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RESEARCH

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Seismic vulnerability assessment of historical minarets in Cairo

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Abstract

Introduction Masonry minarets in Old Cairo are highly susceptible to earthquake damage, particularly those not designed or updated to withstand seismic loads. Therefore, regular monitoring is necessary to ensure their safety and detect any deterioration or reduction in seismic performance. The direct loss of a minaret can lead to the collapse or severe damage to the structure itself. The cascading impacts of partial or complete minaret failure can have significant consequences for the immediate vicinity and the broader community. By studying the effects of earthquakes on minarets and developing mitigation strategies, countries can take proactive measures to protect these structures and ensure the safety of people.

Objective This study focuses on a specific type of Islamic architecture: the historic minarets in Cairo. The research aims to evaluate the seismic vulnerability of eight cultural heritage minarets in Cairo, identifying the parameters influencing their seismic behaviour and susceptibility to earthquake damage.

Methods The research utilizes empirical seismic vulnerability methods and ambient vibration measurements on eight minarets. An empirical approach compatible with the nature and style of the minarets is employed to evaluate their vulnerability using index values and curves. The method's validity is assessed, and areas of conformity and limitations are identified. Ambient vibration tests (AVTs) are also conducted using a temporary seismic network installed at various heights inside each minaret to determine their dynamic characteristics.

Results The seismic vulnerability Index (I_V) is calculated for the selected minarets based on the state of each vulnerability parameter. The contribution of each parameter to the final I_V values of the minarets are presented. Vulnerability curves are developed for each minaret, interpreting the conventional vulnerability indexes in terms of mean damage grades for seismic events with varying intensity on the EMS-98 scale. These mean damage grades can also indicate the expected damage levels of structural and non-structural minaret elements for events with different seismic intensity levels. AVTs are conducted at various heights on the selected minarets, and the dynamic characteristics are extracted from the recorded data. Variations in these characteristics are considered significant for structural health monitoring analysis. The peak-picking method is employed to directly extract each minaret's natural frequencies and mode shapes, as changes in dynamic characteristics are relevant to health monitoring analyses.

Conclusions The recent study examined the seismic vulnerability assessment of eight masonry minarets in the historic Old Cairo district. The assessment revealed vulnerability index values ranging from 10.3 to 26.1, indicating a concerning susceptibility to seismic events among these structures. Vulnerability curves were constructed for each minaret, visually representing potential damage scenarios across different levels of the EMS-98 intensity scale. These

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outcomes are significant as they facilitate prioritizing interventions to safeguard the most vulnerable minarets. Additionally, a novel empirical period equation was introduced to estimate the fundamental period of minarets in Old Cairo based on their heights. The equation was validated against field measurements and data from the literature. The study is limited by its focus on a specific category of minarets, specifically the historical masonry minarets in Old Cairo. Furthermore, limitations arise from the need for detailed finite element models to capture these minarets' dynamic responses accurately. Therefore, ongoing research involves the development of detailed finite element models and calibrating fundamental periods for the selected minarets. The anticipated results hold the potential to enhance our understanding of the structural dynamics of historical minarets, ultimately guiding the formulation of tailored seismic retrofitting and preservation strategies. These strategies, aimed at preserving these cherished cultural heritage assets, represent our collective commitment to ensure the endurance of these timeless landmarks for future generations.

Keywords Seismic vulnerability, Cairo's minarets, Ambient vibration tests, Vulnerability index, Earthquake

Introduction

Old Cairo is a historic district in Egypt's capital city with a rich and diverse cultural heritage. With a population of approximately 10 million, Cairo is the largest city in the country (CAPMAS 2023) and is home to a wide variety of ancient and modern monuments that span different historical periods. These monuments, including Roman, Coptic, and Islamic structures, are often described as open-air museums that offer a glimpse into the city's fascinating past. The Old Cairo area is particularly significant, as it comprises the ruins of Fustat, Fatimid Cairo, Al-Askar, and Al-Qattaa, which served as the Egyptian capital before Cairo was designated and are located to the east of the modern city. In addition, this area is home to numerous archaeological sites, including the oldest mosque in Africa, administrative buildings, mosques, schools, and fountains, which offer valuable insights into the city's history and culture. In recognition of its outstanding cultural value, Old Cairo was designated a World Cultural Heritage site by UNESCO in 1979 (UNESCO 2017), cementing its status as one of Egypt's most important cultural treasures.

Islamic cities are known for their distinctive architecture, with minarets being one of the most recognizable features of mosques. No mosque design in Islamic architecture is complete without at least one minaret, especially those that symbolize prosperity for past dynasties and kingdoms. Old Cairo is home to an impressive collection of historical minarets, extensively studied by researchers such as Creswell (1926) and Behrens-Abouseif (2010). These scholars have delved into minarets' origin, function, and style in Islamic Egypt, highlighting their cultural and historical significance. However, the number of minarets in Cairo has decreased over time, according to Behrens-Abouseif(2010), due to various factors affecting many monuments' structural integrity. In particular, groundwater, poor building conditions, and inadequate seismic resistance have caused irreparable damage to many minarets and other historical monuments. It is crucial to assess the seismic vulnerability of historical monuments and develop preservation policies that prioritize their safety to safeguard these monuments and protect lives and property.

Historical minarets in Cairo are integral to the city's cultural identity. They are symbols of Islamic architecture and serve as a testament to the city's centuries-old Islamic heritage. These minarets contribute to Cairo's unique atmosphere and add to the city's cultural tapestry. Those minarets in Cairo showcase exceptional architectural craftsmanship and design. They often exhibit intricate details, ornate decorations, and unique architectural styles, reflecting the artistic and architectural achievements of the periods in which they were constructed. These minarets stand as remarkable examples of Islamic architectural excellence. Many of Cairo's minarets have historical significance tied to specific events, rulers, or dynasties. They provide insights into the city's past and offer a glimpse into the historical development of Cairo. These minarets have witnessed the rise and fall of empires, political changes, and cultural transformations, making them valuable historical artifacts. The minarets in Cairo serve as prominent landmarks, helping orientate and navigate the city. They stand tall above the urban landscape, guiding people and serving as reference points for locals and visitors alike. The minarets' distinct architectural features make them easily recognizable and contribute to the city's visual identity.The damage to minarets in Turkey and Syria during the February 2023 earthquake sequence highlighted the vulnerability of these structures to seismic events. The cascading impacts of partial or complete failure of minarets can have significant consequences for the immediate vicinity and the broader community.Direct loss of the minaret can result in the collapse or severe damage to the structure itself. The loss of a minaret can profoundly impact the area's aesthetic appeal and diminish the historical and cultural significance of the mosque and surrounding buildings. This loss can devastate countries with a rich heritage of minaret-dominated structures, symbolizing religious and architectural heritage. By studying the impacts of earthquakes

on minarets and developing mitigation strategies, countries can take proactive measures to protect these structures and ensure the safety of people who utilize mosques for prayer or seek shelter during emergencies.

Seismic vulnerability is a fundamental property that reflects a building's susceptibility to damage when exposed to seismic motion (Asteris and Plevris 2015). It is a measure of the reduction in the building's structural efficiency and its residual capacity to withstand earthquake forces (Lang and Bachmann 2003). The first attempts to evaluate building vulnerability were made in the early 1980s in the United States and Central and Eastern Europe (Vicente et al. 2011). Since then, researchers have developed different methods for assessing seismic vulnerability, broadly classified as empirical (i.e., a qualitative evaluation using data collection forms) or analytical (Kassem et al. 2020). Empirical methods rely on qualitative evaluations using data collection forms, while analytical methods are based on mathematical models considering the building's geometry, materials, and structural system. These methods have proven helpful in identifying vulnerable buildings and prioritizing retrofitting measures, ultimately saving lives and preventing property damage during earthquakes.

Several researchers have studied seismic vulnerability and historical structures in various locations. For instance, Catulo et al. (2018) evaluated seismic vulnerability in the Lisbon Heritage City Centre. Ademović et al. (2016) examined the structural condition and repair of the CarevaĆuprija Bridge in Sarajevo. Hadzima-Nyarko et al. (2017) assessed the seismic vulnerability of an old historical masonry building. Additionally, Işık et al. (2019) utilized QR code technology to study the behaviour of Ahlat gravestones in Turkey. Empirical methods for assessing seismic vulnerability evaluate the potential seismic deficiencies of a structure or group of structures by examining their significant components. They can also estimate the likelihood of a structure exceeding its current damage state and the anticipated damage level in an earthquake of a particular intensity. The National Group for Earthquake Defense-GNDT II level (GNDT-SSN 1994) has been widely used to assess the seismic vulnerability of masonry structures. However, this approach has its limitations when it comes to slender masonry structures like historical minarets. Researchers have developed new vulnerability assessment methods based on qualitative and quantitative parameters to address this issue. For instance, Speranza et al. (2006) proposed a method to assess the vulnerability of tower-like masonry structures, while Sepe et al. (2008) and Shakya et al. (2018) modified this method to evaluate slender masonry structures such as historical minarets. Despite the potential benefits of these techniques, they have yet to be applied to the masonry minarets in Cairo. Given the importance of these historical structures, researchers need to develop and apply effective vulnerability assessment methods to protect them from seismic hazards.

The seismic vulnerability of slender masonry structures, including minarets, can be evaluated using analytical methods based on 3D models. Although there are numerous historical minarets in Cairo, few studies have focused on masonry minarets due to the complexity of these detailed techniques, which are typically more suited to individual structures. For instance, Higazy (2004) conducted a 3D spectral analysis on five minarets from different historical periods, including a 100 m high reinforced concrete minaret. El-Attar et al. (2001) investigated the seismic response of two Mamluk-style minarets using finite element analysis. They concluded that these structures were vulnerable to damage from moderate to strong seismic motions due to the irregular distribution of masses and stiffness along their heights.

El-Attar et al. (2005) updated a 3D finite element model of the Manjaq Al-Yusufi minaret with its Mamluk style using dynamic characteristics extracted from recorded ambient vibration data. The estimation of dynamic properties using ambient vibration tests (AVTs) was found to be entirely accurate. Furthermore, they found that the top portions of the minarets were susceptible to damage in moderate earthquakes. Zaki et al. (2008) reported a good correlation between ambient vibration testing and the 3D finite element model of the Emir Shaykhu minarets. In addition, Hassan et al. (2020) developed a detailed 3D numerical model of the Princess Tatar al-Hijaziyya minaret and simulated the 1992 Cairo earthquake scenario. They predicted severe damage to the minaret under the anticipated earthquake scenario.

In recent research, minarets have been the subject of extensive seismic evaluation and vulnerability assessments. For example, Bilgin and Ramadani (2021) delved into the structural behaviour of the Bajrakli Mosque in Kosovo. In a separate study, Işık et al. (2022a) conducted a seismic vulnerability assessment of a historical masonry minaret in Bitlis, Turkey, considering various seismic risks. Furthermore, Işık et al. (2022b) conducted structural analyses on five historical minarets within Bitlis, Turkey. Onat et al. (2023) explored the seismic performance of a masonry minaret in Turkey, utilizing a block masonry equation-based model. Aymelek et al. (2023) also performed a comprehensive structural assessment using a 3D finite element model and vibration measurements on a minaret in Turkey. Trešnjo et al. (2023) conducted experimental investigations and assessed a historical stone minaret's seismic characteristics in Mostar, Bosnia and Herzegovina.Furthermore, Işık et al. (2023a) investigated the influence of different materials

on the seismic vulnerability of Turkish minarets, employing artificial neural networks to determine their fundamental periods. In a related study, Işık et al. (2023b) focused on structural damage evaluation in mosques and minarets in Turkey following the 2023 Kahramanmaraş Earthquakes.

Historical minarets in Cairo are numerous and suffer from significant structural deterioration, making empirical analyses of structural vulnerability necessary at any scale. Collected data on structural vulnerability can provide valuable information about the condition of these structures over time, including the location and extent of damage that could occur due to earthquakes, both qualitatively and quantitatively. Structural health monitoring (SHM) can also support the outcomes of inspections of each minaret by analyzing its response to AVTs to identify dynamic characteristics such as natural frequencies and mode shapes. Several studies have employed AVTs to monitor the dynamic behaviour of structures (Bindi et al. 2015; Hassan and Elgabry 2023). Besides SHM, a database of structures can be established to calibrate their elastic properties for numerical modelling and to track any changes in their characteristics over time. Therefore, municipalities and government agencies can identify highly vulnerable structures requiring immediate attention to prepare for earthquakes. Seismic vulnerability assessment is also essential for rehabilitating and restoring cultural heritage sites since many were constructed without considering earthquake loads.

This study focuses on the seismic vulnerability of masonry minarets in old Cairo, which aims to identify the best seismic vulnerability assessment technique applicable to all such structures. This research employs empirical seismic vulnerability methods and SHM analysis on eight minarets. First, an empirical approach that suits the structure's style and nature is selected and applied, verifying its accuracy and validity. Then, the minarets undergo short-term SHM, with ambient vibration tests used to determine their dynamic characteristics.

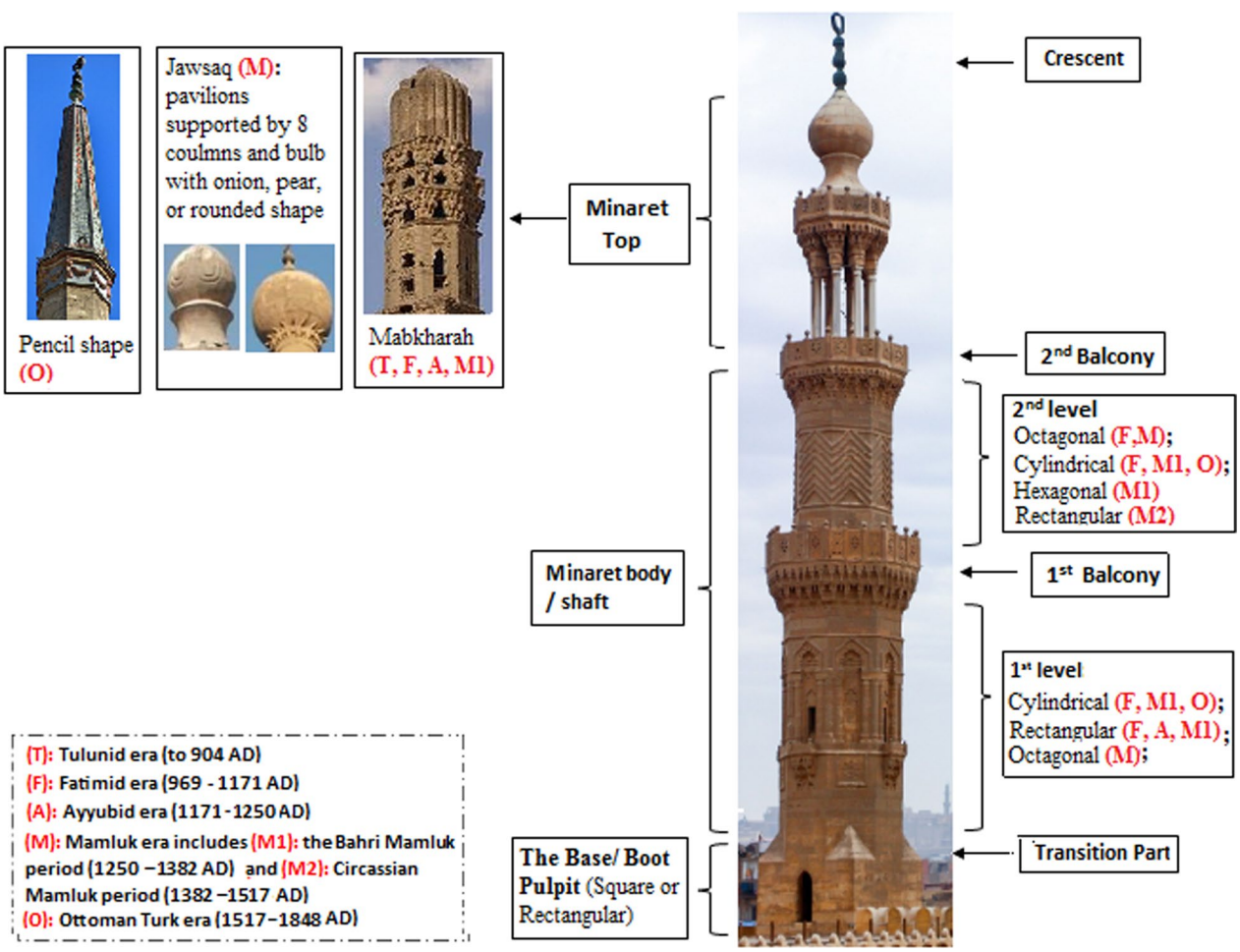

Fig. 1 Anatomy of Cairo's minarets

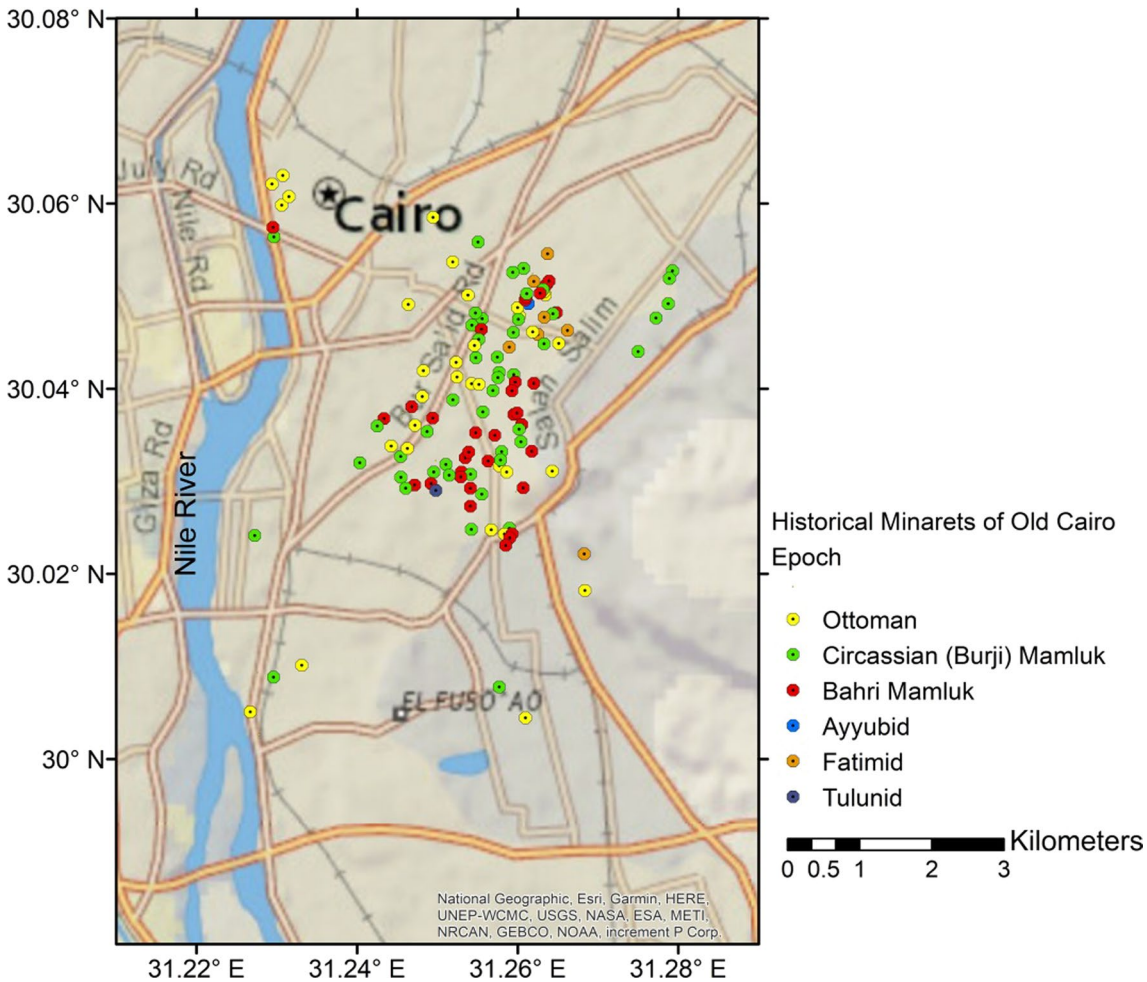

Fig. 2 Geographic distribution of historical minarets in Cairo

The work in the paper is divided as follows. First, a brief view of historical minarets in Cairo is presented in Sect. "Historical minarets in Cairo: anatomy, historical importance and challenges". Then, a review of the geological and seismic aspects of the study area is conducted in Sect. "Geology and seismicity". Sect. "Seismic vulnerability assessment methods" discusses the seismic vulnerability approach used and implemented in the examined minarets. The details and features of the examined minarets, the field measurements conducted on them, the extraction of their fundamental periods, and thecreation of a new fundamental period formula suggested for minarets in Old Cairoare discussed inSect. "Results".Finally, the conclusionsand suggested future work are presentedin Sect. "Results".

Historical minarets in Cairo: anatomy, historical importance and challenges

The minarets in Cairo are considered among the city's most prominent architectural features. Typically, a minaret in Cairo comprises three main parts: a base, a shaft, and a top. The base is usually square, while the shaft tapers towards the top with varying geometries and transitions over various levels. Balconies and staircases are often incorporated to allow access to the various levels of the minaret.

Historically, Cairo's minarets can be categorized into five groups based on the period they were built. These are the Tulunid (to 904), Fatimid (969–1171), Ayyubid (1171–1250), and Mamluk (1250–1517), which isfurther divided into two sub-periods: the Bahri Mamluk (1250–1382) and Circassian (Burji)

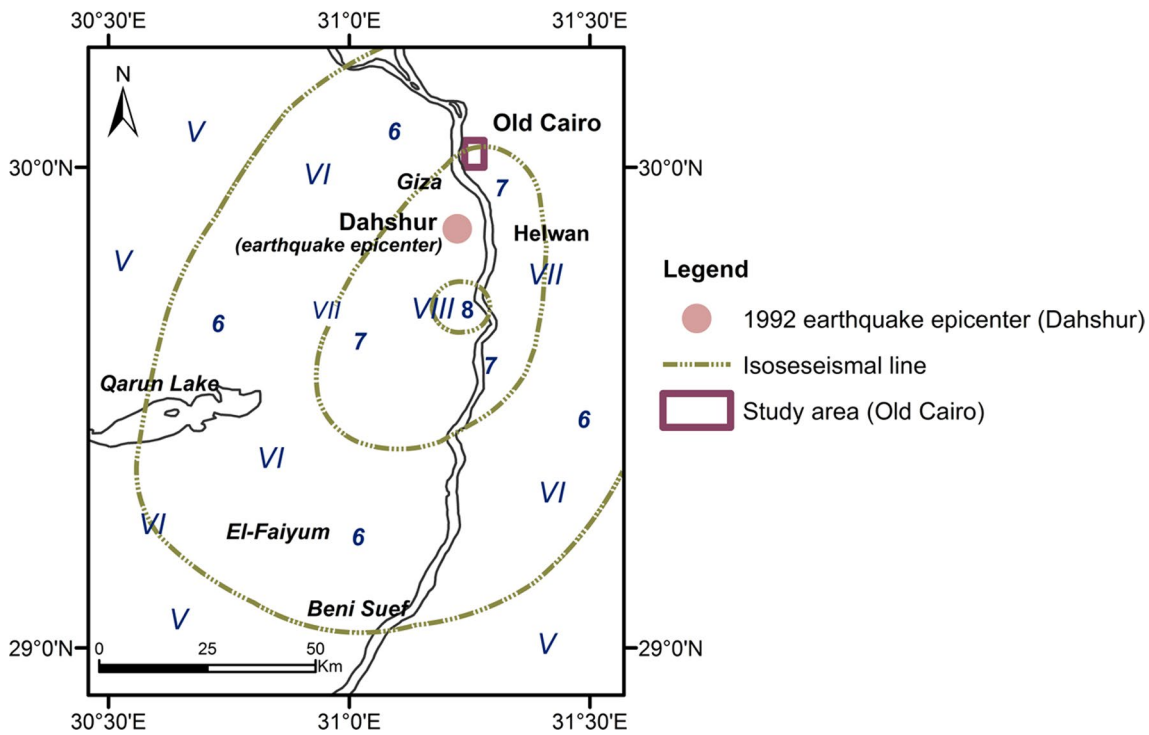

Fig. 3 Iso-seismic map for the 1992Cairo earthquake (after Thenhaus et al. 1993)

Mamluk (1382–1517), and Ottoman Turk (1517–1848). Although the anatomy of the minarets has remained relatively unchanged over time, their dimensions, geometries, and shapes have varied. Figure 1 displays the anatomy of Cairo's minarets and their evolution over time. The minarets in Cairo are not only aesthetically pleasing but also serve as an essential element of Islamic religious practice, with their height and location serving as a call to prayer for the surrounding community.

Historical minarets in Cairo were typically constructed using limestone, the most commonly used material in construction, and bricks, which were used for older minarets. Marble columns supported the tops of the minarets, while the balconies' fences were made from timber and stone. The crescents atop minarets were made of copper, and the tops of Ottoman minarets were covered with lead (Behrens-Abouseif 2010). Figure 2 illustrates the geographic distribution of historical minarets in Cairo. The Old Cairo district has approximately 115 historical mosques and 41 madrasas with minarets and 21 separate minarets (Gaballah and Al-Attar 2000). However, the number of minarets has decreased, with only one Ayyubid minaret remaining in Cairo. Earthquakes have contributed to this decline, as past earthquakes have caused damage and deterioration to many minarets. For example, the earthquakes in 1303, 1847, and 1992 caused significant damage to several historical monuments, including many minarets. The 1992 earthquake, despite its moderate size ($M_w = 5.9$) and distance from Old Cairo, caused considerable damage to more than 200 historical monuments, as shown in Fig. 3, with intensities ranging from VI to VII on the Modified Mercalli Intensity scale (Thenhaus et al. 1993). The earthquake mainly damaged several historical minarets, especially those from the Mamluk era (Sykora et al. 1993).

This study carefully selected eight minarets of different ages, considering different construction methods, architectural styles, and geometrical designs. These minarets are shown in Fig. 4 and include Minaret A from Ahmed ibn Tulun mosque (monument no. 220; Tulunid era), built in 877 on Jabal Yashker. It is the only surviving minaret from the Tulunid era and is unique due to its outside staircase and less slender design compared to other historical minarets in Cairo. Minarets B and C belong to the al-Hakim Mosque (monument no. 15; Fatimid era), founded by Caliph al-Aziz in 990. Al-Hakim added the two minarets in 1003; their bodies were covered by rectangular stone towers in 1010. After the 1303 earthquake, both minarets were decapitated at almost the same level (with only a 1.5 m difference), and Baybars al-Jashnkir rebuilt the missing parts in 1303 (Behrens-Abouseif 2010).

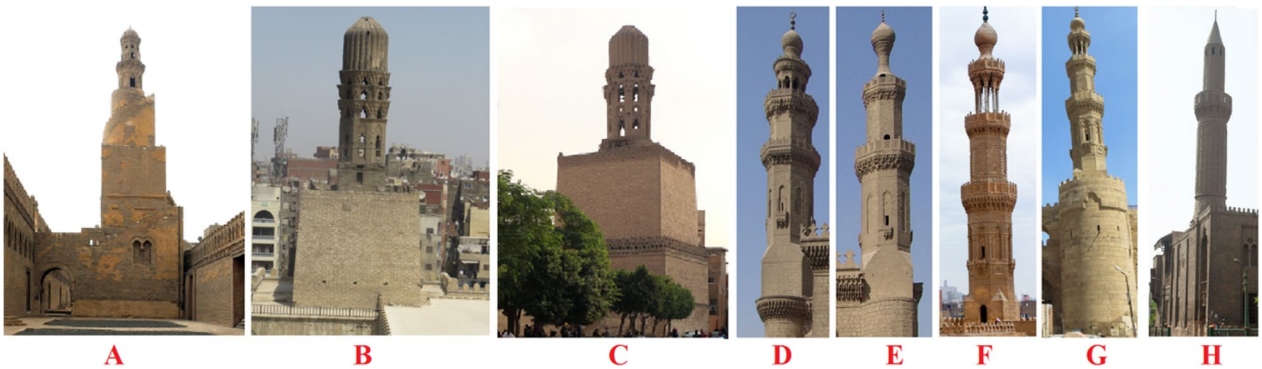

Fig. 4 Recent photos of the selected minarets. **A** Ibn Tulun minaret, **B** the northern minaret of al-Hakim Mosque, **C** the southern minaret of al-Hakim mosque, **D** the southwest minaret of Sultan Hasan mosque, **E** northeast minaret of Sultan Hasan mosque, **F** the west minaret of al-Mu'ayyad Shaykh mosque, **G** the east minaret of al-Mu'ayyad Shaykh mosque, and **H** the minaret of Yusuf Agha al-Hin mosque

Minarets D and E belong to the Sultan Hasan Mosque/Madrasa (monument no. 133; Bahri Mamluk period). The mosque was constructed overlooking Salah al-Din Square between 1356 and 1361 by Hasan ibn al-Nasir Muhammad. The ground on which the mosque was built is rocky and slopes gradually from the citadel to the city. Minaret D is the tallest Mamluk-style minaret, while Minaret E is the second minaret of the mosque. In 1915, the Arabic Committee for Restoring Islamic Heritage dismantled and reconstructed the upper structure of Minaret D. Sykora et al. (1993) documented that the 1992 Cairo earthquake caused a large vertical crack in Minaret D's shaft from inside, a crack between the minaret base and the mosque wall, and cracks in the central column. Meanwhile, Minaret E collapsed in 1659, later rebuilt by the governor Ibrahim Pasha in 1671. The 1992 Cairo earthquake also caused cracks in the central column of Minaret E (Sykora et al. 1993).

The twin minarets F and G are a defining feature of the al-Mu'ayyad Shaykh mosque (monument no. 190; Burji Mamluk period), constructed between 1419 and 1420. The minarets are renowned for their graceful slenderness and are situated on Bab Zuwayla (monument no. 199), a tower built by Badr al-Jamali in 1092. The minarets were added to the existing towers of Bab Zuwayla, and borehole investigations have revealed that the area is composed of rubble fill, which extends up to ten meters in depth. The upper portions of both minarets were lost in the 1863 earthquake, but they were rebuilt in 1892 by the Arabic Committee for Restoring Islamic Heritage. On the other hand, minaret H belongs to the Yusuf Agha al-HinMosque (monument no. 196; Ottoman era), constructed in 1625 as a standalone building overlooking Port Said Street. While the mosque follows Mamluk architecture, its minaret is of Ottomanstyle. The 1992 Cairo earthquake caused significant deterioration to the minaret, leading to a restoration project by the Supreme Council for Antiquities in 1999, which involved assessing the degree of incline, repairing cracks in the balcony and the minaret's body, cleaning the stones, and restoring the original colour (Supreme Council for Antiquities 1999).

Geology and seismicity

Seismic hazards for historical monuments are affected by controlling sources and site conditions. Even if two sites are at the same distance from the epicentre, local site conditions can significantly impact ground shaking intensity (FEMA 2006; Theilen-Willige 2010).In propagating from bedrock to the surface, seismic waves change frequency and amplitude due to geology and topography (Bowden and Tasi 2017; FEMA 2006).Soil-structure interaction can also alter seismic behaviour and damage patterns of structures, with soft soil types and hilltops amplifying ground motions and causing significant damage to structures (Hacıefendioğlu 2010; Gabr 2017; Casolo et al. 2017), especially when the frequency content and natural frequencies of the structures match (Arnold 2006).

Historical structures in Cairo were often constructed on the ruins of earlier structures, with the soil consisting mainly of clay, sand, or rock, depending on the location. Clay is found in lowlands, while rocky soil is more common near Mokattam Mountain (Rappai and Khairy 2012). Groundwater level fluctuations are the primary cause of soil problems in Cairo, with specific areas, such as Port Said Street, having exceptional soil characteristics due to filling large canals (Rappai and Khairy 2012). Cities built on soft sediments have experienced significant earthquake damage due to amplified ground motion, such as Cairo, after the 1992 earthquake (El-Sayed et al. 2001; Hassan et al. 2017; Hassan et al. 2020; Badawy et al. 2017; Goda et al. 2018). Moreover, most of Cairo's historical buildings were not designed to withstand earthquake

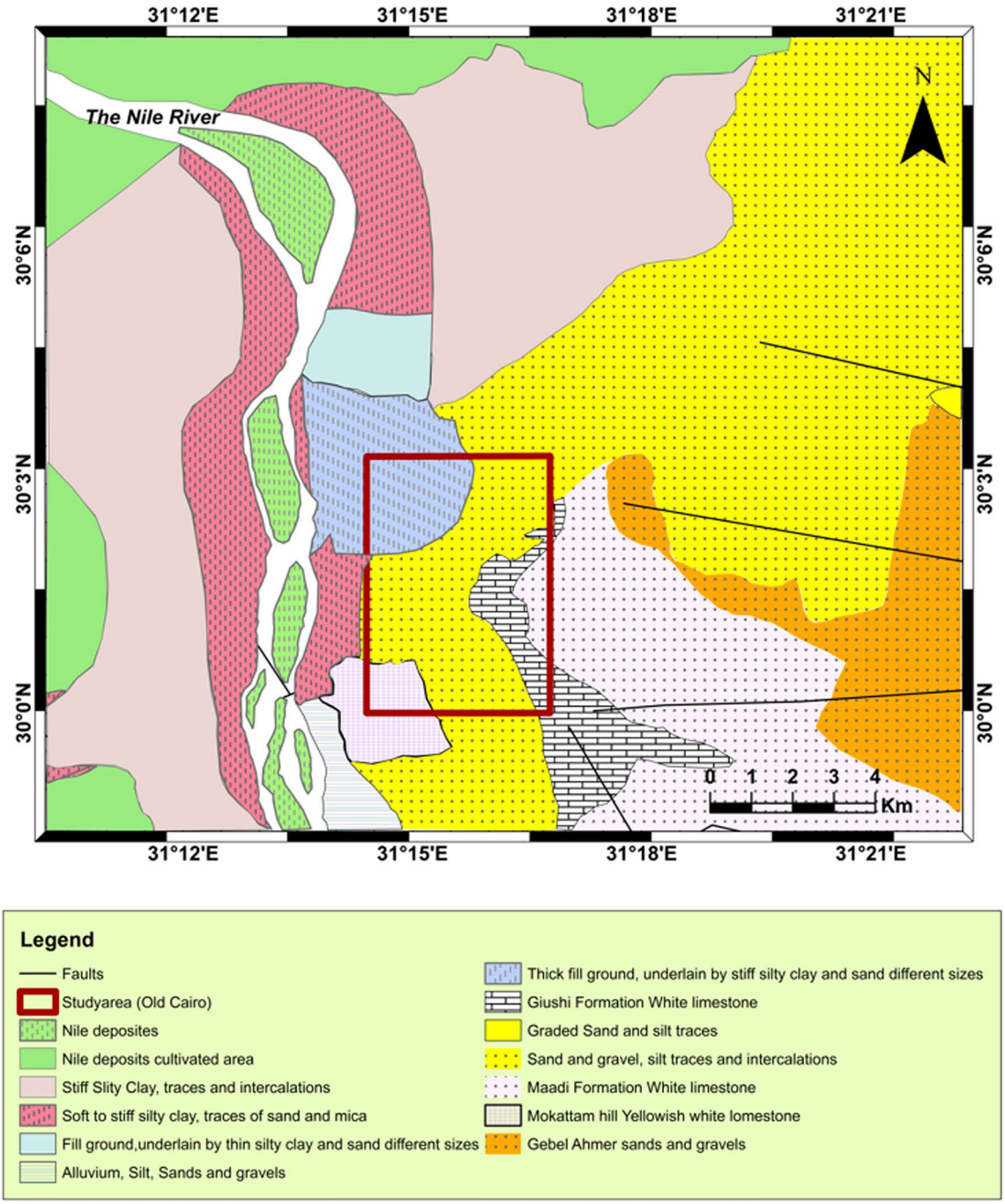

Fig. 5 Surface geology of Cairo

loads, emphasizing the need for a comprehensive understanding of the study area's surface/subsurface geology and seismicity.

Cairo is situated on both sides of the Nile River, approximately 20 km south of the point where the Nile splits into two branches, Rosetta and Damietta. The area encompasses the Nile River floodplain and extends approximately 12 km from the Mokattam Hills in the southeast to the Pyramids plateau in the west.

Cairo's foundation bed is composed of various geological formations, as depicted in Fig. 5. The oldest rocks, dating back to the Cretaceous period, form the base on which the Pyramids of Giza and Abu Roash are situated. The Eocene formation primarily comprises limestone

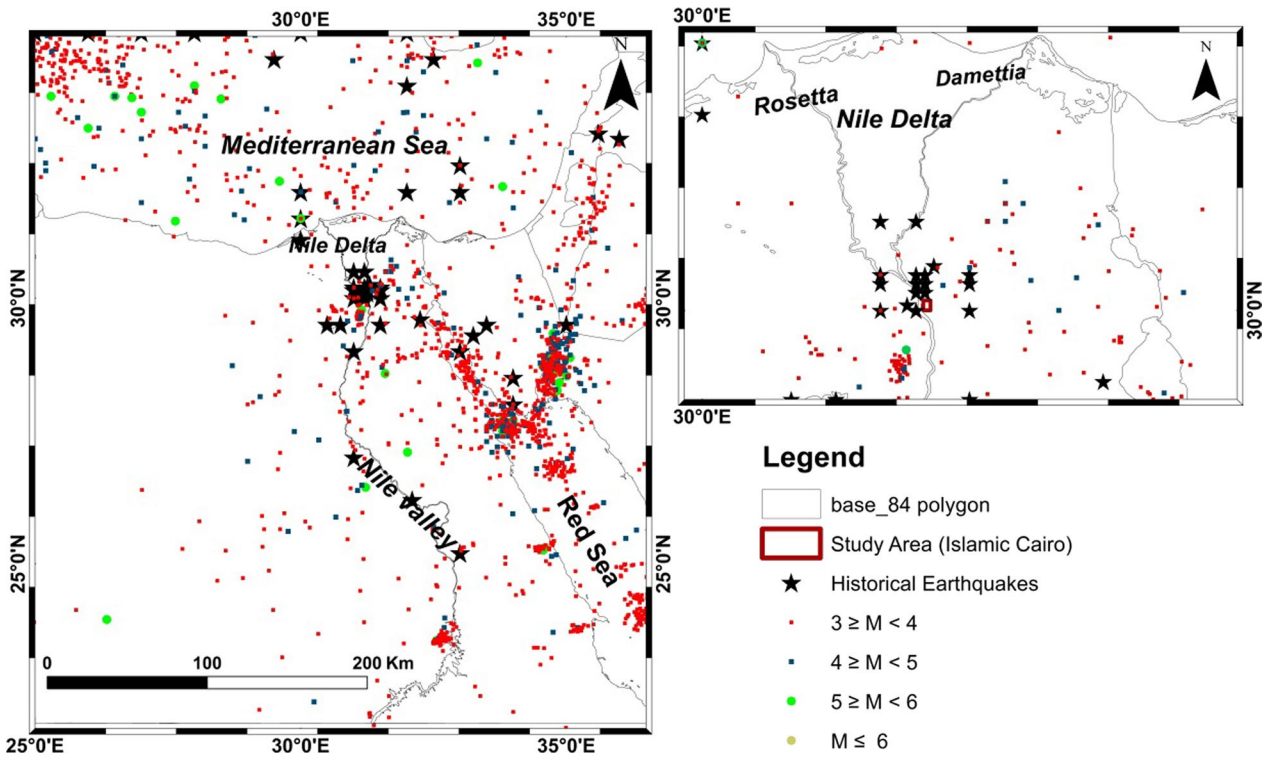

Fig. 6 Seismicity of instrumental and some of the historical earthquakes of Cairo (Instrumental earthquakes on the map are rated M ≥ 3)

outcrops, such as the Mokattam hills in the east and the Pyramids plateau in the west. In the area, the Oligocene formation consists of two facies: (1) Gebel Ahmer gravels and sands and (2) basalt flows. The Miocene outcrops in northeastern Cairo are marine sediments containing sands with fossils and sandy limestone. Finally, the Pliocene marine deposits on the Sphinx ditch's south side are made up of sandy limestone beds and marl.

The surface geology of Cairo has been extensively described by various researchers, including Said (1962), El-Shazly et al. (1977), Said (1981), Strougo (1985), and Moustafa et al. (1985). The region's landscape is affected by several fault systems, with the Mediterranean trend (EW) and the Clysmic trend (NW–SE) being the most prominent within the area of interest. These tectonic trends consist mainly of faults with steep planes, forming part of the Horst complex and Graben (Shata 1988). Minor folding is associated with faulting in Heliopolis's Gebel Mokattam and east areas, while the Syrian Arc System folds dominate the Abu Roash area. This system comprises folds extending across northern Egypt's unstable shelf area (Shata 1988). In addition, Said (1981) indicated that the basin is fault-bounded and was eroded in the late Miocene by the Eonile.

Egypt is in a region of moderate seismic activity, with earthquakes recorded as far back as 2200 BC (Kebeasy 1990). The country's seismic activity is primarily due to the relative movements between the African, Arabian, and Eurasian plates and intraplate earthquake sources (Abou Elenean 2007; Abou Elenean et al. 2009). Figure 6 shows that seismic activity is concentrated in the northern part of Egypt, where the epicentres of historical and instrumental earthquakes are distributed along three main trends: the Levantine Aqaba trend, the Northern Red Sea-Gulf of Suez Alexandria-Cairo trend, and the East Mediterranean Cairo-Fayum trend (Dahy 2010).

Cairo is located in an area susceptible to seismic activity, particularly in the northern Red Sea and eastern Egypt. El-Hadidy (2008) has identified several active seismic zones that may affect Cairo, including Dahshur, the Cairo-Suez district sources, the Northern, Middle, and Southern Gulf of Suez, the Northern Red Sea, Beni Suef, the Cairo-Suez district, North Sinai, and the Mediterranean coastal dislocation zone. The Cairo-Suez district is a tectonically unique region in Egypt's northern part. The northern boundary of the African plate is characterized by convergence and interaction between the African, Arabian, and Eurasian plates, while the east boundary is characterized by divergence. These unique features make northern Africa more prone to seismic activity than other parts.

Table 1 Vulnerability parameters, their weights, scores of classes, and I_V method by Shakya et al. (2018)

Parameter	Weight (W_i)	Parameter	Weight (W_i)
(P1) Type of resisting system	1.00	(P7) Irregularity in the plan	1.00
(P2) Quality of the resisting system	1.50	(P8) Irregularity of elevation	1.50
(P3) Conventional strength	1.50	(P9) Wall openings	1.00
(P4) Slenderness ratio	1.50	(P10) Flooring and roofing systems	0.50
(P5) Location and soil conditions	0.75	(P11) Fragilities and conservation state	1.00
(P6) Position and interaction	1.50	(P12) Non–structural elements	0.25

The seismic history of Egypt has been well documented by several authors, including Ambraseys (1961), Maamoun (1979), Kebeasy (1990), Ambraseys et al. (1995), and Riad et al. (2004), Abd El-Aal et al. (2019). Although only a few earthquakes were recorded during and after the Islamic period, eight were reported in the tenth century. Earthquake numbers dramatically declined in the eleventh and twelfth centuries during the Fatimid era but increased to ten in the fifteenth and sixteenth centuries during the Mamluk era. However, there was another dramatic decline in the seventeenth and eighteenth centuries during the Ottoman era, followed by the highest number of earthquakes (seventeen) recorded in the nineteenth century. Many historical earthquakes with estimated magnitudes ranging from 5 to 7 have caused significant damage in populated areas of Northern Egypt, including Cairo, the Nile Delta, El-Fayum, and the Mediterranean Sea. For instance, the earthquake in 1303 near Fayum severely damaged mosques and minarets in Cairo (Maamoun 1979). Then, in 1847, another earthquake with an estimated magnitude of 6.8 struck Fayum, killing about 212 people, injuring 1000 others, and destroying around 3000 houses and 42 mosques (Kebeasy and Maamoun 1981; Ambraseys et al. 1995). Other destructive earthquakes have also caused extensive damage to Cairo, Alexandria, the Nile Delta region, and Ismailia, such as earthquakes in 887, 1111, 1698, 1754, 1870, 1955, and 1992.

Seismic vulnerability assessment methods

Seismic vulnerability assessment is essential in assessing a structure's ability to withstand earthquakes. It is a diagnostic analysis that aims to evaluate the structure's seismic response and potential levels of damage during an earthquake. Slender masonry minarets are particularly vulnerable to seismic demands (D'Ambrisi et al. 2012). Minarets are known for their remarkable slenderness and limited masonry ductility, resulting in brittle structural behaviourssimilar to a vertical cantilever fixed at the base (Abruzzese et al. 2009). In addition, historical masonry minarets typically lack adequate seismic resistance design (Pineda et al. 2011; Chisari et al. 2015). Seismic vulnerability studies of slender masonry structures gained importance after the collapse of the Civic Tower of Pavia in Italy in 1989 (Gentile and Saisi 2007). In Cairo, historical minarets are prone to challenging deterioration of different magnitudes, leading to partial or total collapse during moderate to significant seismic hazards. As such, it is critical to evaluate the seismic vulnerability of the Cairene minarets using an urgent practical approach.

The assessment of seismic vulnerability involves various approaches that are continuously evolving, and they can be broadly categorized into empirical and analytical methods. Empirical methods rely on the physical inspection of the structure and involve using vulnerability indices. Analytical methods, on the other hand, use ground motion simulations to determine the level of physical vulnerability of the structure (Calvi et al. 2006; Vicente et al. 2011; Kassem et al. 2020). The choice of the appropriate method for evaluating a structure's seismic vulnerability depends on several factors, such as the availability and quality of information, the study's objectives, and the structural characteristics of the building. Therefore, it is essential to consider these factors carefully to ensure that the selected method provides accurate results and implements effective risk-reduction strategies.

Over the last few decades, several analytical methods have been developed to investigate the seismic vulnerability of slender masonry structures. These methods analyze individual buildings in detail, considering various types of uncertainty. However, they are often sensitive to the analysis and modelling approaches used and require significant time and information that may not be readily available for most historical monuments. As a result, many assumptions and generalizations are made to fulfill the basic requirements of the analysis(Kassem et al. 2020). On the other hand, there have been limited efforts to develop relevant empirical assessment tools for historical monument structures. One such tool is the tower-like masonry structures assessment approach, based on the Italian Group of National Defense-II (GNDT II) approach by Speranza et al. (2006), which Sepe et al. (2008) then modified to be more convenient for this specific structure type. In addition, some parameters, such

Table 2 Details and features of the examined minarets

Minaret	Era	Height (m)	Description	Openings	Position	Special features
A	Tulunid	40.4	The minaret has a shaft with a square section that is developed into a circular one, then an octagonal cross-section surmounted by the "mabkhara" and a crescent	Total = 5 (Main door + four openings at the octagonal section)	The minaret was built as a separat-earchitectural element on the north-west side of the mosque	The only Samarra minaret style in Cairo The least slender Cairne historical minaret
B	Fatimid	46	The minaret consists of a tapering cylinder that stands on a square base and carries an octagonal tapering section, then mabkharah with a platform ofwooden railing	Total = 9 (main door + four beneath the mosque roof's level + four above the mosque roof's level)	Both minarets were built as separate structures enclosed by a rectangular stone tower 3 m away that covers its lower portion by whichminarets appear as projected elements at the corners of the main façade of the mosque	3 spiral staircases: The internal stone staircase. And two exterior staircases. A steel external staircase ends at the mosque's roof; the stone staircase starts from the mosque's roof and leads externally to the uppermost part of the minaret
C		41	The minaret has a rectangular section carrying an octagonal tapering section, then mabkharah	Total = 16 (Main door + eightbeneath mosque roof's level + sevenabove mosque roof'slevel)		
D	Bahri Mamluk	81	Each minaret consists of a square base, carrying a vertical shaft with two balconies that change its cross-section from an octagon to a smaller octagon, followed by a cap (i.e., jawsaq) with an onion-shaped bulb. Jawsaq of minaret D is supported on eight columns	Total = 6 (Main door + four openings onthe-firstfloor + firstbalcony door)	Minaretswere erected at the corner on a massive buttress (i.e., a semi-circular faceted tower) of the main façade of the mosque	Minaret D is the tallest minaret with mamluk-style.Access to the main door of the Minaret D is through an adjacent stone structure with a 25-ring-spiral stone staircase.Fourwooden ties supported Minaret E
E		60		Total = 7 (Main door + fouropenings in 1st floor + first balcony door + 1 opening in the secondfloor)		
F&G	Burji Mamluk	39	Each minaret consists of a square base with 13*4.40 m. Only 4m height of this base appears on Bab Zewila roof as a square base that changes to an octagon to a smaller octagon cross section and, finally,jawsaqsupported on eight marble columns. Minarets have shafts with two balconies	Total = 5 (Main door + three openings on the first floor + firstbalcony door)	Both minarets were grafted on Bab Zewila towers	Twin minarets.The special location and notable slenderness between Mamluk minarets
H	Ottoman	29.4	The minaret has a square base with a cylindrical shaft, a balcony that changes to a smaller cylindrical cross-section with eight openings, and a conical cap (i.e., a pencil-shaped top)	Total = 12 (Main door + opening leads to secondmosque floor + opening leads to mosque roof + balcony door + eight openings at the minaret's top)	The minaret has a high base that extends to the upper end of the southeastern façade of the mosque and protrudes slightly from it by 27 cm	It is the shortest minaret in the case study. Three wooden ties supported different parts of the minarets

Fig. 7 Different levels of present deterioration of minarets' parts

as planimetric layout ratio and maximum span between walls, were eliminated, and parameter weights were calibrated based on documentary material of the damage to similar structures.

In recent years, there have been efforts to develop empirical assessment tools for slender masonry structures, including minarets and chimneys. Shakya et al. (2018) have extended the GNDT II approach to these structures by defining parameter classes and weights based on literature, expert opinions, and parametric analysis results. The GNDT II approach is then combined with the Macroseismic method to estimate the damage level of the structure at a specific Macroseismic intensity level (EMS-98 scale) using vulnerability index values. This method represents a promising approach to evaluating the seismic vulnerability of slender masonry structures practically and efficiently.

Empirical methods used in seismic vulnerability assessment have limitations that stem from various factors, including personal judgment during the investigation and a lack of data, especially for old structures that underwent previous interventions such as maintenance, rehabilitation, or rebuilding (Ceroni et al. 2009). However, despite their limitations (Kassem et al. 2020), empirical methods provide a preliminary assessment of the studied structures, identify deficiencies in structural and non-structural components, and anticipate potential damage levels that may occur during an earthquake ata certain intensity. Moreover, these methods can be applied to structures of any scale, rank them based on their seismic vulnerability, and prioritize those needing immediate intervention while reducing the time and cost required to carry out these methods. These reasons, among others, motivated the authors to test and apply an empirical method to assess the seismic vulnerability of historical masonry minarets in Cairo, primarily since these techniques have not been used before for Cairene minarets. In addition, temporary ambient vibration tests on the minarets of interest were performed to enhance the method's effectiveness and provide a database of the dynamic characteristics required for future detailed dynamic and seismic risk reduction analyses.

This study adopts the empirical method that Shakya et al. (2018) developed to evaluate the seismic vulnerability of slender masonry structures. The empirical process can be summarized into two main steps. In the first step, a vulnerability index (I_V) is calculated by considering 12 parameters that influence the structure's vulnerability. The calculation is based on the GNDT II level (GNDT-SSN 1994) using a formula shown in Eq. (1). The parameters considered include construction

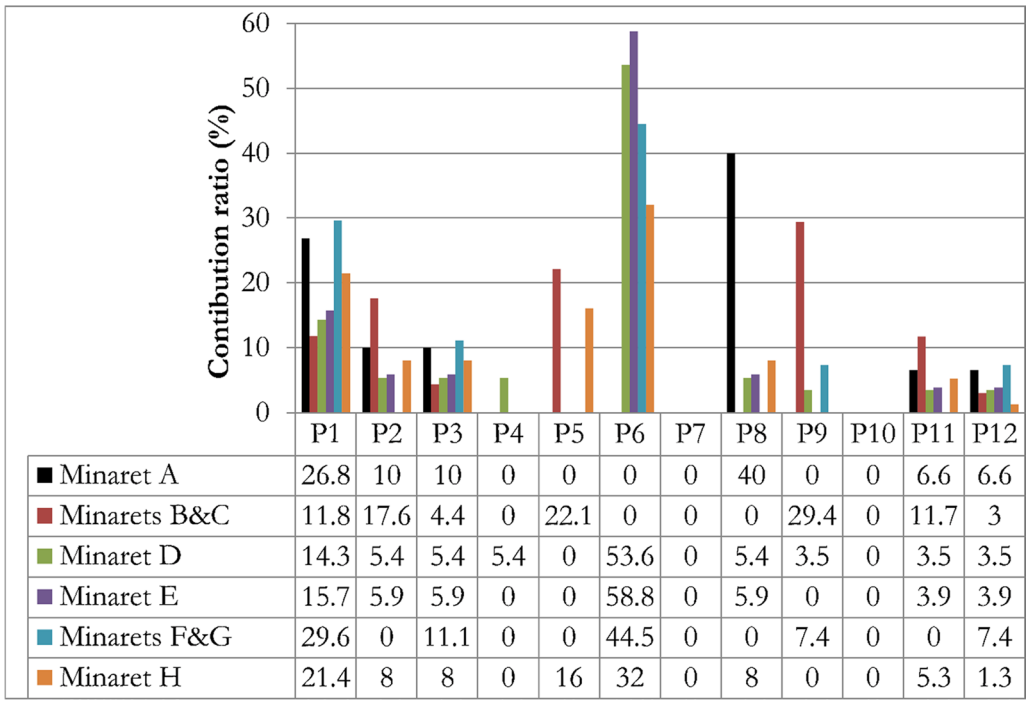

Fig. 8 The contribution of each vulnerability parameter to the final I_V values of minarets in the study

materials, slenderness ratio, soil-structure interaction, the position of minarets, irregularity in plan and elevation, openings, fragilities of minarets, and non-structural elements. Each parameter is assigned a weight that indicates its contribution to the damage caused to the structure during an earthquake. Table 1 shows the weights of the parameters used in this study, which range from 0.25 for less critical parameters to 1.5 for more critical ones. Each parameter is assigned one of four classes (A, B, C, and D), with scores ranging from 0 to 50. The parameter weights and scores in Shakya et al. (2018) were adopted based on pushover analyses and finite element numerical models of selected structures, considering different scenarios of seismic vulnerability. The vulnerability index output value ($0 \le I_V^* \le 650$) is normalized to a range of ($0 \le I_V \le 100$). For more information, refer to Shakya et al. (2018).

$$I_V^* = \sum_{i=1}^{12} i_v W_i \tag{1}$$

where I_V^* vulnerability index before the normalization, i_v is the score of the parameter's class, W_i is the parameter weight.

The second step involves the calculation of the damage probability matrix (DPM), which provides the probability of a particular damage level that a structure may experience when exposed to an earthquake of a given intensity (Whitman et al. 1973). The DPM provides definitions of mean damage grades (μ_D) by an earthquake with a certain intensity in terms of vulnerability curves that give the probability of damage grades as a function of each level of an intensity scale. Vulnerability curves for masonry minarets under investigation are essentially based on the original approach of the GNDT II level (GNDT-SSN 1994), with few significant modifications of slender masonry structures carried by Shakya et al. (2018) and its correspondence on the macro-seismic scale. The correlation of the mean damage grade and seismic intensity (I) can be achieved using the conventional vulnerability index (V) by Eqs. (2) and (3).

$$\mu_D = 2.5\left[1 + \tanh\frac{I + 3.4375V - 8.9125}{Q}\right] \tag{2}$$

$$V = 0.46 + 0.0056I_v \tag{3}$$

where μ_D is the mean damage grade, I is the macroseismic intensity, Q is a ductility factor, V is the conventional vulnerability index, and I_V is the value vulnerability index resulting from Eq. (1).

Results

A detailed inspection of each minaret is achieved to notice its present condition. Some minarets' parts have different levels of deterioration,as shown in Fig. 7.

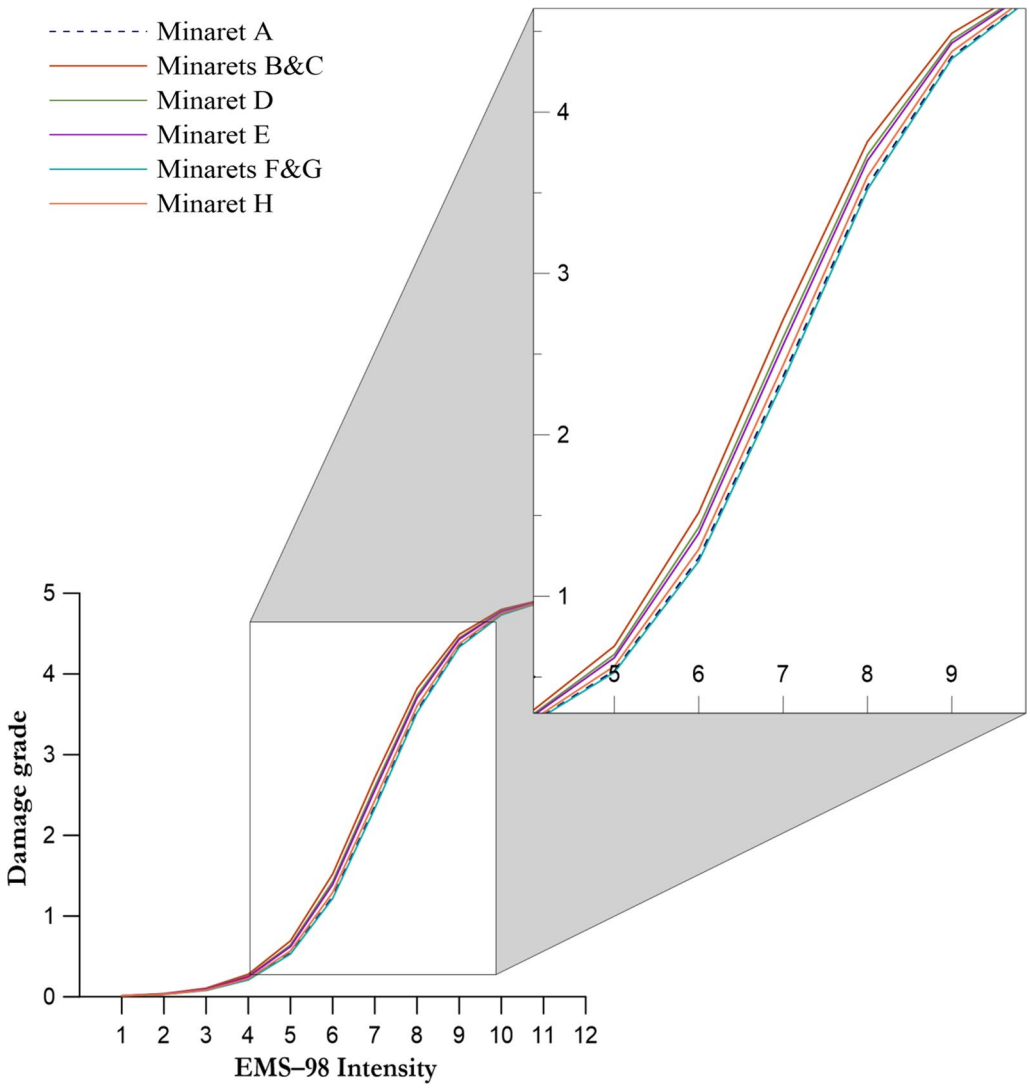

Fig. 9 Vulnerability curves of the minarets

Figure 7(a1) and (a2) show the uppermost part of the Ibn Tulun minaret. Figures 7(b1) and (b2) show the body and the upper part of the northern minaret of al-Hakim Mosque. Figure 7(c1) shows the part beneath the octagonal section and Mabkarah of the southern minaret of al-Hakim Mosque, while Figure (d1) and (d2) shows the staircase and interior surface of the second floor of the southwest minaret of Sultan Hasan Mosque. Figure 7(e1) shows the wooden tie at the northeast minaret of Sultan Hasan Mosque, and Fig. 7(f1) shows the chipped tiles of the west minaret of al-Mu'ayyad Shaykh mosque. Figures 7(h1) and (h2) show the shaft of Yusuf agha al-Hin minaret. Table 2 shows the features and details of the examined minarets.

The I_V are calculated according to the state of each vulnerability parameter. The contribution of each parameter to the final I_V values of minarets are shown in Fig. 8. Based onthese values, shown in Table 1, vulnerability curves are drawn in Fig. 9 for each minaret. In these curves, the conventional vulnerability indexes of the minarets are interpreted in terms of mean damage grades for seismic events with varying intensity on the EMS-98 scale. In addition, as illustrated in Fig. 10, these different mean damage grades can be interpreted in terms of the expected damage levels of structural and non-structural minarets' elements due to events with different seismic intensity levels.

The dynamic characteristics of each minaret were assessed using a non-parametric approach known as

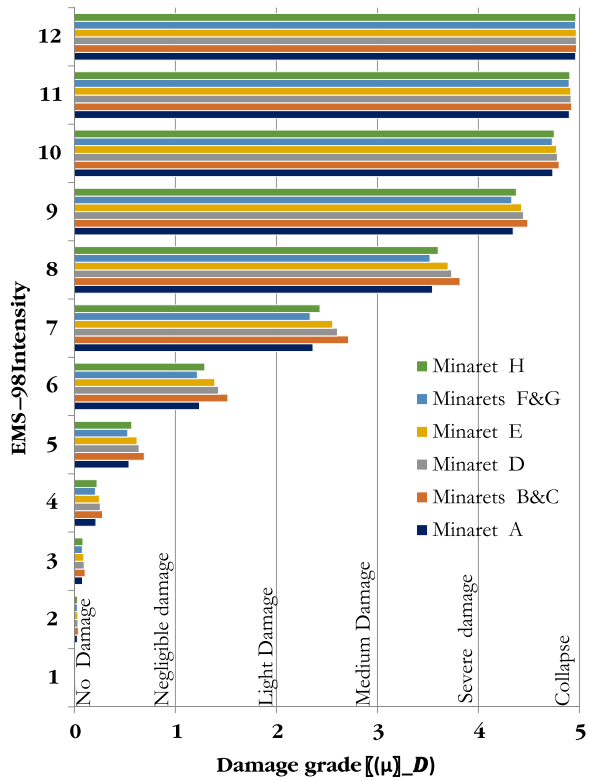

Fig. 10 The interpretation of (μ_D) with different seismic intensity (EMS-98) levels regarding the expected damage levels

the Peak-picking method, a sub-method of AVTs, which directly determines the natural frequencies of structures at each peak of the power spectral density (PSD) graphs (Bindi et al. 2015; Serhatoğlu and Livaoğlu 2019). AVTs were conducted at various heights on the selected minarets, as specified in Table 3 and Fig. 11. Extracting the dynamic characteristics from the AVT data recorded at each station for every minaret, any variations in the obtained values were deemed significant for structure health monitoring analysis. Employing the McSEIS-MT NEO station (model 1134), an accelerometer sensor from OYO Corporation, shown in Fig. 12, was the adopted data logger for AVTs in this study. Each minaret was equipped with 3 or 4 sensors, thoughtfully balanced and oriented northward at different heights along the body of the minaret. The sensors were sequentially named from the base to the top of the minaret. Starting at the base, we have Sensor 1, then Sensor 2 positioned above it, progressively ascending towards the top.

The twin minarets (F and G) were equipped with sensors positioned at the same elevation and direction, configured to record ambient vibrations for one to two hours, utilizing a 100 Hz sampling rate across three channels (EW, NS, and UD), and synchronized through attached GPS antennas. EW is the east–west direction, NS is the north–south direction, and UD is the up-down direction. Post-processing using Geopsy (version 3.4.2 available at http://www.geopsy.org) involved baseline correction and a fourth- or sixth-order Butterworth-Bandpass filter to optimize the data within a suitable frequency range. An exemplary illustration in Fig. 13 showcases of the filtered ambient vibration recorded at the base of Minaret F (al-Mu'ayyad Shaykh mosque), which remarkably required no additional post-processing for baseline correction, showcasing the study's dedication to precise and accurate results. Figure 13 shows that the amplitude of the horizontal components (EW and NS) is higher than the vertical component (UD), as expected due to the natural modes of the minaret. The obtained healthy signal without unwanted signals does not need extra post-processing steps.

Figure 14 displays the power spectrum density of all four sensors, capturing data in both the EW and NS directions for Minarets D and E. From the analysis of Minaret D, the fundamental (first mode) frequency was found to be 0.76 Hz, whereas for Minaret E, it was determined to be 1.8 Hz. Extending this analysis to the

Table 3 Metadata for ambient noise measurements

Minaret	Measurement date	Number of sensors	Start time	End time	Duration (min)	Number of samples
A	April 5, 2021	4	13:00	15:00	120	720,000
B	April 8, 2021	3	14:45	16:40	106	636,000
C		3	12:30	14:08	98	588,000
D	April 9, 2021	4	12:03	13:56	113	678,000
E		4	15:00	16:00	60	360,000
F&G	March 30, 2021	4	12:31	13:38	66	400,096
F		4	15:50	16:44	54	324,000
G		4	14:00	15:00	60	360,000
H	April 7, 2021	4	14:00	16:00	120	720,000

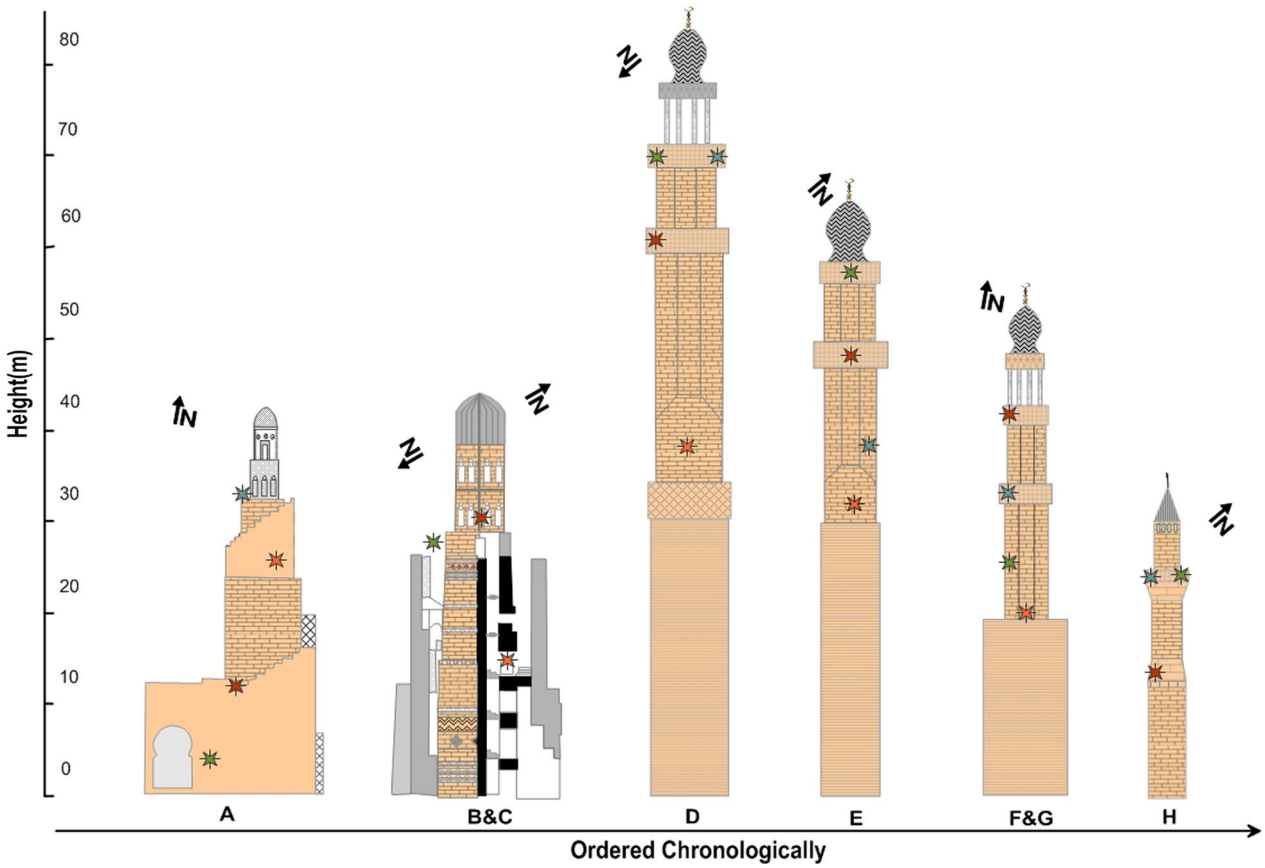

Fig. 11 Location of sensors (as stars) in various minarets

Fig. 12 McSEIS-MT NEO station with model 1134 from OYO corporation

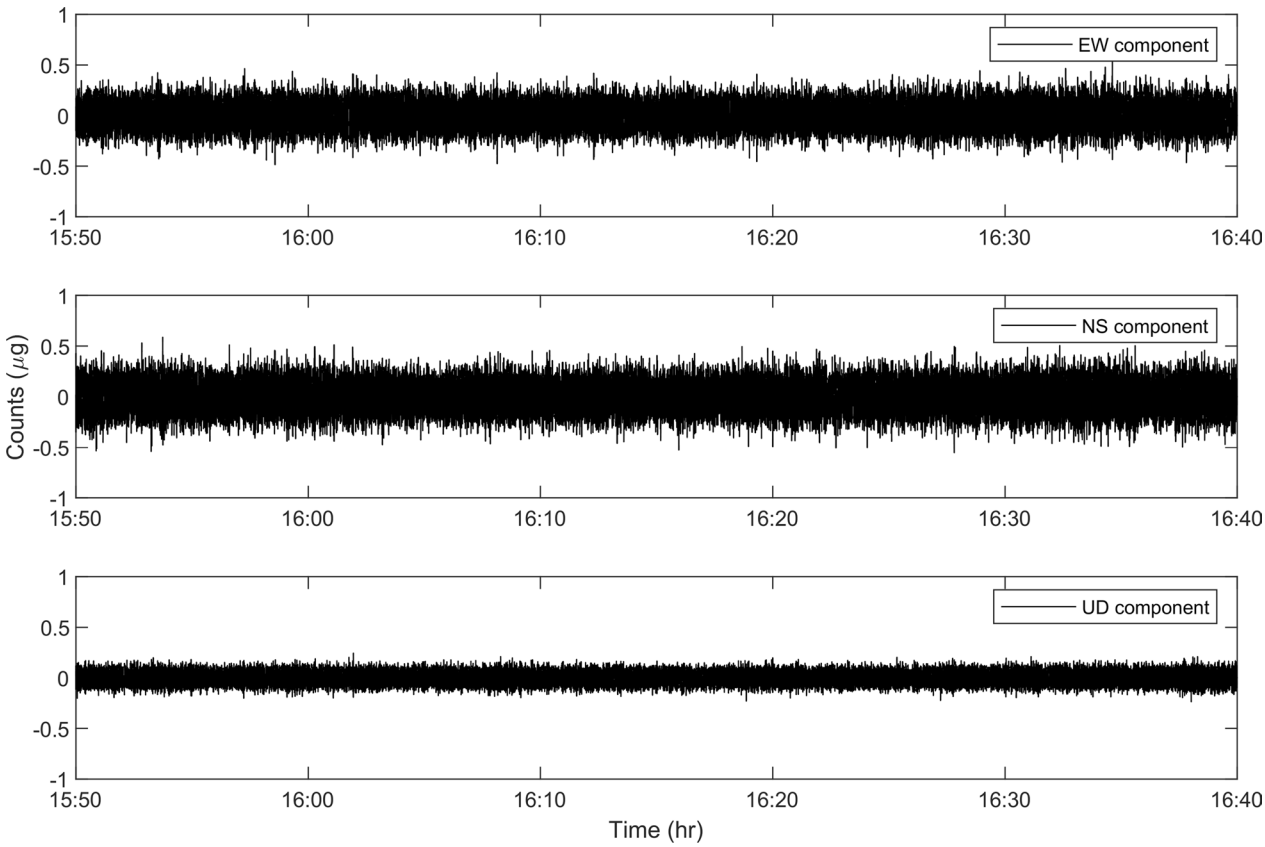

Fig. 13 Ambient noise time series at the base of Minaret F (al-Mu'ayyad Shaykh mosque)

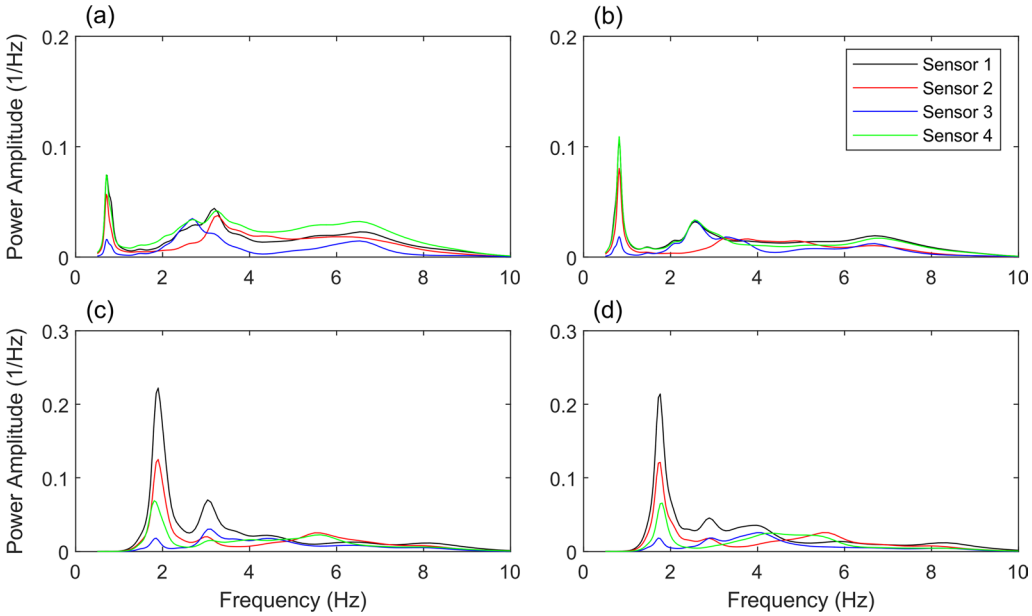

Fig. 14 Power spectrum densityof allfour sensors **a** minaret D in NS direction, **b** minaret D in EW direction, **c** minaret E in NS direction, and **d** minaret E in EW direction

Table 4 The first and second frequencies and the I_V value for all minarets

Minaret	Frequency (Hz)		I_V %
	First mode	Second mode	
A	1.48	3.45	11.5
B	1.47	1.80	26.1
C	1.41	1.95	
D	0.76	2.61	21.4
E	1.80	2.96	19.6
F	1.22	3.12	10.3
G	1.22	3.10	
H	2.51	4.56	14.4

remaining minarets, the fundamental and second mode frequencies of all minarets are summarized in Table 4. Also, the calculated vulnerability index for the minarets is summarized in Table 3.

In developing an empirical equation for estimating the fundamental period of masonry minarets, a comprehensive database from literature was compiled, encompassing geometrical and dynamic characteristics of 52 minarets (e.g., El-Attar et al. 2001, 2005; Doğangün et al. 2008; Zaki et al. 2008; Cosgun and Turk 2012; Oliveira et al. 2012; Amir et al. 2014; Hassan et al. 2023; Serhatoğlu and Livaoğlu 2019; Nohutcu 2019). The database included essential parameters such as height, base dimensions, material properties, and dynamic response data. It is worth noting that Shakya et al. (2014) proposed an empirical equation that estimates the fundamental period of slender structures, as shown in Eq. (4):

$$T = 0.1178H^{0.533} \tag{4}$$

where T is the fundamental period, and H is the structure's height. The relation between the fundamental period and height of structures from the collected 52 structures from literature and minarets in this study, along with Eq. (4), is plotted in Fig. 15. The results show that Eq. (4) could not reasonably match the fundamental period of very short and tall minarets. Therefore, there was a need to propose a new empirical equation that fits the measurements collected in the selected minarets in this study, which then can be applied to most minarets in Old Cairo. The proposed equation was created on the following basis function following various seismic design codes that correlate the fundamental period of the structure with its height as follows:

$$T = \alpha H^{\beta} \tag{5}$$

where, α and β are constants depending on the structural lateral load-resisting system of the structures. The

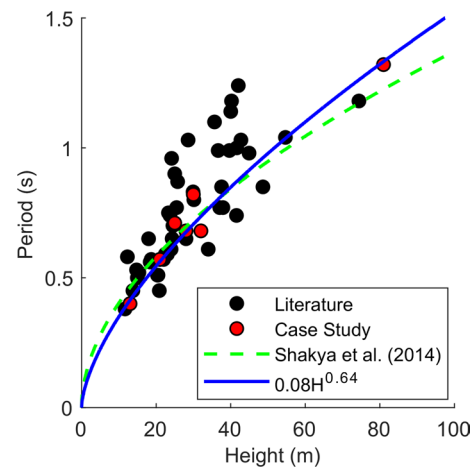

Fig. 15 Measured and calculated the fundamental period of structures

measurements of this study were utilized to estimate the constants that best fit the measured fundamental periods of the minarets. The proposed equation is as follows:

$$T = 0.08H^{0.64} \tag{6}$$

The proposed equation fits the measured fundamental periods, as shown in Fig. 15.

Conclusions and recommenations

Indirect damage to other elements of the mosque, Madrasas or surrounding buildings is another concern. Minarets are typically located near mosques, and their failure can cause structural damage to the main prayer hall, domes, walls, and other architectural components, which can lead to further collapse or instability of the affected buildings, posing risks to the safety of individuals inside and around the mosque.The potential loss of life resulting from minaret failure is a significant concern, particularly during prayer times when mosques are densely populated. Moreover, mosques are sometimes used as shelters during crises or disasters, and the failure of a minaret can endanger the lives of people seeking refuge and assistance.

The recent study examined the seismic vulnerability assessment of eight masonry minarets in the historic Old Cairo district. The examination revealed vulnerability index values from 10.3 to 26.1, signalling a disconcerting susceptibility to seismic events among these structures. Also, the vulnerability curves were constructed for each minaret, visually representing potential damage scenarios across a spectrum of EMS-98 intensity scale levels. These outcomes are significant as they facilitate prioritizing interventions to safeguard the most imperilled minarets.

Despite the persistent uncertainties accompanying empirical methods, the study unveils the spectre of damage wrought by earthquakes of varying intensities on minarets. The study recommends refining the adopted methodology by selectively excluding parameters incongruous with the structural attributes of the selected minarets, such as the flooring and roof system (P10), and instead, accentuating factors like the soil-structure interaction (SSI). In parallel, reconsidering the weightings assigned to various parameters is advocated, notably the parameter of location and soil condition (P5). The need for parametric studies exploring the intricacies of SSI is recommended to discern the true impact of the site and soil conditions on vulnerability,

In light of the region's susceptibility to seismic activity, historical minarets remain perched on the precipice of earthquake-induced peril. Our strategic placement of sensors at multiple elevations along each minaret has yielded invaluable insights into their behaviour under the influence of seismic forces. This initiative enabled extract their natural frequencies, a pivotal determinant in comprehending their response to seismic ground shaking. The recorded vibration data were analyzed using the peak-picking method, unveiling the dominant frequencies of the minarets.

As a significant contribution, a novel empirical period equation wasintroduced to estimate the fundamental period of minarets in Old Cairo to their heights. The empirical equation was validated against the field measurements and data from the literature. The recent study is constrained by its focus on a specific category of minarets, specifically the historical masonry minarets in Old Cairo. Moreover, it encounters limitations due to the requirement of detailed finite element models for these minarets to capture their dynamic responses accurately. Therefore, research work is ongoing, with the development of detailed finite element models of the selected minarets and the calibration of fundamental periods underway. The anticipated results hold the potential to enrich our understanding of historical minarets' structural dynamics, ultimately guiding the formulation of tailored seismic retrofitting and preservation strategies. These strategies, aimed at preserving these cherished cultural heritage assets, stand as our collective commitment to ensure that these timeless landmarks endure for generations.

Future work and development could be extended to cover a wide range and database of historical minarets in Old Cairo. In addition, a potential area of improvement involves revising the vulnerability parameters used in estimating the vulnerability index. The revision should align the parameters with the specific conditions and characteristics of Cairo's historical minaret structures. By tailoring these parameters to the unique attributes of the minarets, a more accurate assessment of their vulnerability can be achieved. Moreover, future work should comprehensively investigate the dynamic response of minarets considering soil-structure interaction (SSI). Such research would enable a better understanding and assessment of the vulnerability of historical minarets.

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Author contributions
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Declarations

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Consent for publication
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Competing interests
Author states that there is no conflict of interest.

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References

Abd El-Aal AEAK, Hagag W, Sakr K, Saleh M, Abd El-Aal AEAK, Hagag W, Saleh, M. (2019). Seismicity, seismotectonics and neotectonics in Egypt. In The Geology of Egypt (pp. 375-413). Cham: Springer International Publishing.

Abou Elenean KM (2007) Focal mechanisms of small and moderate-size earthquakes recorded by the Egyptian National Seismic Network (ENSN), Egypt. NRIAG J Geophys 6(1):119–153

Abou Elenean KM, Mohamed AME, Hussein HM (2009) Source parameters and ground motion of the Suez-Cairo shear zone earthquakes, Eastern Desert. Egypt Nat Hazards 52(2):431–451

Abruzzese D, Miccoli L, Vari A, Ferraioli M, Mandara A, Froncillo S (2009) Dynamic investigations on medieval masonry towers: seismic resistance and strengthening techniques. In: Proceedings of the 1st international conference on the protection of historical buildings (PROHITECH), Rome, Italy

Ademović N, Kurtović A, Madžarević M (2016) Structural repair of CarevaĆuprija Bridge in Sarajevo. Građevinar 68(12):995–1008

Ambraseys NN (1961) On the seismicity of South West Asia, data from an XV-century Arabic manuscript. Revue Pour L'etudes Des Calmites 37:18–30

Ambraseys NN, Melville CP, Adams RD (1995) The seismicity of Egypt, Arabia, and the Red Sea, A historical review. King Abdul Aziz City of science and technology. Cambridge University Press, Amsterdam

Amir Č, Mustafa H, Nerman R (2014) The vulnerability assessment of tall slender masonry structures. Methods 2(3):4

Arnold C (2006) Earthquake effects on buildings 4. Risk management series designing for earthquakes a manual for architects providing protection to people and buildings. FEMA, Oakland, California

Asteris PG, Plevris V (eds) (2015) Handbook of research on seismic assessment and rehabilitation of historic structures, vol 2. IGI Globa

Aymelek A, Yanik Y, Demirtaş B, Yildirim Ö, Çalik İ, Türker T (2023) Full-scale structural evaluations of İskenderpaşa minaret. Structures 55:1028–1044

Badawy A, Korrat I, El-Hadidy M, Gaber H (2017) Update earthquake risk assessment in Cairo, Egypt. J Seismol 21(4):571–589

Behrens-Abouseif D (2010) The minarets of Cairo: Islamic architecture from the Arab conquest to the end of the Ottoman Empire. IB Tauris.

Bilgin H, Ramadani F (2021) Numerical study to assess the structural behavior of the Bajrakli Mosque (Western Kosovo). Adv Civ Eng 2021:1–17

Bindi D, Petrovic B, Karapetrou S, Manakou M, Boxberger T, Raptakis D, Parolai S (2015) Seismic response of an 8-story RC-building from ambient vibration analysis. Bull Earthq Eng 13(7):2095–2120

Bowden DC, Tsai VC (2017) Earthquake ground motion amplification for surface waves. Geophys Res Lett 44(1):121–127

Calvi GM, Pinho R, Magenes G, Bommer JJ, Restrepo-Vélez LF, Crowley H (2006) Development of seismic vulnerability assessment methodologies over the past 30 years. ISET J Earthq Technol 43(3):75–104

CAPMAS, Central Agency for Public Mobilization and Statistics Arabic Republic of Egypt. Report (2023) Census of population, housing, and establishments. Internal report

Casolo S, Diana V, Uva G (2017) Influence of soil deformability on the seismic response of a masonry tower. Bull Earthq Eng 15(5):1991–2014

Catulo R, Falcão AP, Bento R, Ildefonso S (2018) Simplified evaluation of seismic vulnerability of Lisbon Heritage City Centre based on a 3DGIS-based methodology. J Cult Herit 32:108–116

Ceroni F, Pecce M, Manfredi G (2009) Seismic assessment of the bell tower of Santa Maria del Carmine: problems and solutions. J Earthq Eng 14(1):30–56

Chisari C, Macorini L, Amadio C, Izzuddin BA (2015) An inverse analysis procedure for material parameter identification of mortar joints in unreinforced masonry. Comput Struct 155:97–105

Cosgun C, Turk AM (2012) Seismic behavior and retrofit of historic masonry minaret. Građevinar 64:39–45

Creswell KAC (1926) The evolution of the minaret, with special reference to Egypt I-III. Burlingt Mag Connoiss 134–140(252–258):290–298

D'Ambrisi A, Mariani V, Mezzi M (2012) Seismic assessment of a historical masonry tower with nonlinear static and dynamic analyses tuned on ambient vibration tests. Eng Struct 36:210–219

Dahy SA (2010) A study on seismicity and tectonic setting in the northeastern part of Egypt. Res J Earth Sci 2(1):08–13

Doğangün A, Ural A, Livaoğlu R (2008) Seismic performance of masonry buildings during recent earthquakes in Turkey. In: The 14th world conference on earthquake engineering, pp 12–17

El-Attar AG, Saleh AM, Zaghw AH (2005) Conservation of a slender historical Mamluk-style minaret by passive control techniques. Struct Control Health Monit 12(2):157–177

El-Attar AG, Saleh AM, Osman A (2001) Seismic response of a historical Mamluk style minaret. WIT Trans Built Environ 57:745–754

El-Hadidy MS (2008) Seismicity and seismic hazard assessment for Sinai Peninsula: M.Sc. thesis, Faculty of Science, Ain Shams University, Egypt

El-Sayed A, Vaccari F, Panza GF (2001) Deterministic seismic hazard in Egypt. Geophys J Int 144(3):555–567

Fema-454 (2006) Designing for earthquakes: a manual for architects. Mimari Tasarımda Deprem

Gaballah GA, Al-Attar AA (2000) Culture and heritage program: guide of islamic archeology in Cairo. Information and Decision Support Center of the Council of Ministers.

Gabr A (2017) Three-dimensional time history analysis of masonry chimneys considering the soil-structure interaction. In: 16th world conference on earthquake, 16WCEE 2017 Santiago Chile, January 9th to 13th 2017. Paper No. 2348. Registration Code: S-I1464716404

Gentile C, Saisi A (2007) Ambient vibration testing of historic masonry towers for structural identification and damage assessment. Constr Build Mater 21(6):1311–1321

GNDT–SSN (1994) Gruppo Nazionale per la DifesadaiTerremoti, Scheda di esposizione e vulnerabilità e di rilevamentodanni di primo livello e secondo livello (muratura e cementoarmato). Gruppo Nazionale per la DifesadaiTerremoti. (In Italian), Roma, Italy

Goda K, Rossetto T, Mori N, Tesfamariam S (2018) Mega Quakes: Cascading Earthquake Hazards and Compounding Risks. Front Built Environ 4:8

Hacıefendioğlu K (2010) Seasonally frozen soil's effect on stochastic response of masonry minaret–soil interaction systems to random seismic excitation. Cold Reg Sci Technol 60(1):66–74

Hadzima-Nyarko M, Mišetić V, Morić D (2017) Seismic vulnerability assessment of an old historical masonry building in Osijek, Croatia, using Damage Index. J Cult Herit 28:140–150

Hassan HM, Romanelli F, Panza GF, ElGabry MN, Magrin A (2017) Update and sensitivity analysis of the neo-deterministic seismic hazard assessment for Egypt. Eng Geol 218:77–89

Hassan HM, Fasan M, Sayed MA, Romanelli F, ElGabry MN, Vaccari F, Hamed A (2020) Site-specific ground motion modeling for a historical Cairo site as a step towards computation of seismic input at cultural heritage sites. Eng Geol 268:105524

Hassan HM, ElGabry M (2023) Ambient vibrations analysis for vulnerability assessment of the Cairo citadel's minarets. Technical Articals, Fast Times. https://fasttimesonline.co/ambient-vibrations-analysis-for-vulnerability-assessment-of-the-cairo-citadels-minarets/

Hassan HM, Sayed MA, Fasan M, Romanelli F, Amadio C, Hamed A, ElGabry M, Hamama I (2023) Seismic assessment of a cultural heritage Minaret in Cairo. In: Sustainable conservation of UNESCO and other heritage sites through proactive geosciences. Springer, Cham, pp 541–565

Higazy EM (2004) Vulnerability of historical minarets; investigation of their seismic assessment & retrofitting. Emir J Eng Res 9(2):59–64

Işık E, Antep B, Büyüksaraç A, Işık MF (2019) Observation of behavior of the Ahlat Gravestones (Turkey) at seismic risk and their recognition by QR code. Struct Eng Mech 72(5):643–652

Işık E, Avcil F, Harirchian E, Arkan E, Bilgin H, Özmen HB (2022a) Architectural characteristics and seismic vulnerability assessment of a historical masonry minaret under different seismic risks and probabilities of exceedance. Buildings 12(8):1200

Işık E, Harirchian E, Arkan E, Avcil F, Günay M (2022b) Structural analysis of five historical minarets in Bitlis (Turkey). Buildings 12(2):159

Işık E, Ademović N, Harirchian E, Avcil F, Büyüksaraç A, Hadzima-Nyarko M, Bülbül M, Işık M, Antep B (2023a) Determination of natural fundamental period of minarets by using artificial neural network and assess the impact of different materials on their seismic vulnerability. Appl Sci 13(2):809

Işık E, Avcil F, Arkan E, Büyüksaraç A, İzol R, Topalan M (2023) Structural Damage Evaluation of Mosques and Minarets in Adıyaman due to the 06 February 2023 Kahramanmaraş Earthquakes. Eng Fail Anal 151::107345

Kassem MM, Nazri FM, Farsangi EN (2020) The seismic vulnerability assessment methodologies: a state-of-the-art review. Ain Shams Eng J 11(4):849–864

Kebeasy RM (1990) Seismicity. In: Said R (ed) The geology of Egypt. A.A. Balkema, Amsterdam, pp 51–59

Kebeasy RM, Maamoun M (1981) Seismicity and Earthquake Risk of the proposed site of Shoubra al-Khaimah Electric Power Station. Bull Int'l Inst Seismol Earthq Energy 19:21–33
Lang K, Bachmann H (2003) On the seismic vulnerability of existing unreinforced masonry buildings. J Earthq Eng 7(03):407–426
Maamoun M (1979) Macro seismic observations of principal earthquake in Egypt, Helwan Institute of Astronomy and Geophysics. J Bull 183:120
Moustafa AR, Yehia MA, Abdel Tawab S (1985) Structural setting of the area east of Cairo, Maadi, and Helwan. MERC Ain Shams Univ. Sci Res Ser 5:40–64
Nohutcu H (2019) Seismic failure pattern prediction in a historical masonry minaret under different earthquakes. Adv Civ Eng
Oliveira CS, Çaktı E, Stengel D, Branco M (2012) Minaret behavior under earthquake loading: The case of historical Istanbul. Earthq Eng Struct Dyn 41(1):19–39
Onat O, Toy AT, Özdemir E (2023) Block masonry equation-based model updating of a masonry minaret and seismic performance evaluation. J Civ Struct Heal Monit 13:1221–1241
Pineda P, Robador DM, Gil-Marti M (2011) Seismic damage propagation prediction in ancient masonry structures: an application in the non-linear range via numerical models. Open Constr Build Technol J 5(1):71–79. https://doi.org/10.2174/1874836801105010071
Rappai S, Khairy A (Eds) (2012) Urban regeneration project for historic cairo: first report of activities: July 2010–June 2012. UNESCO
Riad S, Taeleb AA, El Hadidy S, Basta NZ, AbuoElela AM, Mohamed AA, Khalil HA (2004) Ancient earthquakes from some Arabic sources and catalogue of Middle East historical earthquakes. EGSMA, NARSS, UNDP, UNESCO, pp 71–91
Said R (1962) The geology of Egypt. Elsevier, Amsterdam, p 377
Said R (1981) The geologic evolution of the Nile River. Springer, New York
Sepe V, Speranza E, Viskovic A (2008) A method for large-scale vulnerability assessment of historic towers. Struct Control Health Monit 15(3):389–415
Serhatoğlu C, Livaoğlu R (2019) A fast and practical approximation for fundamental period of historical Ottoman minarets. Soil Dyn Earthq Eng 120:320–331
Shakya M, Varum H, Vicente R, Costa A (2018) Seismic vulnerability assessment methodology for slender masonry structures. Int J Archit Herit 12(7–8):1297–1326
Shakya M, Varum H, Vicente R, Costa A (2014) Predictive formulation for the estimation of the fundamental frequency of slender masonry structures. In: Second European conference on earthquake engineering and seismology, Istanbul AUG, pp 25–29
Shata AA (1988) Geology of Cairo Egypt. Environ Eng Geosci 25(2):149–183
El Shazly EM, Abdel Hady MA, El Kassas IA, El Amin H, Abdel Megid AA, Mansour SI, El Shazly MM, Tamer MA(1977) Geology and groundwater conditions of Tushka basin area, Egypt. In: 11th international symposium on remote sensing of environment; groundwater in arid areas in Egypt, pp 25–29)
Speranza E, Viskovic A, Sepe V (2006) Integrated methods for the assessment of the structural vulnerability of historic towers. In: Proceedings of SAHC 06, New Delhi, November 6–8, vol 1, pp 651–58
Strougo A (1985) Eocene stratigraphy of the eastern greater Cairo (Gebel Mokattam-Helwan) area. Middle East Res. Centre, Ain Shams Univ Sci Res Ser 5:1–39
Supreme Council for Antiquities (1999) Project: Restoration of YusufAgha al-Hin mosque
Sykora D, Look D, Croci G, Karaesmen E (1993) Reconnaissance report of damage to historic monuments in Cairo, Egypt Following the October 12, 1992, Dahshur Earthquake. Army Engineer Waterways Experiment Station Vicksburg Ms. Geotechnical Lab
Theilen-Willige B (2010) Detection of local site conditions influencing earthquake shaking and secondary effects in Southwest Haiti using remote sensing and GIS methods. Nat Hazards Earth Syst Sci 10(6):1183–1196
Thenhaus P, Sharp R, Celebi M, Ibrahim A-B, Van de Pol H (1993) Reconnaissance Report on the October 12, 1992, Dahshur, Egypt, Earthquake, Open File Rpt, U.S. Geological Survey, Denver, CO, pp 93–181
Trešnjo F, Humo M, Casarin F, Ademović N (2023) Experimental investigations and seismic assessment of a historical stone minaret in Mostar. Buildings 13(2):536
UNESCO, United Nations Educational, Scientific & Cultural Organization (2017) Historic Cairo. UNESCO. https://whc.unesco.org/en/list/89
Vicente R, Parodi S, Lagomarsino S, Varum H, Silva JM (2011) Seismic vulnerability and risk assessment: a case study of the historic city center of Coimbra, Portugal. Bull Earthq Eng 9(4):1067–1096
Whitman RV, Reed JW, Hong ST (1973) Earthquake damage probability matrices. In: Proceedings of the fifth world conference on earthquake engineering, vol 2. International Association for Earthquake Engineering, Rome, Italy, pp 2531–2540
Zaki MA, Hassan AF, Mourad SA, Osman AM (2008) Evaluation of the structural integrity of historical stone minarets. In: Proceedings of the 14th world conference on earthquake engineering, pp 12–17

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