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Multidisciplinary Approach of Proactive Preservation of the Religions Complex in Old Cairo—Part 2: Structural Challenges

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Abstract: Old Cairo, also known as Islamic Cairo, is a UNESCO World Heritage Site representing a rich tapestry of history and culture. Today, among various significant aspects, its cultural heritage necessitates the elaboration of a proactive conservation strategy, which should take advantage of the intrinsic support provided by the efforts documented in the literature that have been made in several scientific fields, disciplines, and directions over the years. Most historic religious monumental buildings in Old Cairo, in particular, not only face the effects of local seismic hazards, which are emphasized by damage by past earthquakes, but also suffer the consequences of several influencing parameters that are unique to the Cairo city context. In this sense, it is known that the structural retrofitting of these monumental buildings requires sound knowledge of technical details and criticalities, based on inspections, numerical simulations, the in-field integration of technologies, and laboratory tests. Many other gaps should also be addressed, and a sound conservation strategy should be elaborated on the basis of a multi-target approach, which could account for the structural engineering perspective but also contextualize the retrofit within the state of the art and the evolution of past events. This is the target of the contemporary “Particular Relevance” bilateral Italy–Egypt “CoReng” project, seeking to define a multidisciplinary strategy for conserving Old Cairo’s cultural heritage and focusing primarily on the case study of the Religions Complex. To this end, a review analysis of major oversights and challenges relating to historic monuments in Old Cairo is presented in this paper. Learning from past accidents and experiences is, in fact, the primary supporting basis for elaborating new operational steps and efficient approaches to mitigating challenges and minimizing the consequences of emergency events. As such, this review contribution specifically focuses on the structural vulnerability of historic monumental buildings in Old Cairo, reporting on past efforts, past strategy proposals, research experiences, and trends.

Keywords: seismic risk; seismic vulnerability; heritage conservation; retrofit; technology



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1. Introduction

The historic monumental stock in Old Cairo includes a multitude of architectural forms, like mosques, madrasas, hammams, sabils, and fountains (Figure 1), which have coexisted for centuries, but each belongs to different ages, employs different constructive

and structural technologies, and consequently requires different conservation skills and strategies [1,2]. Presently, the structural health conditions of many of these historic monuments are progressively deteriorating, and the reason can be found in a multitude of natural and artificial factors. First of all, Egypt is classified as an area of moderate seismicity, with a number of well-known past earthquake events throughout its history [3,4]. Moreover, the combination of several influencing parameters (i.e., groundwater, weak building conditions, limited seismic resistance, absence of maintenance, protection, and preservation policies) may lead these monuments to more complicated and irreparable conditions. In such a critical scenario, even a modest earthquake could cause significant and irreparable damage to Cairo's monuments.



Figure 1. Examples of monumental buildings and architecture in the city of Cairo (figures reproduced with permission, under the terms and conditions of ©Unsplash).

Among other sites, the Religions Complex represents a testament to the rich and diverse history of Cairo, encompassing places of worship for the three Abrahamic faiths—Islam, Christianity, and Judaism [4]. Over the past few years, several significant advancements have been made in the heritage revival and restoration of archeological sites here. However, much more could be accomplished with enhanced technical knowledge and the availability of new technologies, along with their sound application to monumental buildings. In this context, the contemporary bilateral Italy–Egypt “CoReng” project aims to establish a multidisciplinary and integrated methodology for conserving the Religions Complex in Old Cairo [4].

The basic assumption of the present study—which represents, along with [4], a starting step in CoReng’s plans—is that preserving the Religions Complex is a national obligation and a shared global responsibility if we are to safeguard collective cultural heritage. Its proper preservation, however, requires a comprehensive understanding of the current situation in Old Cairo, focusing on a complex site and taking a multidisciplinary view of the problem, joining geoscientific and technical engineering knowledge, along with much more. While geoscience and seismological experts can provide a more realistic description of seismological aspects and thus offer a robust estimation of the seismic hazard at the Old Cairo site [4], additional skills are in fact required to elaborate an efficient conservation methodology. Major efforts should thus be made to design a work plan that could fill these existing multidisciplinary gaps and help us to achieve proper risk assessments. Moreover, in doing so, this strategy should account for the specific features and criticalities of the Cairo context. In this sense, the present document offers a comprehensive review that could support the elaboration of a site-specific inventory of multidisciplinary studies to aid in the conservation of Old Cairo and thus assists in raising the current level of knowledge and offering a basis for future studies.

Differing from [4], where the attention was dedicated to geoscience aspects of the Cairo site, this review article focuses specifically on structural engineering challenges that

should be taken into account for the conservation and retrofit of Cairo's monumental buildings. To this end, the following sections briefly report on past conservation efforts and strategies, shortly recalling the spatial and temporal distributions of historic monuments, with their architectural features, as well as their present conditions. Knowledge of their vulnerability, with a view on the most important factors influencing their stability and longevity, is a basic but challenging step for the elaboration of further strategies. At the same time, structural engineering studies that assessed the seismic vulnerability of selected buildings and components are briefly reported. As shown, the description of a robust Finite Element (FE) structural model can be particularly challenging and uncertain due to multiple factors. At the same time, however, it is a basic need for the elaboration of vulnerability and retrofit considerations.

Extracting valuable lessons from historic monuments can also help to efficiently design a robust approach for the Religions Complex, as well as possibly adapting it in the future to other relevant cultural heritage sites.

2. Past Conservation Efforts

In 2008, the UNESCO mission reported that many conservation studies and initiatives had been elaborated for the city of Cairo in the previous decades [5], focusing on the restoration of historically relevant monuments and urban areas. As stipulated by Article 5 of the Convention concerning the Protection of World Cultural and Natural Heritage [5], in particular, the State Parties were expected to implement legislative and regulatory frameworks to protect their World Heritage Sites. Consequently, the Egyptian government has enacted several decrees and laws to support the safeguard of the historic city.

Among various influencing factors, the moderate 5.9-magnitude earthquake that struck the city of Cairo in 1992 was generally recognized, over the years, as one of the most important threats (see [5–7] and Figure 2). A major response to some concerns raised by an International Council on Monuments and Sites (ICOMOS) monitoring mission—regarding the urban and architectural heritage after the 1992 earthquake [8]—come from the Ministry of Culture (MoC), which organized an International Symposium on the Conservation and Restoration of Islamic Cairo, held in February 2002 [9]. This event brought together conservation experts to discuss the challenges of preserving cultural heritage in Old Cairo as a vibrant urban environment [10].



Figure 2. Example of historic monument in Old Cairo, after the 1992 earthquake. Photo by the authors.

2.1. Conservation of the Old City of Cairo (UNESCO Study, 1980)

Between February and August 1980, UNESCO consultants conducted a comprehensive study of Islamic Cairo [11]. This study underscored the historic city's multifaceted challenges, such as inadequate infrastructure, soaring land prices, affordable housing shortages, evolving market dynamics, and transportation difficulties. Given the scale and density of the designated area, the study recommended prioritizing conservation efforts in six pivotal clusters encompassing significant monuments and architectural ensembles. Furthermore, the study acknowledged the importance of social, economic, and environmental factors in enhancing the quality of life.

2.2. Revitalization of Historic Cairo (UNDP and SCA, 1997)

In 1997, a significant initiative was launched by the United Nations Development Program (UNDP), in collaboration with the Supreme Council of Antiquities (SCA), to establish a cohesive urban conservation strategy for historic Cairo. The reason was the Dahshour earthquake, which had an intermediate magnitude and epicenter up to 30 km from historic Cairo. The UNDP and SCA report [12] emphasized the interconnectedness of various activities, transportation, and infrastructure systems as crucial elements shaping the perception of this World Heritage Site. The proposed Framework Plan revolved around a rehabilitation strategy organized into five key urban zones (Figure 3). Urban policies were recommended to facilitate the effective implementation of these rehabilitation strategies, while fostering community engagement, which was recognized as a vital approach to preserving the exceptional value of historic Cairo [13]. This report represented (and still does) a significant reference for large-scale urban rehabilitation initiatives in the city.

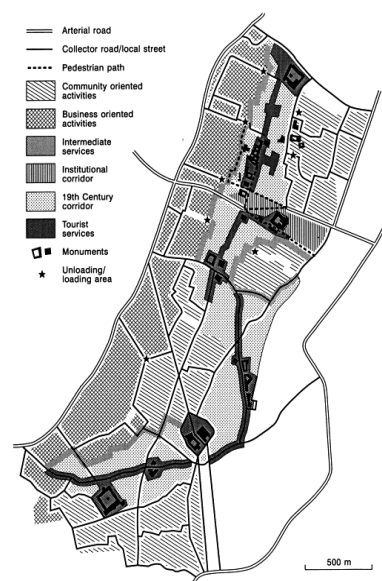


Figure 3. UNDP rehabilitation plan. Adapted from the UNDP and SCA report [12] with permission.

2.3. Old Cairo Rehabilitation Initiative (Mugamma' al Adyan, 1999–2002)

The Mugamma' al Adyan project represented an important conservation initiative, focusing explicitly on Old Cairo's al-Fustat district. Funded by the Ministry of Tourism (MoT) and executed in partnership with the Cairo Governorate, the initiative involved the renovation of approximately 350 buildings, including residential and commercial properties. This project also aimed to enhance public services and improve open spaces within the neighborhood, particularly along the streets bordering the Coptic Quarter. Strong emphasis was placed on community involvement, encouraging residents to actively participate in the rehabilitation process.

A key aspiration of the project was to rejuvenate Old Cairo's traditional arts and crafts. To this end, a new center for traditional crafts (Suq al-Fustat) was established between the mosque of Amr ibn al-As and the Coptic Cairo complex, utilizing traditional materials to highlight the region's heritage. Al-Fustat, historically celebrated for its exceptional pottery workshops, saw many artisans relocating due to the city's expansion. In response, the MoT aimed to revive this iconic Egyptian craft by establishing a new pottery village. The project's efforts continued in 2003, supported by funding from the Italian–Egyptian Debt for Development Swap Program, and the initiative was completed in 2006.

3. Seismic Vulnerability of Historic Monuments in Old Cairo

3.1. Basic Needs

To design a proactive conservation strategy for Old Cairo monuments, the literature analysis shows that a comprehensive database of historic buildings, as well as a sound revision of their seismic vulnerability, is still lacking. Such a database would represent an essential tool and important preliminary step for effective heritage conservation, risk assessment, and emergency management purposes. Such a database could in fact help to detect those monuments that are most susceptible to seismic damage. Also, it would implicitly allow for the focusing of conservation efforts on the most vulnerable structures, ensuring optimal use of financial resources. Such a database would be even more important in the case of a new earthquake, since it would represent (i) quick access to information about the condition of monuments for technicians, (ii) a tool for the public administrations, and (iii) a contact with the community, to inform them about the high risks that historic monuments suffer and the strategic importance of their preservation.

Only by understanding the seismic vulnerability of historic monuments in Old Cairo, new, efficient, proactive measures can in fact be established to mitigate these intrinsic risks and contribute to the long-term sustainability of cultural heritage. This is the direction that CoReng team members plan to support.

3.2. Inventory of Historic Religious Monuments

A sound structural and retrofit analysis of Old Cairo's historic monuments must necessarily respect the city's history and its major evolution periods, given that they are strictly characterized by the use of different architectural choices, construction materials, technical solutions, and structural typologies.

3.2.1. Coptic Period

Orthodox Christianity in Egypt dates back to the 1st century AD. The Coptic architecture in Cairo developed from the Christian basilica style and was influenced by the Byzantine style [14]. Churches were typically constructed with oblong masonry bricks, with side aisles separated by Roman or Greek columns and covered by a dome roof style like the Byzantine or wagon-vaulting Roman roof style, as in Christian architecture [15]. Some columns were used to support the nave's walls, while others were arranged in cross rows, forming the narthex [15]. The sanctuary has a raised platform with a wooden screen and railing, and three chapels called haikals. These early churches were orientated primarily east–west and then to the east, with a triple-door entry to the west [15,16]. Coptic churches, more often, have chapels and niches added in later, distinguishing them from other churches. Later on, Coptic churches developed their architectural styles mostly internally, rather than externally, with an orientation that matched the direction of the streets, similar to the architecture of mosques [15].

Churches in old Cairo can be found with square and rectangular floor plans (Figure 4). Their layout combines the basilica and the Byzantine styles. According to [16], some of

these churches have a rectangular layout that consists of a main façade and a transverse vestibule entrance, with longitudinal structures and porticoes, such as those that can be seen in some monuments of Old Cairo (e.g., Hanging Church, Barbara Church, and Abu Seifin Church). Other examples with a typical square layout are not very common (e.g., the Church of Prince Tadros Al-Mashriqi). Most of these churches underwent renovations after being damaged in the Fustat burning during the reigns of Harun al-Rashid (Abbasid era) and Al-'Aziz Billah (Fatimid era); see [16].



Figure 4. Examples of Coptic Cairo monumental buildings. (a) Hanging Church, (b) The Church of Mar Girgis (St. George).

3.2.2. Islamic Period

The Islamic period is characterized by the presence of numerous monuments in Old Cairo that reflect different civilization layers and styles, inherited by a succession of governments. The Arab conquest (639 AD), the founding of the Fustat City (641 AD), and the Amr ibn al-As mosque marked the beginning of Islamic architecture in Cairo. The Islamic ruling society is typically divided into five main periods, starting in 827 and lasting until 1848.

Among the numerous archaeological monuments that can be found in Cairo, as a result of the evolution of Islamic architecture throughout time, typical examples include several mosques and *madrasas* with a multitude of *minarets* but also many other public, administrative, and residential buildings, *sabils*, bathrooms, and fountains [1]. Table 1 summarizes some Islamic monuments found in Cairo, according to the Egyptian Ministry of Antiquities [17], while a glossary of architectural terms is also reported in [15]. Figure 5a presents a typical example of the period, and the Amr ibn al-As mosque is also part of the Religions Complex.

Table 1. The total number of monuments in the city of Cairo, according to the Egyptian Ministry of Antiquities [17].

Monument Type	Number	Description
Dome–cemetery–mausoleum–Mashhad–tomb	140	Sanctuary or shrine
Sabil	121	Drinking fountains, usually for public charity
Masjid–Jami’–mosque	115	Masjid is the origin word of mosque, which is a prostration place (Jami’ is a congregation mosque)
Churches and synagogues	10	Mainly located in Cairo and Sinai
Kuttab	80	A charitable foundation used as a primary school to teach children how to write, read, and recite the Qur’an
Bayt/palace	62	“Abayt” is the Arabic term for “house”

Table 1. Cont.

Monument Type	Number	Description
Madrasa	41	Higher education institute for religious sciences
Bab	24	Gate of the city (or for part of it)
Minaret	21	Slender structure/tower to call for prayers
Corner	16	Corner
Khanqah	13	A monastery of Sufi order
Coptic churches	10	Coptic and Christian monuments, mainly located in Coptic Cairo
Tikiyya/Tekke	7	Sufi hospice replacing the term “khanqah”. It is an open courtyard with arcades, having sides of small rooms (i.e., cells) on its four sides, a small mosque, and a graveyard
Iwan	4	Vaulted open hall with an arched or rectangular façade (entrance of mosque or prayer hall, or prayer hall itself)
Maristan/Bimaristan	2	Hospital (derived from Persian)
Citidal–Castle	2	Fortress/castle
Burj	1	Fortress tower (or city walls with towers)



Figure 5. Examples monumental buildings in Cairo: (a) Amr ibn al-As mosque (the first and oldest mosque ever built in Egypt) and (b) Ahmad Ibn Tulun mosque. Photos by the authors.

Tulunid Period (641–904 AD)

The architectural styles of Samarra, Baghdad, and Damascus influenced Tulunid monuments. The only surviving example of this period, in Old Cairo, is a Samarran-style mosque (Ahmad Ibn Tulun; Figure 5b). This mosque was constructed with well-fired red brick, stucco coverage, and fine plaster decoration [18]. It is a mosque with a large *sahn* (courtyard), a flat hypostyle roof, and a unique minaret style, with exterior stairs around the square base that convert into a spiraling stair in the upper part, according to a Mabkhara top style (i.e., incense burner-shaped); see [19].

Fatimid (969–1171 AD)

Cairo rose from a provincial town to an imperial capital during the Fatimid period, and Fatimids helped to shape the native Cairene architectural style, with many mosques, gates, and *shirns* being rapidly constructed. Stone was used for structures in place of bricks, combining elements of Samarran, Byzantine, and Coptic architecture [20]. Mosques started to be orientated towards the street, with minarets directly above the main portal (as in the original al-Aqmar and al-Juyushi mosques), including a typical square base (of moderate height), converting into cylindrical and then octagonal section, and a Mabkhara top. The latter represented a typical solution for about two centuries [21].

Ayyubid (1171–1250 AD)

The city walls were expanded by the Ayyubids in 1169, and a Citadel was constructed in 1183 above Mokattam hill for defense against the Crusaders. Several structures, such as *madrasa* and *khanqah* types (of Sufi order), were constructed. The *madrasas* were established in palaces, mosques, and houses that combined domestic and religious architectures [20]. The Ayyubid minarets of this period are typically taller and more slender than earlier minarets. They have a square base, an octagonal section, and a Mabkhara top. Unfortunately, the only surviving minaret belongs to the *madrasa* of al-Salih Najm al-Din Ayyub [19]. It is considered the ancestor of the Bahri Mamluk minaret style [22].

Bahri Mamluk Period (1250–1382 AD)

The late 13th and early 14th centuries witnessed the dynamic evolution of Islamic architectural design. Bahri Mamluk's architectural style was primarily derived from the Fatimid and Ayyubid ones. The number of congregational mosques (i.e., Friday mosques) rapidly increased, and their typical layout was characterized by the presence of an hypostyle with off-axis main entrances [20].

The funerary architecture increasingly gained more importance. Several mausoleums with large domes were built and frequently added to mosques. Earlier domes were typically characterized by tiers of squinches alternating with niches and windows, all sharing a similar shape. Pendentives were subsequently employed, initially in stone and then in wood [20].

Regarding the style of minarets, the earlier Mamluk ones were built similarly to the Ayyubid period. A marked evolution appeared only in the late 13th century, with the introduction of hexagonal and octagonal second levels, as in the Fatima Khatun minaret (1284 AD). In the 14th century, the typical Mamluk minaret further evolved into an even more slender structure, with the third level as in Sanjar al-Jawli (1304 AD); see [21–23]. The most important innovation of this period was indeed represented by replacing square/rectangular base sections with octagonal ones and combining them with a cylindrical story, to create smoother transition zones [22]. Moreover, the typical Mabkhara-style top was replaced by *jawsaq*, i.e., a pavilion with eight columns holding a crown, having a bulb-shaped pear, sphere, or onion [21].

Circassian or Burji Mamluk Period (1382–1517 AD)

The second Mamluk dynasty was established in 1382 after the Last Bahri sultan was overthrown by a group of Circassians in the army [15]. The Circassian Mamluks followed the earlier Mamluk period in constructing mosques and madrasas for education and charity. Cairo grew so densely by the fifteenth century that Circassian Mamluk monuments were typically built on small, irregular, vacant lands [15].

Most Burji Mamluk minarets are slender structures with octagonal shafts, followed by a circular section and a *jawsaq* top [21]. Starting from the al-Mardani minaret, the octagonal style for all levels reappeared only in al-Ghawri's minaret (1502 AD), with a modification of its top [22]. This top change is a significant feature especially for the last Mamluk minarets, for example, the al-Ghawri's complex (1502 AD), the Qanibay al-Rammah mosques (1503 AD), and the minaret of al-Ghawri at al-Azhar.

Ottoman Turk Era (1517–1848 AD)

Cairo was lowered to the status of a provincial capital after falling to the Ottoman Turks in 1517. About 100 religious buildings called *sabils* and *kotabs* were constructed by using the Ottoman and Mamluk styles. These are freestanding structures with curved façades and loggias of Turkish influence.

Takiyyah, a new shape of *khanqah*, was developed, wherein a courtyard was encircled by cells situated apart from the mosque. During the Ottoman reign, moreover, mausolea

and funerary domes were not erected. Such a change aligned with the return of mosque domes, which became flatter and round with no transition zones.

The Turkish mosque style was introduced to have slender minarets and flat, round domes, created by renowned 16th-century architect Sinan. The mausolea resurfaced with domes shaped like onions.

An architectural development of the minaret style with a pencil-shaped shaft appeared after the conquest by the Ottomans, who brought their craftsmen to Egypt [22]. Ottoman minarets had a square base and a polygonal shaft, with conical caps like the Sulyman Pasha mosque (1528 AD) or the Sinan Pasha mosque (1571 AD). A remarkable improvement appeared in Muhammad Ali's minarets (1848 AD), which had a very slender appearance. The Sulyman Pasha minaret in the Citadel was placed next to the portal, a relatively uncommon feature for both the Mamluk and Ottoman minaret styles. Four minarets with Mamluk style were also constructed as a revival of this style, like the Shaykh al-Burdayin minaret (1629 AD), the al-Kurdi minaret (1732 AD), the Abu-l'Dahab minaret (1774 AD), and the Hasan Paha Tahir minaret (1809 AD).

4. Seismic Structural Challenges for Heritage Conservation in Old Cairo

In general terms, it is well known that the poor structural performance of historic monuments can be justified by a variety and combination of factors. These can include the use of weak construction materials, inadequate design and detailing, and the lack of appropriate maintenance, or deficiencies in craftsmanship, among many others. Some of these factors are separately discussed in the following sections.

4.1. Constructional Materials

Islamic monuments in Old Cairo are mainly composed of unreinforced masonry. According to [15], brick and plaster were frequently used for exterior and interior walls, especially in the early pre-Fatimid period. During the Fatimid era, limestone became common in interior and exterior walls and essential structures, and brick and mortar were used for the interior walls of madrasas, *bayts* (houses), and *maristans* (hospitals).

Behrens-Abouseif [22] and Khallaf [23] pinpointed that limestone was the most used construction material in the Islamic period. Bricks were also the standard choice for the construction of earlier minarets. Indeed, for the *Mabkhara* style, the top of minarets was made of woven timber lath, filled with gypsum plaster, and then coated with a layer of lime render to obtain the desired profile. Lead was common, especially at the top of Ottoman minarets. Marble columns were used to support the top, while wood was commonly involved for fences for balconies. Finally, spiral staircases of stone minarets typically wind around the central masonry column, which comprises superposed blocks.

4.2. Seismic Resistance of Masonry Monumental Buildings

Worldwide, engineers face inadequate seismic resistance or lack thereof as a major criticality for most historic monuments made of unreinforced masonry. As such, specific simulation and diagnostic strategies are typically required [24–26]. Ancient masonry buildings exhibit in fact a particular weakness when subjected to seismic events, particularly if they are not built or retrofitted to withstand such loads. Historic masonry structures typically have high levels of heterogeneity and suffer from severe stress peaks, which could promote local collapse [26]. Thus, even a moderate increase in these stress peaks, as a consequence of seismic events, may result in major structural failure [27,28]. Additionally, shear damage concentrates at the base [29], which makes historic masonry buildings intrinsically brittle and even more vulnerable to seismic activity due to their progressive deterioration [15,30,31].

According to [15], the Islamic architecture in Old Cairo has generally poorly designed connections, and the problems get worse by increasing the building size. Large domes and arches, moreover, typically involve reaction forces that are hardly accommodated by wooden tie beams or poor masonry connections. Analyzing the dynamic response of Old Cairo's cultural heritage is even more challenging due to the presence of complex floors and roofs, which are commonly characterized by unusual and irregular shapes.

As a simple and practical example, Cairo presents more than 200 minarets in total that differ greatly in architectural style, height, slenderness, and technical details. The combination of these features with inadequate foundations and poor masonry mechanical capacity makes them generally unable to withstand earthquakes. Extreme compressive and flexural stress peaks (such as under earthquake conditions) can in fact cause cracks in these structures and make them out of plumb. Additionally, compared with other styles, brick minarets can withstand earthquakes with a relatively high degree of flexibility and the capacity to accommodate the input of seismic events without collapsing, as pinpointed in the studies [15,22,23]. In this sense, one additional critical aspect to consider (in the case of collapse) is the considerable weight of minaret bricks and components possibly involved in the collapse and their effect on the adjacent constructions. This was the case of the roof of the Baybars al-Jashnakir mosque or the vaults in the al-Nasir Muhammad minaret and al-Salih Najm al-Din passages, which were unable to prevent the minaret from collapsing.

4.3. Lack of Maintenance

Lack of maintenance in monumental buildings in Old Cairo may cause an irreparable situation or a long, expensive restoration process, leading to their unavoidable demolition. According to the National Park Service, urgent maintenance can cost three times as much as regular maintenance [15]. In Old Cairo, several examples indicate a similar situation and suggest urgent interventions. In the past, for example, the Gamāl al-Din Yusuf minaret was demolished because of its poor structural condition and the associated difficulty for repair [32].

4.4. Wrong Restoration and Retrofit

Wrong restoration strategies may cause severe monument deterioration. This is what happened to the minaret of Emir Baydar al-Aydumuri / Aydumur al-Bahlawan (1347 AD), which rapidly deteriorated due to a retrofit intervention with poor gypsum mortar. The intervention, in particular, caused the migration of salts to the stone walls and their crystallization. The presence of a large, deteriorated stone surface, especially at the minaret's base, was reported by Comité de Conservation des Monuments de l'Art Arabe [33,34] and required additional expensive restoration.

This is only one of the possible examples, which suggests the urgent need of consolidated retrofit strategies and technical competences. Most importantly, more invasive bad restoration interventions can both reduce the historic value of a monument and further affect its resistance, by adding or changing the original layout (see, for example, Figure 6). During the Ottoman era, some Mamluk minarets were subjected to interventions that damaged their pavilions and restored them with Ottoman-style tops [23]. According to [33], some of them were successively restored to their semi-original shape, such as those of the Qady Abd al-Basit and Bersbai mosques. Other minarets indeed still present an Ottoman top, as it can be seen in the Inal al-Yusufi madrasa (1391–1393 AD) or in the Emir Uljay al-Yusufi madrasa (1373 AD).

Another example of poor restoration effort can be found in the wooden and mortar roof structural components of the Saraya el-Adl monument, constructed in 1813 by the Governor of Egypt, Muhamed Ali Pasha, to be the main court of the Cairo Castle. During a past retrofit, part of the original roof was in fact replaced by a concrete slab. The residual

wooden roof and the adjacent concrete one, however, exhibited severe interconnection issues and noticeable misalignments, leading to considerable dynamic deformations during the Cairo earthquake in 1992 [35]. Consequently, both the unrepaired and the partly restored roof components experienced extensive damage in 1992 and required re-restoration.

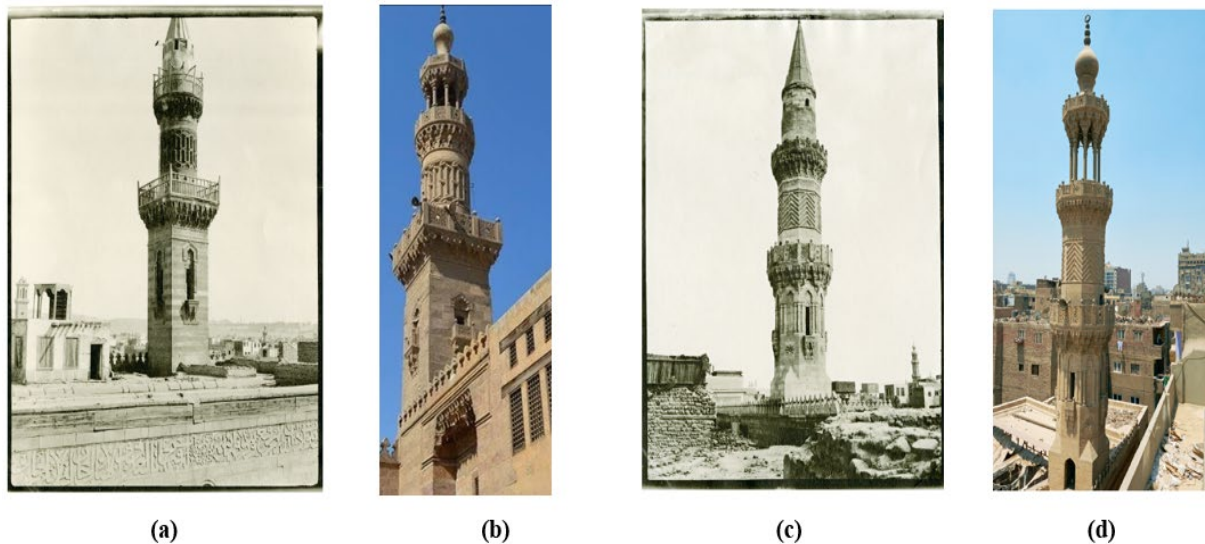


Figure 6. Example of selected minarets: (a,b) Bersbai and (c,d) Qady Abd al-Basit. Minarets (a,c) present an Ottoman-style top after bad restoration; minarets (b,d) present a Mamluk-style top after restoration. Adapted from [34] with permission.

4.5. Impact of Surrounding Community and Commercial Activities

Throughout the centuries, political conflicts of the Egyptian governorship affected most of the historic monuments in Cairo [15,16]. The majority of Cairo's monuments are located in areas of dense population, and both residential and commercial activities close to those monuments had a negative impact on them.

For example, Old Cairo experienced frequent fire accidents, as a result of negligence. Among others, on 23 December 2018, a short circuit caused a fire that broke out in the stores beneath the al-Fakahani mosque, in the al-Ghawri area [36,37]. The improperly controlled local dewatering procedures also caused the collapse of the Emir Qanybey al-Rammah minaret. The study in [38], in particular, reports that the minaret collapsed during the local pumping process to draw down the water.

Additional issues for the historic monuments derived, in the centuries, from the increasingly surrounding urbanization, with the construction of many buildings and streets. The management of severe road traffic, for decades, is one of the open challenges for all the Greater Cairo metropolitan area [39]. The progressive increase in streets in the city center, on one side, has led to unbalance between historic monuments and modern constructions. At the same time, the continuous vehicle-induced vibrations were observed to achieve high intensity and induce damage to the architectural and archaeological heritage of the city [40].

4.6. Environmental Hazards

Historic monuments deteriorate due to various environmental factors, which may have minor effects but lead to long-lasting consequences. Many Cairene sites, for example, suffer from pollution, groundwater, salt deposition, and other destructive phenomena [41]. According to [15], building stone in historic Cairo may also become discolored as a result of vehicular traffic, and such discoloration may cause permanent damage if the effect is sustained.

Among others, one of the most critical challenges facing the preservation of historic monuments in Cairo is the impact of moisture on masonry stone and palm wood. The

Ministry of Public Works was among the first to highlight this risk in 1902. Although medieval builders are said to have implemented waterproof foundations, the significant rise in groundwater levels has compromised these protective measures. In fact, at many historic sites, groundwater is alarmingly close to the surface and likely exceeds the level of the foundations. The limestone blocks used in construction act like wicks due to capillary action, often called rising damp. This allows moisture to infiltrate the stone and travel vertically until capillary pressures stabilize, which can occur well above the ground level. In several historic monuments, excessive moisture can be observed up to several meters above ground level. The effects of groundwater are not only harmful to masonry; they also pose a threat to wooden structures.

Long exposure to moisture in masonry blocks can lead to the chemical degradation of limestone, a process that is accelerated by the presence of soluble salts [23]. These salts migrate to the stone's surface, where they eventually evaporate. As the soluble salts evaporate, they begin to recrystallize. This can result in substantial salt accumulation on the stone's surface, a phenomenon known as efflorescence [23]. When they dry out, these salts transition from crystalline structures to a powdery form. Since limestone is highly porous, these crystals may also form within its pores [23]. Often, the size of the salt crystals exceeds that of the pores, leading to spalling on the stone's surface. Crystals that develop beneath the stone's surface are referred to as sub-florescence. As a result, the exterior of the block can become so fragile that it can be scratched with a fingernail, often breaking away due to gravitational forces. According to [23], the Yashbak bin Mahdi minaret suffered from the deterioration of the lower part of its walls, having a white surface crust caused by soil moisture rise and salt depositions beneath the minaret. When the author of that study performed an X-ray diffraction analysis, he discovered that the mortar samples under the Yashbak minaret contained halite salt among its components.

Microbial growth may be facilitated by the wet and salty environmental circumstances surrounding the monuments [42]. Moreover, when not cleaned, these high-porosity limestone buildings' walls continuously deteriorate due to biological colonization [42]. For example, microbiological and biological tests of the Yashbak minaret proved that some bacteria and fungi have grown under moisture and light conditions. Minaret stones may become acidic if the amount and density of bacteria increase [23].

Water infiltration into the ground beneath monuments can decrease their structural integrity, as happened to the Qanibay al-Jarkasi minaret, which was leaning southeast in 1900 and gradually became inclined eastward [32,34]. Humidity and air pollution negatively impact and compromise the quality and strength of monument stone. A thin layer of black and grey encrustation externally covers the walls of these exposed limestone buildings. This crust occurs in an environment where humidity rises due to carbonaceous gas combustion [43]. The stone's exterior is gradually removed when this black sheet falls off. These discolored walls can be found in many historic buildings in Cairo, including the Sultan al-Ghawri Complex [42].

4.7. Construction Errors

Many historic structures constructed in Old Cairo before specific building/seismic codes were adopted typically need to be revised to present design requirements. For instance, most historic Cairene minarets were built by Muslim architects with structural balance and no inclinations. However, some design errors occurred, such as the *jawsaq* columns' weakness in withstanding design loads. The slight inclination might occur in a structure due to its height and small diameters or the irregular mass distribution and stiffness along the minarets' heights, especially for Mamluk styles [23,44,45]. For that reason, the third minaret of the Sultan Hassan mosque fell right after its construction [22]. Minarets

without tops represent common damage patterns, especially in the Mamluk top style. Examples of minarets that have lost their top include Aydumur al-Bahlawan, Yashbak min Mahdi, Qanibay al-Jarkasi, Ahmad al-Mihmindar, the Khushqadam al-Ahmadi minaret, and Emir Mugulbay Taz (see Figure 7).



Figure 7. Examples of minarets in Old Cairo without top: (a) the minaret of Aydumur al-Bahlawan and (b) the minaret of Khushqadam al-Ahmadi. Adapted from [34] with permission.

4.8. Damage by Past Earthquakes

Due to non-regular and improper maintenance or restoration, especially after destructive earthquakes, structures may become more vulnerable to damage and lose their ability to withstand it [19]. Many historic monuments in Old Cairo 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. Literature reports typically indicate that mosques have suffered damage and destruction in earlier seismic events. Research investigations reported in [15,20,46] note that the minarets of the al-Hakim Bi-Amrillāh and al-MansūrQala'ūn mosques were severely damaged during the 1303 earthquake, leading to the reconstruction of al-Hakim Bi-Amrillāh's minaret, while al-MansūrQala'ūn's minaret underwent repairs. Many historic monuments in Old Cairo exhibit cracks or other signs of past seismic activity that have struck the city but represent an influencing parameter that can hardly be quantified.

5. Learning from Past Earthquakes

When, on 12 October 1992, a moderate 5.9-magnitude earthquake struck near Cairo, consequences were quantified in the tragic loss of approximately 540 lives, with around 6500 individuals injured and 8300 buildings either damaged or destroyed. The 1992 earthquake, in particular, highlighted the urgent need to enhance awareness, education, and preparedness across all tiers of government and within the private sector [47,48]. Thus, mitigation initiatives for comprehensive preparedness planning, establishing response and recovery strategies, robust engineering assessment of vulnerabilities, and retrofitting strategies for structurally unsafe buildings and infrastructures are nowadays still essential.

Despite its moderate magnitude and distance from Cairo (Figure 8), the earthquake significantly destroyed a large number of monuments. According to the initial assessments made by the National Earthquake Information System, the earthquake caused considerable harm to post-pharaonic monuments, particularly impacting Islamic mosques. During a

press conference (5 November 1992), the Egyptian Minister of Culture revealed that the quake had affected 212 out of the 560 Islamic monuments in Cairo, in addition to ancient Coptic churches and Jewish synagogues. The Egyptian government promptly committed USD 30 million to repair and restore the damaged mosques in response to the devastation. Furthermore, the EAO issued an international appeal for experts to evaluate the extent of the damage and facilitate reconstruction efforts.

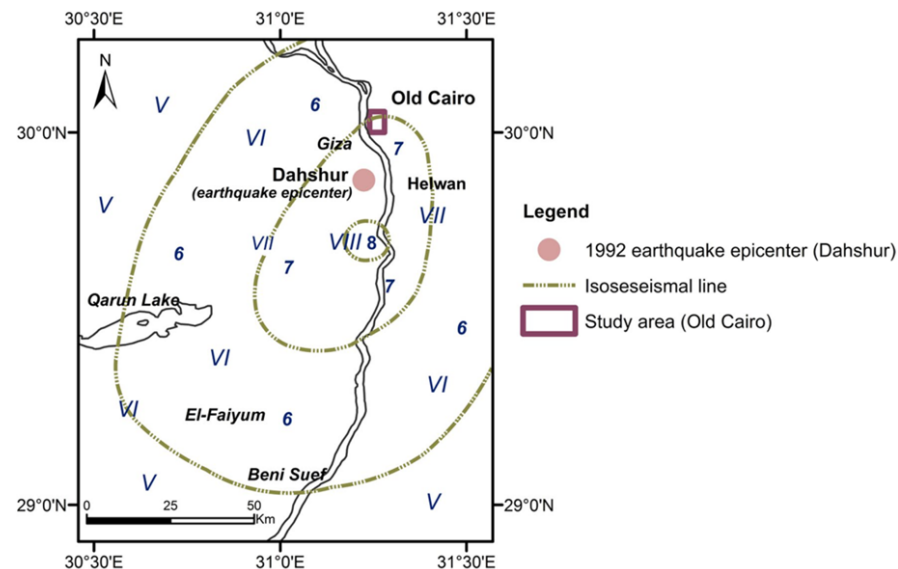


Figure 8. Iso-seismic map after the 1992 Cairo earthquake. Adapted from [49], under the terms and conditions of a CC BY 4.0 agreement.

5.1. Pre-1992 Earthquake Damage Assessment

Following [15], all the post-pharaonic monuments inspected before the 1992 earthquake were generally in disrepair, showing insufficient protection from societal and natural threats. According to the Egyptian Friends of Antiquities, nearly 600 monuments were catalogued in the 20th century, but by 1979, only 400 of them had survived [15]. In 1981, the Egyptian Antiquities Organization (EAO) estimated that 90% of the remaining monuments were either dangerously close to collapse and in poor condition or, in any case, requiring extensive restoration [15]. Antoniou et al. [11] specified that these monumental buildings were well preserved until the early 1950s. However, the progressive rise in the groundwater level and the increasing insufficient maintenance contributed to the swift deterioration of both masonry and wooden structures. The precarious state of most of these monuments is still evident from the occasional collapses that occur, even without significant seismic activity. A notable example of this condition was represented in 1990 by the collapse of the minaret in the Mosque of Qani-Bay al-Rammah, which tragically resulted in two fatalities [15].

5.2. Post-1992 Earthquake Damage Assessment

Sykora et al. [15] reported three damage classes for the inspected Cariene monuments after the 1992 earthquake. They can be summarized as follows:

- **Light damage:** Characterized by the propagation or expansion of small, distinct cracks in various structures, including walls, domes, arches, minarets, sagging floors, and parapets. This level of damage has been observed in several historic monuments, such as the Abu Sufein Church (6th century), the Al-Azhar mosque (972), the Al-Hakim bi Amr Allah mosque (990–1013), the Mausoleum of al-Nasir Muhammad (1295–1304), the Madrasa of Emir Sarghitmish (1356), the Mosque of Sultan Barquq (1386–1387), the

Mosque and Sabil of Sultan Barsbay (1425), and the Al-Gawhara Palace in the Citadel (1814). Figure 9 illustrates some examples of documented damage patterns.

- Moderate damage: Structures displayed characteristics such as leaning minarets, considerable gaps between adjacent structural components, and notable fractures in minarets and large domes. Monuments that have experienced this level of damage include but are not limited to the madrasa and minaret of al-Salih Najm al-Din Ayyub (1243–1250), the Mausoleum of Sultan Qalawan (1284–1285), the Palace of the Emir Beshtak (1334–1339), the mosque of Emir Shaykhu (1349); the khanqah of Emir Shaykhu (1355), the mosque, mausoleum, and madrasa of Sultan Hasan (1356–1359), the Mosque of Ibrahim Agha Mustahfzan (also known as the Blue Mosque; 1456–1544), the Hasan Pasha Tahir mosque (1809), and the Old Wing of the Coptic Museum (1910, renovated in 1984). Some examples are shown in Figure 10.
- Severe damage: Characterized by conditions such as collapsed domes, significant floor depressions, bulging walls, and severely fractured minarets. Notable monuments exhibiting this level of damage include the El-Muallaqa Church (6th century), the minaret of Al-Saghir mosque (1426–1427), the mosque of Al-Ghawiri (1504–1505), the Mosque of ad-Dashtiiti (1506), Bayt al-Sihaymi (1648–1796), and the Saraya el-Adl in the Citadel (1811), along with the Mint in the Citadel (1812); see Figure 11.

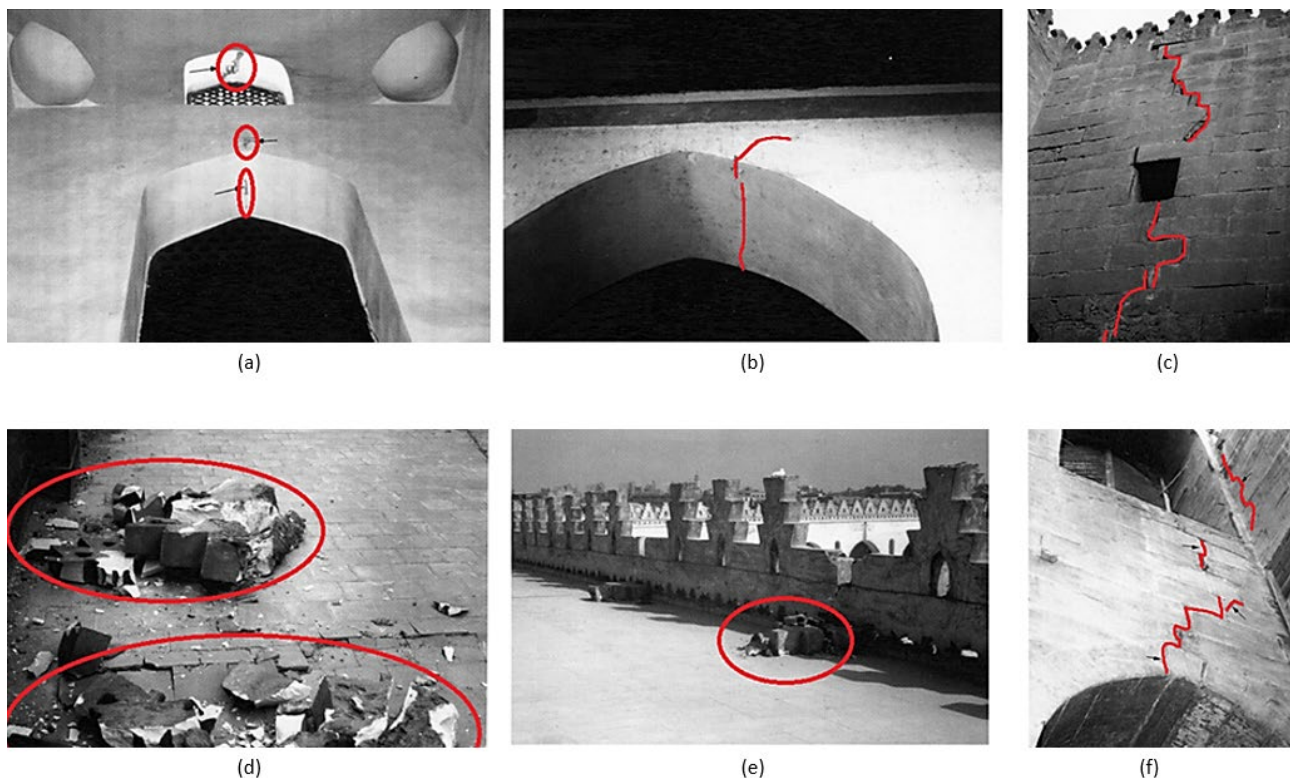


Figure 9. Examples of minor damage after the 1992 earthquake. Adapted from [15] with permission: (a) Abu Sufien Church; (b) al-Hakim mosque; (c) Sultan Barquq Mosque; (d,e) collapsed parapets (al-Azhar and al-Hakim mosques); (f) Sultan Barquq Mosque.

Wight et al. [38] also reported some observations of damage patterns related to the 1992 earthquake. They observed that some minarets tilted dangerously, and there were failures at the junctions with the mosque structures. In several cases, minarets suffered partial or total collapses. Beyond these collapses, the earthquake worsened existing deterioration that had been gradually undermining the integrity of these monuments, even before the seismic event.

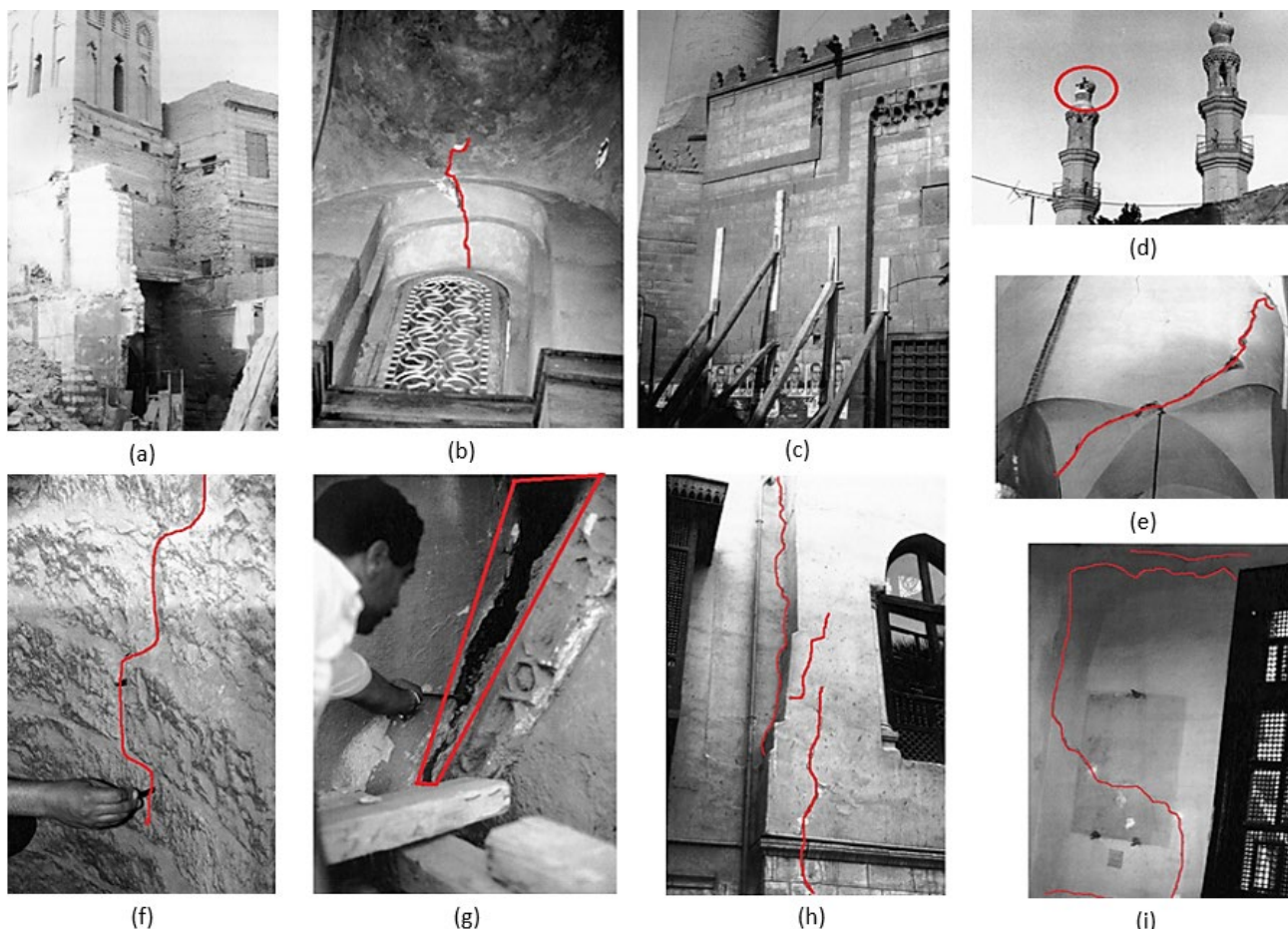


Figure 10. Examples of medium damage after 1992 earthquake. Adapted from [15] with permission: (a) ruins of al-Salih Najm al-Din Ayyub madrasa; (b,c) cracks in Sultan Qalawan Mausoleum; (d) Emir Shaykhu minaret; (e) cracks in Emir Beshtak Palace and (f) Sultan Hasan mosque; (g) separation of Hasan Pasha Tahir mosque and its minaret; (h,i) cracks in the Coptic Museum.

In particular, Wight et al. [38] investigated several Coptic Christian churches in Old Cairo, focusing on prominent locations such as Abu Sarga and Sitt Barbara. While there were no visible signs of earthquake damage, it was discovered that the groundwater level at Abu Sarga was only half a meter beneath the surface, leading to a completely flooded basement in the church. In various parts of the church, the stone flooring showed dampness, suggesting the possibility of capillary rise.

Additional studies and observations have been reported after the 1992 Cairo earthquakes by [6,15,44,47,50]. As a common consideration, a monument's overall structural health condition (rather than its age) gained greater significance as an indicator of potential damage. For instance, monuments from the Tulunid and Fatimid eras demonstrated better performance following earthquakes, with reduced impact compared with several two-century-old structures that experienced moderate to severe damage. For example, the Al-Ghawiri and Al-Azhar mosques are situated relatively close to each other. The Al-Ghawiri mosque, which was already in a deteriorated state before the earthquake, suffered extensive damage, whereas the Al-Azhar mosque, despite being older, incurred only minor harm. The Muhammad Ali mosque (the most prominent and largest structure in the Citadel) remained intact, while nearby structures such as the Mint and Saraya el-Adl, located merely a few hundred meters apart, experienced severe damage (Figures 11j and 12). A key parameter of their vulnerabilities stems from their natural frequencies compared with the dominant ground vibrations experienced in the Citadel.

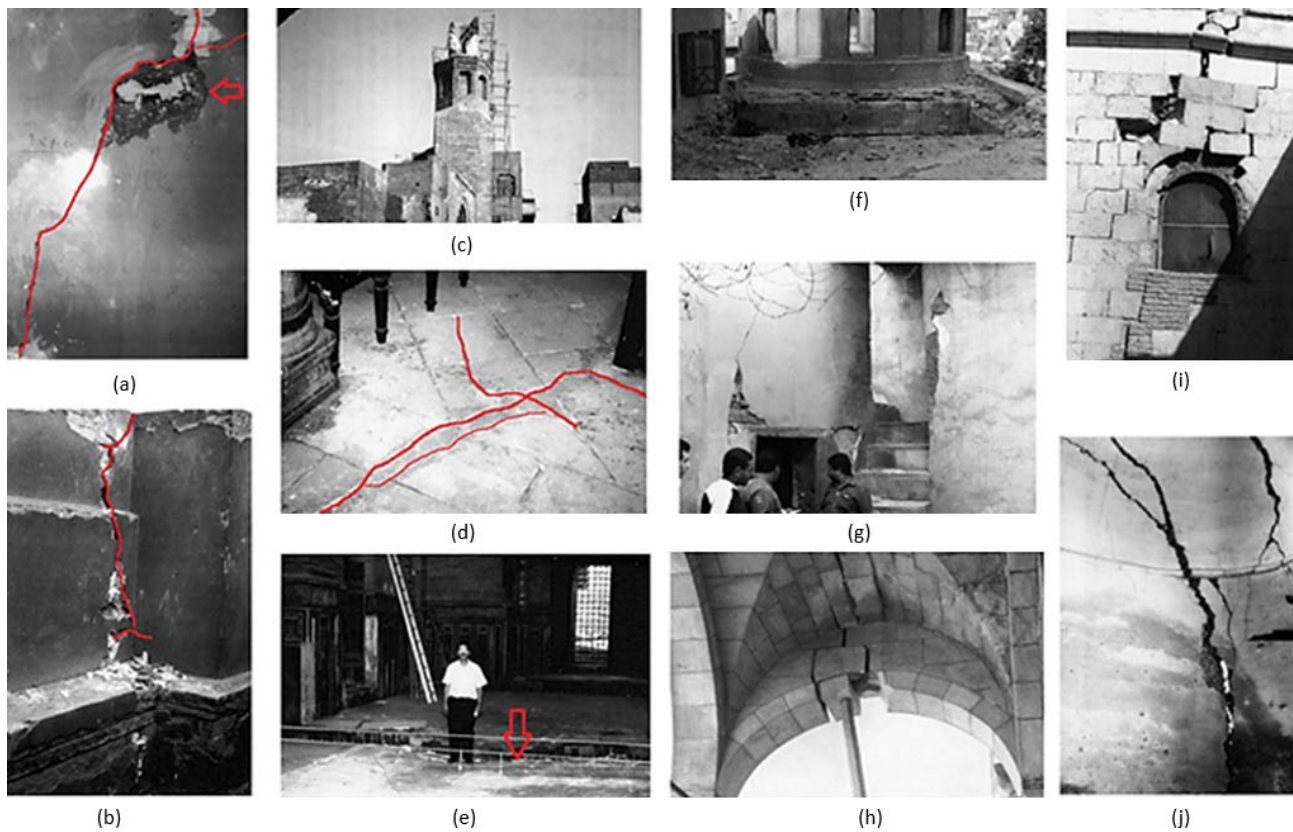
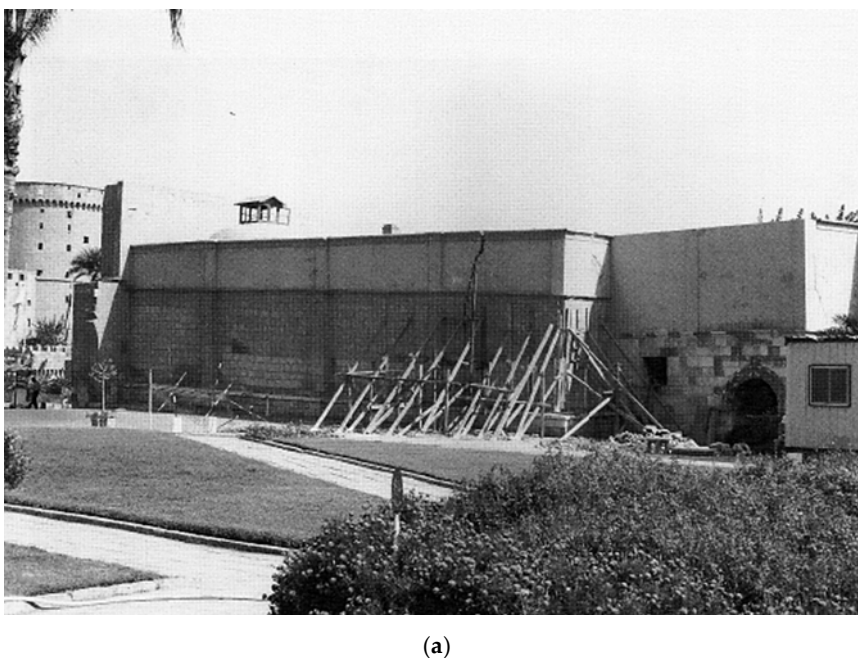


Figure 11. Examples of severe damage after the 1992 earthquake. Adapted from [15] with permission: (a,b) Hanging church; (c) Al-Saghir minaret; (d) hanging church's floor; (e) Al-Ghawiri mosque floor; (f) dome of Mosque of ad-Dashtiiti; (g) Bayt al-Sihaymi; (h,i) Saraya el-Adl (Citadel); (j) Mint (Citadel).



(a)



(b)

Figure 12. Examples of severe damage in the Citadel after the 1992 earthquake. Adapted from [15] with permission: (a) Mint and (b) Saraya el-Adl.

Leaning was a common damage pattern for minarets that suffered from moderate to severe damage levels; for instance, those of the Hasan Pasha Tahir mosque, the Sultan Barquq Mosque, the Ibrahim Agha Mustahfzan Mosque, the al-Ghawri Complex, and

the al-Salih Najm al-Din madrasa, exhibited noticeable leaning [15]. A slight inclination was reported for Emir Qanibay al-Muhammadi's minaret (Mourad and Osman, 1994). Al-Azhar's al-Ghawri minaret also had a notable inclination of 27.23 degrees [23,44]; the upper 4–5 m of the al-Saghir minaret was broken and fell on both the roof and portal steps [15]. Non-structural elements also suffered from the earthquake's ground motion. For instance, cracks appeared in the al-Ghawri Complex's staircase [23]. Additionally, parapets collapsed at various monuments, posing significant safety risks to individuals.

6. Recent Studies on Seismic Vulnerability of Historic Cairo Monuments

So far, some examples of seismic vulnerability investigations in Old Cairo monuments have been carried out and can be found in the literature. They represent useful feedback for future studies and try to point out the potential deficiencies of structural and non-structural components with robust and refined approaches. On the other hand, most of them focus on individual buildings, or parts of buildings, with different methodologies, and a general approach for a large-scale application is still missing. In this sense, CoReng plans to establish a general procedure for conserving the Religions Complex and an extension to other cultural heritage sites.

El-Attar et al. [45] applied FE analysis to examine the seismic response of two Mamluk-style minarets, finding that irregular stiffness mass distribution along their height made both vulnerable to earthquake damage. El-Attar et al. [51] successively extracted the dynamic characteristics from ambient vibration tests (AVTs) performed on the Mamluk-style minaret of the Manjaq Al-Yusufi mosque, to update its 3D model. The study proved the accuracy of numerical simulations with respect to the extracted dynamic characteristics from the AVTs. The seismic vulnerability study by [45] also concluded that the top and upper portions of these minarets, given their architectural style, are highly susceptible to damage by moderate earthquakes. The slender columns supporting the typically heavy top was identified as the most vulnerable components in the Mamluk minaret design. A good correlation was also found in [52] between estimates from a 3D model of the Emir Shaykhu minaret and ambient vibration tests. Higazy [19] also performed a 3D spectral analysis of four historic masonry minarets of various Islamic eras, as well as a reinforced concrete one, of 100 m in height.

Hassan et al. [53] made some first attempts to numerically describe the 1992 Cairo earthquake scenario and described a 3D structural numerical model for the Princess Tatar minaret (Figure 13). They provided different acceleration response spectra at the site of the minaret to be used for the assessment of its dynamic behavior by joining both seismological and engineering knowledge. In support of modeling, a visual inspection was performed to identify the construction materials and components, as well as the presence of cracks. Two seismic analysis types were conducted: a linear–dynamic response spectrum analysis and a time history analysis. The response spectrum analysis was selected to replicate the 1992 Cairo earthquake excitation scenario. It was shown that a careful assessment of the seismic excitation on the historic minaret, based on numerical analyses based on the Conditional Maximum Credible Seismic Input for a soil site (C-MCISIS) response spectrum and inclusive of time history simulations, can support efficient structural estimates and damage predictions on similar structures.

Kamh et al. [54] investigated various factors related to the soil/bedrock and the construction of buildings that may influence the seismic vulnerability of monumental buildings. The research study focused on 38 Islamic archaeological sites situated in the El-Gammalia region. Comprehensive field assessments were conducted to categorize the extent of damage, both before and after an earthquake, with supporting documentation of the observed impact due to the 1992 earthquake. The study included measurements of

groundwater depth, the height of buildings before the earthquake, and various bedrock conditions for geotechnical analysis. Mathematical and graphical methods were employed to analyze the primary factors contributing to building vulnerability during seismic events. The research findings from [54] indicate that sites with pre-earthquake heights between 12 and 14 m experienced the most significant structural damage. Buildings categorized with severe pre-existing damage were identified as more prone to additional deterioration during earthquakes, while structures erected on alluvial soil suffered major impact, compared with those built on Eocene limestone. The depth to sub-surface water was also found to be a critical factor affecting the foundation integrity of structures, specifically through the process of salt weathering.

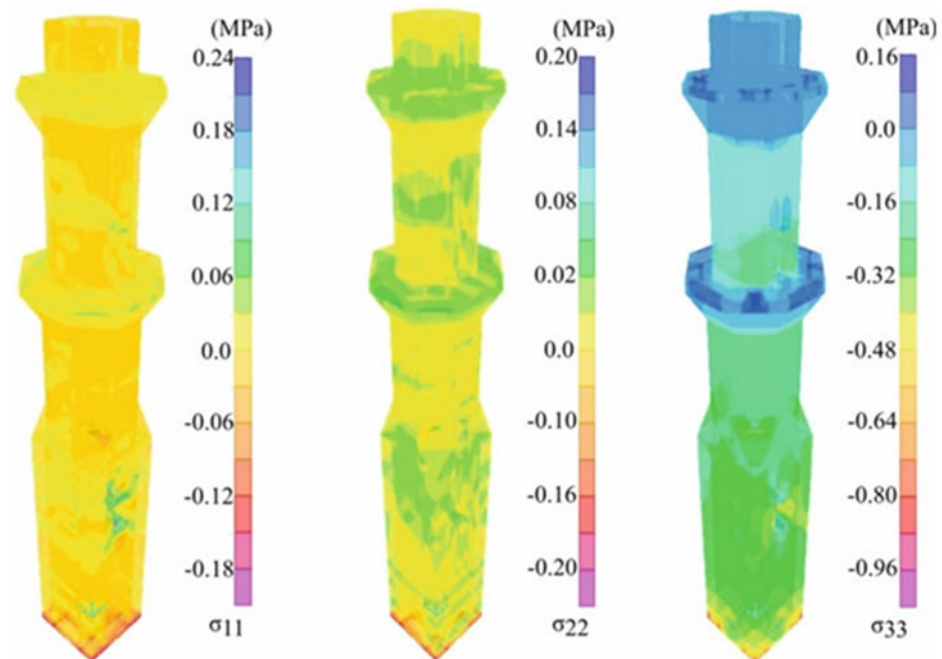


Figure 13. Example of structural vulnerability studies on the Princess Tatar minaret in Old Cairo. Adapted from [53] with permission. Highlighted are the principal stresses due to gravity loads.

Moharram et al. [55] presented an investigation on loss assessment in the Greater Cairo area through scenario-based analysis. A seismic risk model was initially developed for the region, drawing on prior studies on hazard, geological, and inventory data. Fragility functions were estimated based on dedicated structural models, representative of the city's building stock. By using the Latin Hypercube Sampling technique, three sets of reinforced concrete building populations were created, each one with different material characteristics. Ground motion variability was integrated into the fragility functions by incorporating scatter from the selected ground motion prediction equations. A modified capacity spectrum approach was employed to evaluate the seismic performance of various building types, as informed by the ground-shaking model developed earlier. The outcome performance points served as input for the fragility curves, enabling the assessment of probable damage distribution across different limit states for each geocode and earthquake scenario. Mean damage ratios were calculated as an overall measure of the impact on each building category, incorporating relative repair-to-replacement costs and the number of buildings likely to be affected by seismic activity. These ratios facilitated the estimation of monetary losses linked to the specified scenarios.

Hemeda [56] studied the ElSakakini Palace, a notable historic landmark in Cairo. The performed ambient noise studies determined that the fundamental frequency of the ground

falls within the range of 3 to 3.5 s, closely matching the fundamental frequency of the palace itself. The major conclusion was the need for careful attention to possible resonance phenomena, which should be properly considered in structural analyses. An experimental study was also conducted in Hemeda [57] to preliminarily investigate the soil–structure interaction and possible nature of resonance phenomena for the Ben Ezra Synagogue, the oldest example of Coptic architecture in Old Cairo. Additional trials of similar coupled experimental and numerical studies are reported in [57,58].

Hassan et al. [3] also focused on a seismic vulnerability assessment of the Al Khalifa District’s building stock in Fatimid Cairo, paying particular attention to the historic structures, including both masonry and reinforced concrete buildings. Based on field inspection and the well-known GNDT method, the vulnerability index of over 100 buildings was estimated. It was found that the inadequate seismic design had led to significant damage even during moderate-magnitude earthquakes. Many structures were found to have poor seismic performance, such as heavy and long overhangs, weak connections, and limited separation between adjacent buildings.

Sallam et al. [49] investigated the seismic vulnerability of eight different masonry minarets located in Old Cairo. A detailed inspection of each minaret was carried out (Figure 14). The assessed vulnerability index values for these minarets ranged from 10.3 to 26.1, indicating a relatively high level of vulnerability to seismic events. Additionally, vulnerability curves were created for each minaret, visually illustrating the potential damage scenarios across various seismic intensity levels, as per the EMS-98 scale. In support of the analysis, vibration tests and data were elaborated by using the peak-picking method to obtain the dominant frequencies of the selected minarets. As a noteworthy contribution by the study in [49], a new empirical equation was introduced and validated to estimate the fundamental period of minarets in Old Cairo, based on their height. However, the major limitation of the study is its application to specific types of minarets—namely, the historic masonry minarets of Old Cairo. In this sense, the approach should be extended and validated to different minaret styles. Furthermore, it faces major challenges that derive from the need for detailed 3D structural models of the minarets object of study, in order to properly capture their dynamic response.



Figure 14. Examples of structural vulnerability studies of historic masonry minarets in Old Cairo. Adapted from [49] under the terms and conditions of a CC BY 4.0 agreement. Different patterns of deterioration found in (a) the uppermost part of the Ibn Tulun minaret; (b) the body and the upper part

of the northern minaret of al-Hakim mosque; (c) the portion beneath the octagonal section and Mabkarah of the southern minaret of al-Hakim mosque; (d) the staircase and interior surface of the second floor of the southwest minaret of Sultan Hasan mosque; (e) the wooden tie at the northeast minaret of Sultan Hasan mosque; (f) the chipped tiles of the west minaret of al-Mu'ayyad Shaykh mosque; (g) the shaft of Yusuf agha al-Hin minaret.

In this sense, while the literature presents convincing experimental and numerical investigations and applications to some monumental buildings in Old Cairo, the same studies reveal that most of these initiatives are restricted to single components/buildings or suffer for lack of experimental validation to draw general considerations. Major efforts are hence necessarily required in this direction.

7. Conclusions and Next Steps

In general, the preservation and conservation of cultural heritage and historic monumental buildings is a key goal for many reasons. On the practical side, however, many challenges should be faced, and a multidisciplinary analysis should be carried out. In this review paper, in particular, the attention was focused on the multifield investigation of the Old City of Cairo and possible factors that should be taken into account in the conservation of its Religions Complex, which represents a unique example of the coexistence of religious, historical, cultural, and economic aspects.

Preserving the Religions Complex, as shown, requires addressing key gaps in current studies, including the lack of robust integrated multidisciplinary approaches, the need for high-resolution sub-surface models, and the availability of comprehensive in situ testing and structural modeling. So far, however, limited literature research has been conducted on the combined impact of geological and seismic structural factors for monumental buildings located in the Old Cairo area. Even fewer literature studies have been performed including environmental factors or even the effects of rising groundwater on structural stability. Future efforts should hence necessarily focus on detailed geotechnical and geophysical surveys, site-specific modeling, and real-time monitoring to enhance hazard assessments and develop effective conservation strategies. These steps are essential to ensuring the long-term resilience and sustainability of this invaluable cultural heritage.

From a purely structural point of view, it was shown that the proactive conservation of the Religions Complex faces the uncertainties and challenges of structural interventions that should be carried out on monumental buildings that are affected by the combined effect of several factors, such as different ages, construction materials, architectural technological solutions, previous damage due to past events, and the level and type of the existing retrofit (if any). In this sense, any possible conservation strategy would be possible with the support of a database and inventory of all these critical aspects.

For a first step for structural engineering considerations, robust literature data and feedback details are in fact required to describe a sound structural numerical model of the system object of study. Often, however, basic literature information can fairly support this modeling definition, requiring indeed extended investigations based on non-destructive investigations, structural health monitoring strategies, and in-field and laboratory characterization tests.

On the other hand, for seismic vulnerability assessment purposes, detailed soil investigations are also preliminary needed, in order to support the initial evaluation of a site's physical and geological condition, its seismic hazard, and the corresponding structural integrity. In this sense, the present document wants to represent a basis of review of key gaps, challenges, and influencing factors for the elaboration of a multidisciplinary conservation strategy for the cultural heritage in Old Cairo.

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References

1. UNESCO: Historic Cairo. Available online: <https://whc.unesco.org/en/list/89/> (accessed on 2 February 2025).
2. Fakharany, N. Revitalizing Historic Cairo: May Al-Ibrashy’s Vision for Heritage, Community, and Sustainable Conservation, ArchDaily. 2024. Available online: <https://www.archdaily.com/1023805/revitalizing-historic-cairo-may-al-ibrashys-vision-for-heritage-community-and-sustainable-conservation> (accessed on 2 February 2025).
3. Hassan, M.M.; Elyamani, A.; Mourad, S.A. Seismic vulnerability assessment of buildings: Case study of Al Khalifa district, Fatimid Cairo. *SN Appl. Sci.* **2022**, *4*, 310. [CrossRef]
4. Hassan, H.M.; Abdel Hafiez, H.E.; Sallam, M.A.; Bedon, C.; Fasan, M.; Henaish, A. Multidisciplinary Approach of Proactive Preservation of the Religions Complex in Old Cairo—Part 1: Geoscience Aspects. *Heritage* **2025**, *8*, 56. [CrossRef]
5. UNESCO—United Nations Educational, Scientific & Cultural Organization. Convention Concerning the Protection of the World Cultural and Natural Heritage, WHC-08/32.COM/7B. 2008. Available online: <https://whc.unesco.org/en/documents/9973> (accessed on 2 February 2025).
6. Osman, A. The 12 October 1992 Dahshur Earthquake “Seismological, Geotechnical and Structural Aspects”. In Proceedings of the Seventh International Colloquium on Structural and Geotechnical Engineering, Cairo, Egypt, 17–19 December 1996.
7. El-Sayed, A.; Arvidsson, R.; Kulhánek, O. The 1992 Cairo earthquake: A case study of a small destructive event. *J. Seismol.* **1998**, *2*, 293–302. [CrossRef]
8. Sadek, A.W. Damage statistics of 12 October 1992 earthquake in the greater Cairo area. *Earthq. Eng. Struct. Dyn.* **1997**, *26*, 529–540. [CrossRef]
9. ICOMOS Report on the ICOMOS Reactive Monitoring Mission to World Heritage Site: Islamic Cairo (Egypt). Available online: <https://tegnestuen-raadvad.dk/wp-content/uploads/2016/04/Islamic-Cairo-Reactive-Monitoring-Report-2005.pdf> (accessed on 2 February 2025).
10. Swidani, A.M.; Elazm, F.M.A. The City of Tomorrow and Culture Heritage Urban regeneration as an effective tool to accomplish the sustainable development in Arab cities—A Case study of Cairo, Egypt. *Int. J. Cult. Herit.* **2017**, *2*, 126–135.
11. Antoniou, J.; Bianca, S.; El-Hakim, S.; Lewcock, R.; Welbank, M. *The Conservation of the Old City of Cairo*; UNESCO: London, UK, 1985.
12. UNDP & SCA. *Rehabilitation of Historic Cairo. Final Report*; Technical Cooperation Office: Cairo, Egypt; United Nations Development Program & Supreme Council for Antiquities: New York, NY, USA, 1997.
13. Sutton, K.; Fahmi, W. The rehabilitation of old Cairo. *Habitat Int.* **2002**, *26*, 73–93. [CrossRef]
14. Butler, A.J. *The Ancient Coptic Churches of Egypt (Volume 2)*; Clarendon Press: Oxford, UK, 1884.
15. Sykora, D.; Look, D.; Croci, G.; Karaesmen, E.; Karaesmen, E. *Reconnaissance Report of Damage to Historic Monuments in Cairo, Egypt, Following the October 12, 1992 Dahshur Earthquake*; Technical Report NCEER-93-0016; National Center for Earthquake Engineering Research—State University of New York: Buffalo, NY, USA, 1993; p. 164. Available online: <https://apps.dtic.mil/sti/tr/pdf/ADA325190.pdf> (accessed on 18 February 2025).
16. Mahmoud, H.A. Coptic Churches in Old Cairo, An Archaeological, Architectural And Artistic Study. *Int. J. Cult. Inherit. Soc. Sci.* **2024**, *6*, 25–61.
17. Gaballah, G.A.; Al-Attar, A.A. *Culture and Heritage Program: Guide of Islamic Archeology in Cairo*; Information and Decision Support Center of the Council of Ministers: Cairo, Egypt, 2000.

18. John, D.H. *Islamic Architecture*; Electa Editrice: Milan, Italy, 1975; Reprinted in Rizzoli: New York, NY, USA, 1987; p. 1.
19. Higazy, E.M. Vulnerability of historical minarets; investigation of their seismic assessment & retrofitting. *Emir. J. Eng. Res.* **2004**, *9*, 59–64.
20. Behrens-Abouseif, D. *Islamic Architecture in Cairo: An Introduction*; The American University in Cairo Press: Cairo, Egypt, 1989.
21. Behrens-Abouseif, D. *Islamic Architecture in Cairo: An Introduction (Volume 3)*; Brill: Leiden, The Netherlands, 1992.
22. Behrens-Abouseif, D. *The Minarets of Cairo: Islamic Architecture from the Arab Conquest to the End of the Ottoman Empire*; IB Tauris: London, UK, 2010; p. 448. ISBN 1848855397.
23. Khallaf, K.M. Study of Treatment, Restoration and Conservation of Archaeological Minarets in Cairo Applied on One Selected Archaeological Minaret. Ph.D. Thesis, Cairo University, Giza, Egypt, 2004. (In Arabic).
24. Lourenço, P.B.; Oliveira, D.V.; Leite, J.C.; Ingham, J.M.; Modena, C.; da Porto, F. Simplified indexes for the seismic assessment of masonry buildings: International database and validation. *Eng. Fail. Anal.* **2013**, *34*, 585–605. [\[CrossRef\]](#)
25. Pineda, P.; DRobador, M.; Gil-Marti, M. Seismic damage propagation prediction in ancient masonry structures: An application in the non-linear range via numerical models. *Open Constr. Build. Technol. J.* **2011**, *5*, 71–79. [\[CrossRef\]](#)
26. Salvatore, W.; Bennati, S.; Della Maggiora, M. On the collapse of a masonry tower subjected to earthquake loadings. *Earthq. Resist. Eng. Struct. IV* **2003**, *13*, 141.
27. Sepe, V.; Speranza, E.; Viskovic, A. A method for large-scale vulnerability assessment of historic towers. *Struct. Control. Health Monit.* **2008**, *15*, 389–415. [\[CrossRef\]](#)
28. Binda, L.; Gatti, G.; Mangano, G.; Poggi, C.; Landriani, G.S. Collapse of the civic tower of Pavia: A survey of the materials and structure. *Mason. Int.* **1992**, *6*, 11–20.
29. Casolo, S.; Pena, F. Dynamics of slender masonry towers considering hysteretic behaviour and damage. In Proceedings of the ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Rethymno, Greece, 13–16 June 2007; pp. 1–12.
30. Wyllie, L.A., Jr.; Lew, H.S. Performance of Engineering Structures. *Earthq. Spectra* **1989**, *6*, 70–92.
31. Murty, C.V.R. *Earthquake Tips*; National Information Center of Earthquake Engineering, Indian Institute of Technology Kanpur: Kanpur, India, 2005.
32. Ishak Bakhoun, D. Mamluk Minarets in Modern Egypt: Tracing Restoration Decisions and Interventions. *Ann. Islam.* **2016**, *50*, 147–198.
33. Metwally, N. (Ed.) *The Bulletins of the Comité de Conservation des Monuments de l'Art Arabe*; Arabic Edition; American University in Cairo Press: Cairo, Egypt, 2019; Volume 29.
34. Sallam, M.A. Evaluation of Seismic Vulnerability of Some Historical Structures in Old Cairo. Master's Thesis, Benha University, Banha, Egypt, 2022.
35. Sayed, H.; Mario, M.; Nourhan, M.; Nourhan, H.; Hader, S. Numerical Damage Assessment in Saraya El-Adl Citadel, Cairo, Egypt Due to October 12, 1992 Dahshour Earthquake. *Int. J. Conserv. Sci.* **2021**, *12*, 987–1002.
36. Mobtada News. A Fire Broke Out in Al-Fakahani Mosque. Mobtada Newspaper. 13 December 2018. Available online: <https://www.mobtada.com/details/798259> (accessed on 18 February 2025). (In Arabic).
37. See Egy. Antiquities Destroyed in the Museum of Islamic Art in Cairo. SADA ELBALAD. 31 January 2014. Available online: <https://www.elbalad.news/801673> (accessed on 18 February 2025). (In Arabic).
38. Wight, J.K.; Hryciw, R.D.; Naaman, A.E. *Field Investigation of Damage to Islamic Monuments Caused by the Egyptian Earthquake of October 12 1992*; University of Michigan College of Engineering: Ann Arbor, Michigan, 1992.
39. Ali, S.A.; Tamura, A. Road traffic noise levels, restrictions and annoyance in Greater Cairo, Egypt. *Appl. Acoust.* **2003**, *64*, 815–823. [\[CrossRef\]](#)
40. Mohamed, M.M.M. The Effect of the Archeological and Architectural Nature of the Cities on the Form and Design of Public Transportation Vehicles. In *Conservation of Architectural Heritage*; Advances in Science, Technology & Innovation; Springer: Cham, Switzerland, 2019. [\[CrossRef\]](#)
41. Cowell, A. *Underground Pollution Imperils Egypt's Relics*; The New York Times: New York, NY, USA, 1990.
42. El-Metwally, A.A.; Ramadan, A.B. The role of air pollutants and sewage waste in acceleration of degradation of the Islamic cultural heritage of Cairo. In *Comparative Risk Assessment and Environmental Decision Making*; Springer: Dordrecht, The Netherlands, 2004; pp. 363–370.
43. Fitzner, B.; Heinrichs, K.; La Bouchardiere, D. Limestone weathering of historical monuments in Cairo, Egypt. *Geol. Soc. Lond. Spec. Publ.* **2002**, *205*, 217–239. [\[CrossRef\]](#)
44. Mourad, S.A.; Osman, A.M. *Seismic Risk Appraisal of Islamic Minarets*; Faculty of Engineering—Cairo University: Giza, Egypt, 1994; p. 1.
45. El-Attar, A.G.; Saleh, A.M.; Osman, A. Seismic response of a historical Mamluk style minaret. *WIT Trans. Built Environ.* **2001**, *57*, 745–754.
46. Behrens-Abouseif, D. *The Minarets of Cairo*; The American University in Cairo Press: Cairo, Egypt, 1985.
47. Badawi, H.S.; Mourad, S.A. Observations from the 12 October 1992 Dahshour earthquake in Egypt. *Nat. Hazards* **1994**, *10*, 261–274. [\[CrossRef\]](#)
48. Degg, M. The 1992 “Cairo Earthquake”: Cause, Effect and Response. *Sisasters* **1993**, *17*, 226–238. [\[CrossRef\]](#)
49. Sallam, M.A.; Hassan, H.M.; Sayed, M.A.; Abdel Hafiez, H.E.; Zahra, H.S.; Salem, M. Seismic vulnerability assessment of historical minarets in Cairo. *Geoenvironmental Disasters* **2023**, *10*, 30. [\[CrossRef\]](#)

50. Khater, M. *Reconnaissance Report on the Cairo, Egypt Earthquake of October 12, 1992*; National Center for Earthquake Engineering Research: Buffalo, NY, USA, 1992.
51. El-Attar, A.G.; Saleh, A.M.; Zaghw, A.H. Conservation of a slender historical Mamluk-style minaret by passive control techniques. *Struct. Control Health Monit.* **2005**, *12*, 157–177. [[CrossRef](#)]
52. Zaki, M.A.; Hassan, A.F.; Mourad, S.A.; Osman, A.M. Evaluation of the structural integrity of historical stone minarets. In Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China, 12–17 October 2008. [[CrossRef](#)]
53. Hassan, H.M.; Sayed, M.A.; Fasan, M.; Romanelli, F.; Amadio, C.; Hamed, A.; ElGabry, M.; Hamama, I. Seismic assessment of a cultural heritage Minaret in Cairo. In *Sustainable Conservation of UNESCO and Other Heritage Sites Through Proactive Geosciences*; Springer International Publishing: Cham, Switzerland, 2023; pp. 541–565.
54. Kamh, G.M.E.; Kallash, A.; Azzam, R. Factors controlling building susceptibility to earthquakes: 14-year recordings of Islamic archaeological sites in Old Cairo, Egypt: A case study. *Environ. Geol.* **2008**, *56*, 269–279. [[CrossRef](#)]
55. Moharram, A.M.; Elghazouli, A.Y.; Bommer, J.J. Earthquake risk model for Greater Cairo. In Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China, 12–17 October 2008; pp. 12–17.
56. Hemeda, S. Seismic Hazard Analysis for Archaeological Structures—A Case Study for ELSakakini Palace Cairo, Egypt. In *Engineering Seismology, Geotechnical and Structural Earthquake Engineering*; IntechOpen: London, UK, 2013. [[CrossRef](#)]
57. Hemeda, S. 3D finite element coupled analysis model for geotechnical and complex structural problems of historic masonry structures: Conservation of Abu Serga church, Cairo, Egypt. *Herit. Sci.* **2019**, *7*, 6. [[CrossRef](#)]
58. Hemeda, S. Dynamic characteristics of built heritage using ambient noise recordings. *Herit. Sci.* **2022**, *10*, 100. [[CrossRef](#)]

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