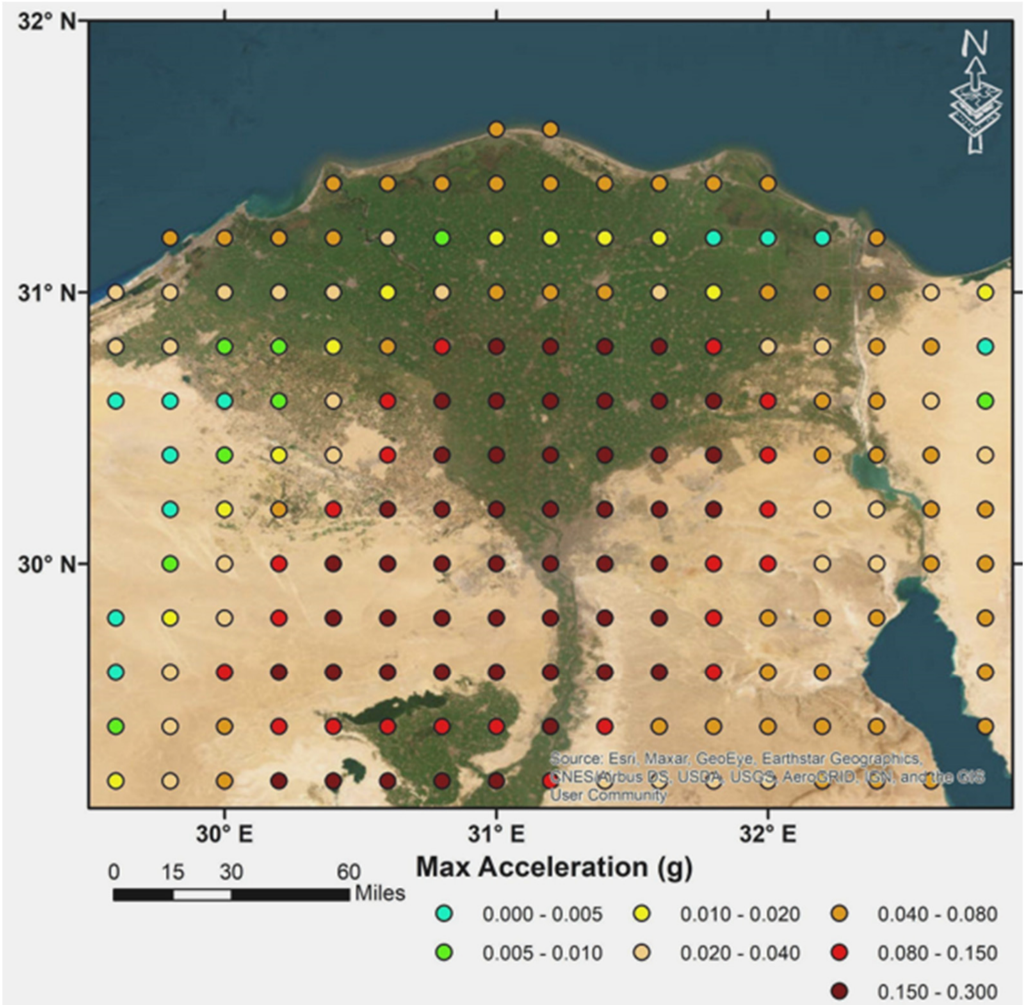

Figure 7. Seismic hazard map for Cairo and vicinity computed by Neo-Deterministic Seismic Hazard Assessment—NDSHA approach.

Khalil et al. [46] assessed the anticipated seismic hazards in Islamic Cairo using deterministic and probabilistic methods. They employed a catalog identified as the most reliable and up-to-date for the region of interest. The analysis integrated all the available data sources, each assigned varying levels of importance to address the shortcomings of the Grünthal and Wahlstrom catalog [47]. The findings indicate that nearby seismic sources with moderate to high magnitudes predominantly influence shorter periods (higher frequencies). In contrast, more distant sources with larger magnitudes have a more significant impact on more extended periods. These outcomes have been illustrated through the Uniform Hazard Spectra (UHS) and seismic hazard curves (i.e., Figure 8). The calculations suggest that the PGA for a 2475-year return period reaches 142 cm/s^2, with a maximum average spectral acceleration at 0.2 s estimated at approximately 360 cm/s^2.

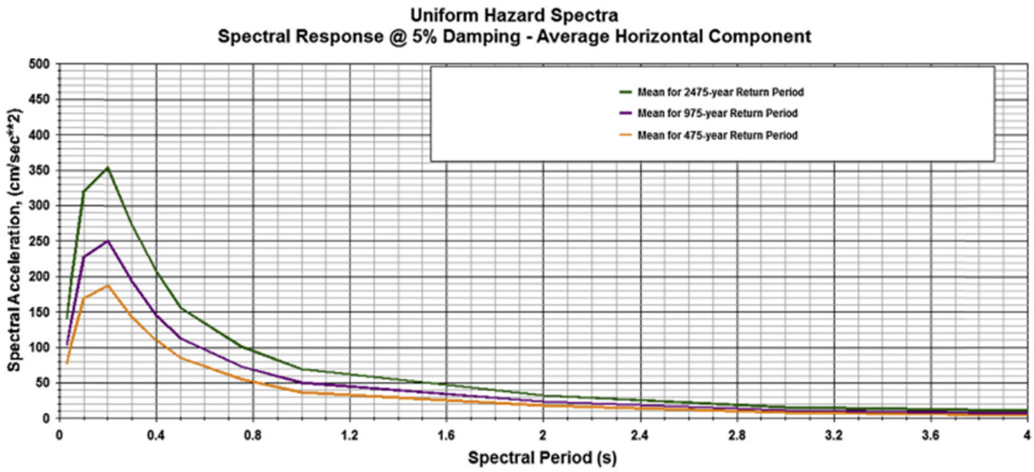

Figure 8. Uniform hazard curve for the site under consideration on bedrock (source: adopted from [46]).

Previous work in [20] on Egypt's probabilistic seismic hazard analysis reported similar findings, with an average peak ground acceleration of 150 cm/s^2. Additionally, the average spectral acceleration experiences a slight increase at a return period of 0.3 s. The deterministic seismic hazard spectra were evaluated with 5% critical damping, both median and 84th percentile. The response spectra were assessed across spectral periods from PGA to 4 s. The median PGA was estimated at around 140 cm/s^2, linked to a 6.3 magnitude earthquake originating from the Dahshour source. The seismic hazard results, particularly the 84th percentile, are recommended for designing new structures and retrofitting the existing ones in the region.

Badawy et al. [11,31] evaluated the earthquake hazard across 27 districts in Cairo utilizing the probabilistic seismic hazard assessment (PSHA) method. The findings suggest that Cairo experiences a moderate level of seismic risk, with PGA ranging from 0.08 to 0.2 g for a return period of 224 years and from 0.1 to 0.3 g for a return period of 4745 years. These observations are aligned with earlier studies conducted by [13,20,48].

Badawy et al. [31] also estimated, for the 27 districts of Cairo, the percentage of possible damaged buildings in case of seismic event; see Table 2. It is worth mentioning that the Religions Complex area is already included in the Masr El-Qadima (Old Cairo) district. The resulting seismic hazard maps, in particular, revealed that the eastern region of Cairo exhibits higher PGA values than the northern and western areas.

This indicates that seismic activity related to northeastern earthquake dislocations, such as the Cairo–Suez district, may pose a more significant threat than those in the southwestern regions, like Dahshour. Badawy et al. [11] mentioned that the height of buildings primarily influences spectral periods. Their analysis indicates that five stories or fewer structures tend to have higher PGA values than taller buildings.

Consequently, these shorter constructions require reassessment to determine the necessary measures for seismic retrofitting. Furthermore, the disaggregation analysis in this study provides insights into the contributions from both near-field (first-order) and far-field (second-order) seismic sources surrounding Cairo. The lateral impact of soil, observed from the western El Sharabiya district to the eastern El Nozha district, is highlighted in these findings.

Table 2. Expected number and percentage of damaged buildings in the 27 investigated Cairo districts according to the study by [31].

District	Concrete No.	Concrete %	Concrete Risk Level	District	Unreinforced No.	Unreinforced %	Unreinforced Risk Level
El-Nuzha	73	0.88	Very high	Ain shams	4	0.18	Very low
El-Matariya	97	1.17	Very high	El-Nuzha	9	0.4	Low
Wassat (center)	132	1.59	Very high	Al-Marg	11	0.49	Low
Egypt El-Gadida	141	1.7	Very high	Rood-El Farag	27	1.2	Medium
El-Mosskey	163	1.97	Very high	Bolaq	33	1.47	High
Manshiyat Naser	169	2.04	Very high	Bab El-Shariya	37	1.64	High
Bab El-Shariya	183	2.21	Very high	Shubra	44	1.95	High
Bolaq	223	2.69	Very high	Madinat Nasr Garb	46	2.04	High
Shubra	230	2.77	Very high	El-Mosskey	52	2.31	Very high
Rood-El Farag	238	2.87	Very high	El-Zawia El-Hamra	54	2.4	Very high
El Khalifa	247	2.98	Very high	El Sharabiya	55	2.44	Very high
Madinat Nasr Sharq	253	3.05	Very high	Wassat (center)	69	3.06	Very high
Ain shams	262	3.16	Very high	El-Matariya	71	3.15	Very high
El-Zawia El-Hamra	268	3.23	Very high	El-Waily	77	3.42	Very high
Aabdeen	280	3.38	Very high	Masr El-Gadida	89	3.95	Very high
El-Waily	289	3.49	Very high	El Sahel	91	4.04	Very high
Hdayek El-Qobba	333	4.02	Very high	Hdayek El-Qobba	93	4.13	Very high
El Zaitoon	363	4.38	Very high	El Zaitoon	94	4.17	Very high
El Sayeda Zeinab	411	4.96	Very high	Aabdeen	99	4.4	Very high
Al-Marg	433	5.22	Very high	El Sayeda Zeinab	101	4.48	Very high
El Sharabiya	436	5.26	Very high	Madinat Nasr Sharq	140	6.22	Very high
Madinat Nasr Garb	498	6.01	Very high	El Basateen, Dar El-Salam	145	6.44	Very high
Gharb	512	6.17	Very high	Gharb	164	7.28	Very high
El Sahel	553	6.67	Very high	ElKhalifa	169	7.5	Very high
Masr El-Qadima (Old Cairo)	610	7.36	Very high	Manshiyat Nasser	182	8.08	Very high
El Basateen, Dar El-Salam	895	10.79	Very high	Masr El-Qadima (Old Cairo)	296	13.14	Very high
Sum 1.20%	8292	4.42%			2252	1.20%	

Hemeda [49] conducted geophysical studies and seismic hazard assessments to obtain the shear strength based on S-wave velocity and determine the average bedrock depth at the Ben Ezra Synagogue in Old Cairo. The findings revealed that the S-wave velocity outside the synagogue is approximately 900 m/s at an average depth of about 6.5 m, increasing to 1600 m/s at depths ranging from 15 to 28 m. Consequently, the bedrock velocity at the synagogue site was estimated to be between 4 and 6 m (by USGS, which considered an S-wave velocity greater than 765 m/s indicative of bedrock). This study indicated a moderate level of seismic activity at Ben Ezra Synagogue, providing two key types of maps for Ben Ezra Synagogue: the “Maximum Intensity Zonation Maps” and the “Iso-Acceleration Contour Maps”. Based on PGA measured in Gals (cm/s^2), the hazard assessments at the synagogue revealed a moderate hazard rate of 0.15 g for a 10% probability of exceedance over 50 years and 0.2 g for 100 years. Such a level of PGA (PGA > 10% g) is significant for engineering considerations. Hemeda also declared that the Ben Ezra Synagogue falls into the highest seismic risk category, known as “Rsl” as per the technical legislation in Egypt. This classification indicates a substantial risk of collapse with an earthquake according to the code of the seismic intensity relevant to Cairo (a = 0.16 g). Hemeda [49] selected the 1992 Cairo earthquake as the most suitable event for developing a design response spectrum for the Ben Ezra Synagogue, as it is situated in the most seismically active area nearby. He found that the maximum acceleration response spectrum recorded for Ben Ezra Synagogue reaches approximately 100 cm/s^2 for an oscillator with 5% damping at its fundamental resonance frequency. Similar levels of spectral acceleration, around 0.1 g, are observed at the other resonance peaks associated with the roof. These findings align well with the probabilistic PGA estimated for the exposure durations of 50 and 100 years, which range from 0.15 to 0.2 g.

Hassan et al. [22] assessed the seismic hazards in historical Cairo, which encompasses the analysis of sources, the propagation path of seismic waves, and potential local site effects. A comprehensive ground motion modeling uses a hybrid method that integrates modal summation with finite difference techniques to obtain site-specific seismic input in response spectra for a cultural heritage site. For this analysis, three earthquake scenarios were considered, and calculations were conducted along three site cross-sections (two in the North–South direction and one East–West). Synthetic accelerograms, generated based on physical principles, were computed along the selected profiles. The calculations performed using the 1D model illustrate ground motions at the bedrock level, excluding the influence of local site conditions. The ratios of response spectra between the 2D and 1D model results highlight the impact of sub-surface topography at the selected cross-sections. These ratios indicate that the locations featuring steeper transitions in their geometric sub-surface profiles exhibit more excellent amplification effects. Specifically, the maximum response spectral ratios for the site of interest fall between 2 and 5, occurring within the frequency range of 1.0 to 7.0 Hz. Upon assessing these amplification values, a site-specific multi-scenario seismic analysis was conducted for a cultural heritage building, considering local effects, including the horizontal and vertical variances across cross-section profiles. The focus of the study was the madrasa (which means "school" in Arabic) built for Princess Tatar al-Higaziya. Hassan et al. [8] also mentioned that according to a report by the Japanese Expert Team [50] on earthquake damage, one- and two-story adobe buildings suffered significantly during the seismic event, resulting in over 500 fatalities. The observed damage of these low-rise structures suggests that site amplification may occur at higher frequency ranges, aligning with the study's findings. In contrast, high-rise constructions, such as brick kilns with masonry smokestacks about 20 to 30 m in height, are prevalent throughout the Nile Valley. Yet, none were documented as having collapsed during the earthquake.

Hemeda [51] investigated the Abu Serga Church site. He detected the shear wave velocity is approximately 1000 m/s at an average depth of around 3.5 m. In contrast, outside the Abu Serga Church, the measured S-wave velocity is about 900 m/s at an average depth of roughly 6.5 m. This difference is likely attributed to the varying ground levels, which are elevated by approximately 2 to 4 m outside the church. Accordingly, the bedrock velocity at the Abu Serga Church location is estimated to be between 4 and 6 m. This aligns with the USGS guideline 1980, which established a bedrock velocity threshold of over 765 m/s. He calculated the return periods for seismic events with magnitudes of $M \geq 5$, $M \geq 6$, and $M \geq 7$ in the areas most impacted around Abu Serga Church. The hazard maps for Abu Serga Church, based on peak horizontal acceleration measured in Gals (cm/s^2), indicate a moderate hazard level with rates of 0.15 g for a 10% probability of exceedance over 50 years and 0.20 g over 100 years. Hemeda [51] selected the 1992 Cairo earthquake as the most suitable event for developing a design response spectrum for Abu Serga Church. He mentioned that, typically, at higher frequencies greater than 10 Hz (with a short period of 0.1 s), the acceleration response approaches its peak value of 40 cm/s^2 as noted in the original time history. In contrast, at lower frequencies below 0.1 Hz (representing an extended period), the displacement response approaches the maximum displacement recorded in the initial time history. With an increase in damping, the overall response diminishes, resulting in a smoother response spectrum. A key point that has to be noted is that the maximum acceleration response spectrum for Abu Serga Church corresponds to its fundamental resonance frequency of 5.5 Hz, which reaches approximately 100 cm/s^2 with 5% damping in the soil. Furthermore, the spectral acceleration for the resonance peaks associated with the second and third floors remains relatively consistent at around 0.1 g.

7. Conclusions

For several reasons (such as identity and connection, economic benefits, educational value, ethical responsibility, and sustainable development), cultural heritage conservation and protection represent a pillar of societies and governments. Cultural heritage provides a tangible link to the past and fosters a sense of community and belonging. It is generally recognized that well-preserved cultural sites attract tourism, generating revenue and supporting local economies. Cultural heritage serves also as a living museum, offering valuable educational opportunities for both locals and visitors. It promotes knowledge exchange and cross-cultural understanding. Many cultural sites hold immense historical and spiritual significance for communities.

In these conditions, it is clear that integrating cultural heritage conservation into development plans can promote sustainable tourism, revitalize urban areas, and enhance the quality of life for residents. The risks to cultural heritage come in fact in various forms, ranging from abrupt and disastrous events such as earthquakes, floods, fires, and armed conflicts to gradual and cumulative processes due to geotechnical conditions; chemical, physical, or biological deterioration; and even a combination. These risks, often combined, lead progressively to a diminished value of heritage assets. For instance, if a historic building catches fire, it typically results in a substantial or complete loss of value for the structure and its contents. Similarly, the overall worth is compromised if heritage buildings or sites are damaged during an earthquake.

Moreover, some threats do not manifest through direct physical damage but instead involve the cascade impacts on the heritage site or the loss of access to local sites and geotechnical conditions. Also, an archeological site may only accept value if inadequately documented. It is, thus, crucial, in support of heritage managers, administrations, and technicians, to establish a multidisciplinary inventory of the information and datasets of historical sites and make it possible to comprehend these risks thoroughly. In this case, it will be possible for them to make informed decisions to safeguard the cultural legacy for future generations, protect customers, and ensure access for present audiences.

In this study, the focus was specifically on the cultural heritage of Old Cairo and its proactive preservation against seismic hazards. Although Cairo is characterized by low to moderate earthquake hazard, it has high risk. Moreover, multiple influencing factors (regarding site effects and building features) make this goal even more challenging and complex, requiring a multidisciplinary intervention and strategy plan.

A detailed soil investigation is the first basic step in providing an initial evaluation of the physical condition and structural integrity of the site of intervention. Geophysical and seismologic aspects are also fundamental and interconnected influencing parameters, which should be considered adequately for seismic vulnerability assessment and retrofit of the cultural heritage.

In this research contribution, attention was given to the multidisciplinary analysis of significant factors and literature studies that—in the decades—focused on the seismic hazard estimation and classification of Cairo city. As shown, whilst many specific studies are available in the literature, some gaps still exist in the application (at the small and large scale) of robust seismological and engineering approaches for the seismic vulnerability analysis of historical buildings and monuments in Cairo, and CoReng will promote these developments.

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