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INTEGRATING GEOSCIENCES AND EARTHQUAKE ENGINEERING FOR THE CONSERVATION OF HISTORIC MONUMENTAL BUILDINGS IN OLD CAIRO: CORENG PERSPECTIVE AND FIRST RESULTS

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Abstract

The Religions Complex in Old Cairo is a significant site in urgent need of informed conservation measures. To this aim, the running bilateral Italy-Egypt "CoReng" project integrates geosciences and earthquake engineering skills to assess and mitigate seismic risk affecting these monuments. CoReng's key feature is represented by physics-based ground-motion simulations to address the absence of real local accelerometers, and investigate the seismic vulnerability of Cairo's heritage fabric. Cutting-edge simulation techniques are combined with advanced structural modelling, and a new approach for cultural heritage conservation in seismically active regions is elaborated. This paper presents some first results from the application of CoReng strategy in the analysis of the minaret of the Madrasa of Princess Tatar al Higaziya. Synthetic accelerograms are generated through physics-based models and employed to perform displacement-based checks by comparing their demands with the capacity, which is evaluated using non-linear pushover analyses. The numerical findings show that – while the minaret withstood the 1992 Cairo earthquake – new seismic events could cause major damage or even collapse. This outcome highlights the role of synthetic accelerograms: their application to Old Cairo site exemplifies how interdisciplinary methodologies can inform global strategies for the preservation of historic structures in seismic regions.

Keywords: Old Cairo, Cultural Heritage, Seismic Risk, Synthetic Accelerograms, Pushover Analysis.

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1 INTRODUCTION

The Religions Complex in Old Cairo stands as a site of immense cultural and historical significance, necessitating rigorous conservation and preservation strategies. However, the region's moderate seismic activity, combined with a scarcity of instrumental earthquake records, represents a significant challenge for accurate seismic hazard assessment. To address this issue, the running Italy-Egypt “Particular Relevance” bilateral project “CoReng” [1, 2] proposes an integrated approach, combining geoscientific modelling with earthquake and structural engineering principles and technical skills. A key component of the CoReng methodology, in particular, is the application of physics-based ground motion simulations (PBGMS).

PBGMS offer in fact a robust alternative to conventional empirical ground motion prediction equations (GMPEs), particularly for those regions (like Old Cairo) with limited strong-motion data. To note that while PBGMS are inherently capable of generating synthetic accelerograms that are suitable for detailed time-history analyses, in the present study, they were utilised to derive site-specific response spectra. This approach allows for a more refined assessment of the expected structural behaviour under seismic loading, capturing site-specific ground motion characteristics that may not be adequately represented by generalized GMPEs.

As such, this paper presents some preliminary results of a PBGMS-based seismic vulnerability assessment for a case-study structure, namely the minaret of the Madrasa of Princess Tatar al Higaziya, which is located in Old Cairo, close to the Religions Complex site. Synthetic accelerograms, generated through physics-based modelling, are used to derive site-specific response spectra. These spectra are the key input for structural pushover analyses, providing insights into the minaret's non-linear behaviour under seismic loading. The obtained results demonstrate a significant vulnerability of the minaret to potential future seismic events, despite the limited damage observed during the 1992 Cairo earthquake. These findings underscore the critical importance of PBGMS-derived site-specific response spectra in accurately characterising seismic hazards and guiding conservation strategies for cultural heritage sites. The CoReng project's integrated methodology – combining advanced simulation techniques with detailed structural modelling and pushover analysis – establishes a robust framework for the sustainable preservation of cultural heritage in seismically active regions, with broader implications for global conservation practice.

2 CASE-STUDY

The Madrasa of Princess Tatar al-Higaziya, located in Old Cairo, is a historically significant complex (Figure 1). Originally constructed in 1348 as a mausoleum, it was converted into a Madrasa in 1360, incorporating the main school building, an ablutions court, and, notably, a minaret. Today, the Madrasa complex is a rare example of a religious and educational institution endowed by a woman in Cairo city.

Of particular interest in this paper is its minaret, which represents a prominent architectural feature of the Madrasa. Due to its unique geometry and location within an active seismic area, it poses an interesting case-study for architectural preservation. It rises about 24 m above the ground level, exhibiting a distinct geometrical transition in its elevation. The square ground plan, measuring 3.45 m in width, extends up to 11 m in height. Above this point, the plan evolves to an octagonal shape, and such a transition is emphasised by bevelled corners. Notably, the minaret lacks its traditional upper cap, or “*mabkhara*”, which is reproduced in Figure 1, and was possibly lost due to damage sustained in past seismic events. The Madrasa complex, including the minaret, has undergone multiple restoration campaigns, the most significant of which was carried out between 1980 and 1982 by the Egyptian government in collaboration with the German Cultural Center. The condition of the was previously investigated, most notably through a UNESCO-led study following the 1992 Cairo earthquake. The minaret represents a significant historic structure within the old city of Cairo; its distinctive geometry and location within an active seismic area make it an instructive case study for architectural preservation.

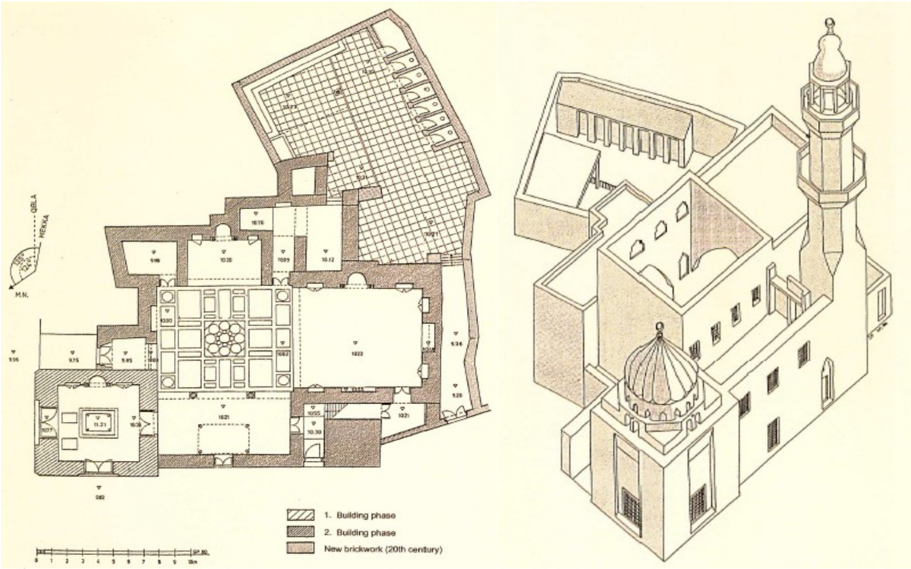

Figure 1: the Madrasa of Princess Tatar al-Higaziya in Old Cairo, with evidence of the case-study minaret in its original configuration.

3 METHODOLOGY

The methodology is based on comparing the seismic demand derived from PBGMS, with the structural capacity. Capacity is evaluated through mass-proportioned non-linear analyses using a validated numerical model. The N2 method is subsequently applied to interpret the structural response and calculate the behaviour factor of the minaret.

3.1 Seismic hazard computation

PBGMS are used in this paper to model ground-shaking scenarios for seismic hazard assessment, implemented via a validated web application [3, 4]. The methodology employs the extended source (ES) model to account for rupture process complexity (directivity, fling step) and ground motion variability. Ground motions are calculated using the tensor product of the earthquake source and the Green's function [5], considering the rupture process, site, and path effects. This approach was validated against past events and GMPEs.

Synthetic accelerograms, more in detail, were calculated in two phases: fault rupture simulation and wave propagation/accelerogram calculation. This requires modelling the seismic source, the crustal model of the earth and the local site-specific conditions. The ES model simulates the distributed slip field on the fault surface using the PULSYN algorithm [6]. Given the uncertainty in future fault motion, a Monte-Carlo approach was used to take into account the rupture variability. The fault surface was discretised into sub-sources, with seismic moment from a non-stationary random process. The model generated a source spectrum (amplitude and phase) considering rupture and directivity.

Seismograms were calculated in laterally homogeneous media (semi-infinite space with parallel layers) up to 10 Hz, using the discrete wavenumber (DWN) techniques [7]. Parameters for seismic hazard evaluation (earthquake scenarios, crustal model, site conditions) were taken from [8] for the crustal model and site conditions, and from [9] for earthquake scenarios. Source parameter variability is also considered, based on [10, 11]. The so-obtained four seismic scenarios are summarises in Table 1.

Event id	M_w	Lon [°]	Lat [°]	Depth [km]	Strike [°]	Dip [°]	Rake [°]
Sce01	5.8	31.1	29.8	10	285	66	254
Sce02	5.8	31.1	29.8	20	285	66	254
Sce03	6.5	31.1	29.8	10	285	66	254
Sce04	6.5	31.1	29.8	20	285	66	254

Table 1. Scenarios and key parameters.

The first two scenarios in Table 1 (Sce01 and Sce02) are the reproduction of the 1992 Cairo earthquake, accounting for uncertainty related to focal depth. Figure 2 shows a representation of source rupture and its location, along with the minaret site. The last two scenarios in Table 1 (Sce03 and Sce04) account for the maximum expected magnitude from the modelled seismogenic source, also considering the uncertainty in depth evaluation. Figure 3 shows the resulting acceleration response spectra.

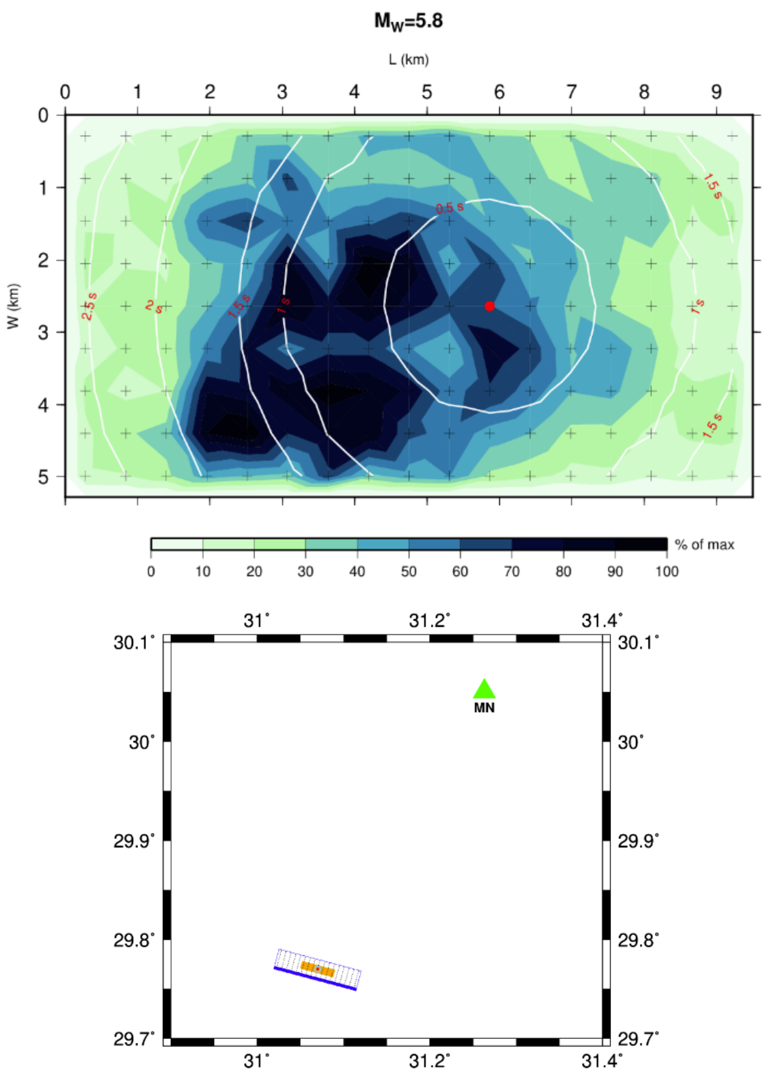

Figure 2: Example of source rupture for the simulated scenarios.

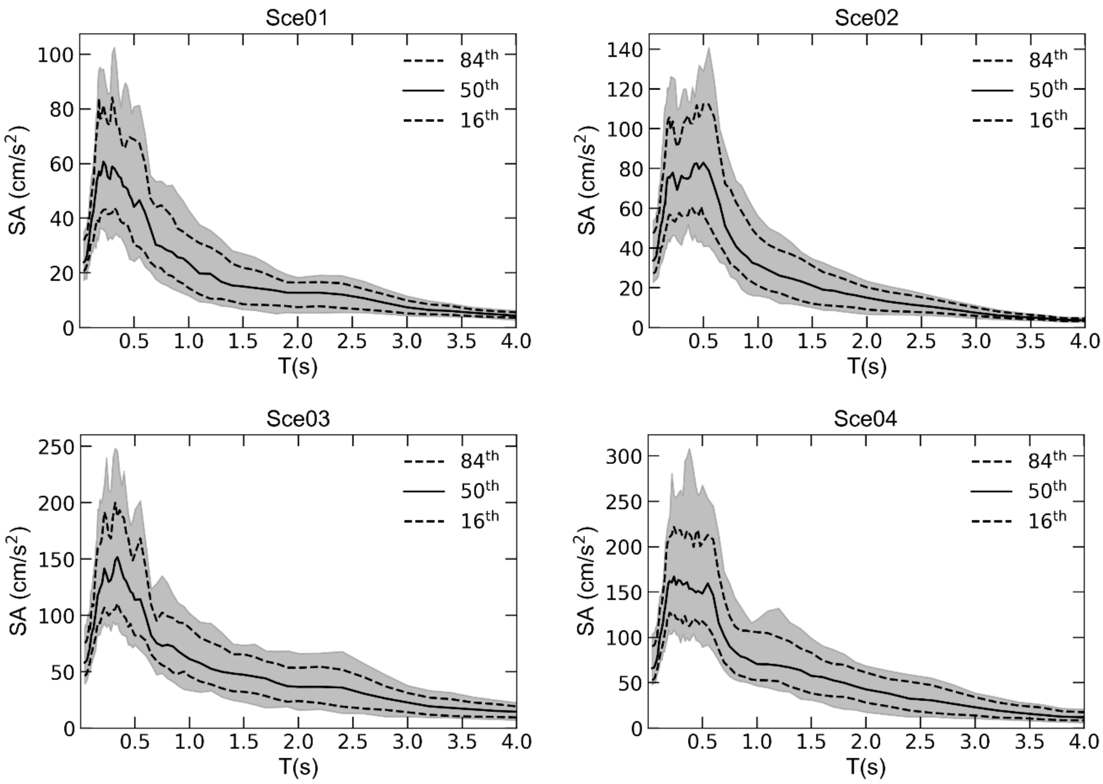

Figure 3: Acceleration response spectra from PBGMSs.

3.2 FE structural model

The geometrical model of the investigated minaret was developed using the software Rhino 3D [12], which efficiently represents spatial geometries through a non-uniform rational B-spline (NURBS) approach. The FE structural model was then generated in the advanced commercial software ABAQUS [13], see Figure 4.

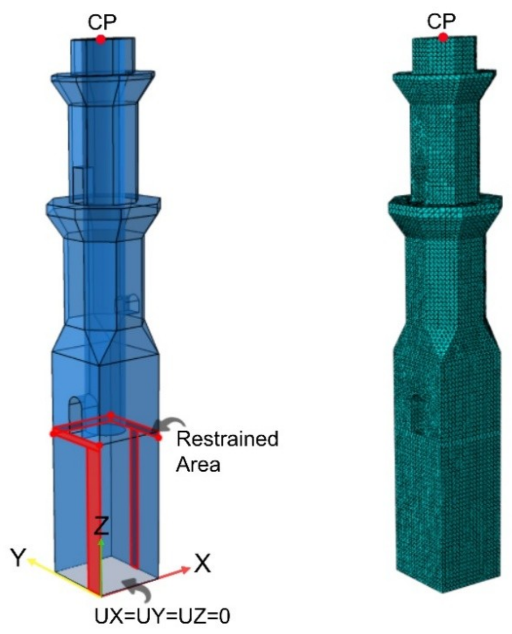

Figure 4: Geometrical model of the minaret, boundary conditions and mesh discretisation (CP= control point).

A macro-modelling approach was adopted, with the masonry arrangement smeared over a homogeneous material. This approach is particularly suitable for the analysis of large-scale structures [14], as it allows for the reproduction of the macroscopic mechanical behaviour of masonry through various material models, such as the smeared crack concrete, the brittle cracking, or the concrete damage plasticity (CDP) models. Specifically, CDP integrates plasticity with a scalar-based damage model and, being originally developed for concrete, assumes an isotropic elastic behaviour [15], [16]. A linear softening response in tension represents the quasi-brittle nature of masonry. In compression, a plateau follows the peak strength, succeeded by a linear softening behaviour. Damage variables are introduced when softening occurs, aiming to reduce the initial (undamaged) elastic modulus through the following equations:

$$\sigma_c = (1 - d_c)E_0(\varepsilon_c - \varepsilon_c^{pl})$$
$$\sigma_t = (1 - d_t)E_0(\varepsilon_t - \varepsilon_t^{pl}) \quad (1)$$

In Eq. (1), E_0 is the elastic modulus of the undamaged unit, σ_i is the current stress, ε_i is the total strain, and ε_i^{pl} is the plastic strain. The subscript i reads as c or t, if associated with the compressive or tensile regime, respectively. Instead, d_i is the damage variable that represents deterioration in tension (cracking) and compression (crushing), ranging from zero (no damage) to one (fully damaged). Moreover, a non-associative flow rule is employed to consider dilatancy and define the plastic strain rate, while a multiple-hardening Drucker-Prager type surface is used as the yield surface. Tables 2 and 3 summarise the input properties for this study.

The mechanical parameters defining the structural performance of the masonry were evaluated using the formulations provided in EC6 [17] to estimate the characteristic compressive strength. The compressive strength of the masonry units, determined through core extraction and subsequent testing, was measured as 30.6 MPa. A lime-based mortar with an estimated compressive strength of 1 MPa was adopted. The coefficients K, α, and β were taken as 0.5, 0.8, and 0.2, respectively.

Compressive behaviour		
Stress [MPa]	Inelastic strain	d_c
6.95	0	0
7.73	0.003	0
0.1	0.015	0.8

Tensile behaviour		
Stress [MPa]	Cracking strain	d_t
0.26	0	0
0.01	0.001	0.9

Table 2. Compressive and tensile stress-strain relationships.

Dilation angle [°]	Eccentricity	f_{b0}/f_{c0}	K_c	Viscosity parameter
10	0.1	1.16	2/3	1e-5

Table 3. Drucker-Prager strength domain parameters.

It should be noted that EC6 provides an estimate of the characteristic compressive strength, representing a lower-bound value to ensure structural safety. However, for the implementation of the non-linear model, the average compressive strength is required, as it more accurately reflects the material's actual response. While this difference is typically accounted for by applying a factor of 1.2 to the characteristic value, in this study no adjustment was made to maintain a conservative approach in the analysis. The elastic modulus was then calculated as $800f_c$, while the tensile strength of the masonry was determined as $f_c/30$. The non-linear portion of the curve, namely the estimated compressive and tensile fracture energy, were calculated using the formulation recommended in [18]. To ensure numerical consistency, these calculations were performed considering a mesh size with a characteristic length of 200 mm.

3.3 Spring Calibration for the Structural Model

While the minaret is an integral part of the overall structure and is fully enclosed by restraining structural elements at its base (Figure 1), its structural behaviour cannot be considered independently. The surrounding wall structures provide restraint conditions that must be accurately accounted for, in order to ensure a reliable structural assessment.

To incorporate these effects, the restrained areas were properly identified, and equivalent elastic springs acting only in compression were introduced at the interface (Figure 4). A trial-and-error procedure was employed to achieve the best fit between the first two experimentally measured modal frequencies of the minaret, earlier recorded as 1.993 Hz and 2.124 Hz, respectively. Based on this calibration process, a spring stiffness value of 200000 kN/m^3 was assigned to all the regions highlighted in Figure 4, and taken into account for the seismic analyses presented in this paper.

4 ANALYSIS AND RESULTS

Pushover analysis is widely employed to assess the seismic capacity of historic masonry structures. The structural response is characterised by a capacity curve, where the vertical axis represents the base shear, and the horizontal axis denotes the displacement of the control point, typically located at the structure's apex.

The analysis begins with the application of vertical loads, including self-weight and imposed actions. The system is then reinitialised from this pre-loaded state, incorporating seismic forces independently along the principal geometric axes (X and Y, as shown in Figure 4). A mass-proportional force distribution is adopted to ensure a realistic representation of seismic demand. The capacity curve is truncated at a displacement corresponding to 85% of the peak base shear, following established methodologies [19].

From a numerical perspective, the arc-length method is employed, controlling the incremental step size based on a combined measure of displacement and load to ensure convergence under highly non-linear conditions. Structural performance is assessed using the N2 method, as prescribed by current design codes, following the methodology outlined in [15]. Results in Figure 5 and Table 4 are expressed as the ratio between displacement demand (d_D^*) and displacement capacity (d_C^*), along with the observed damage pattern at the ultimate displacement and the estimated value of the behaviour factor q^*.

Figure 5, in particular, presents the pushover curves obtained using a mass-proportional approach, performed in accordance with the procedure described in the previous section. Additionally, the plots illustrate the tensile damage occurring at the ultimate displacement (with blue colour for the undamaged masonry).

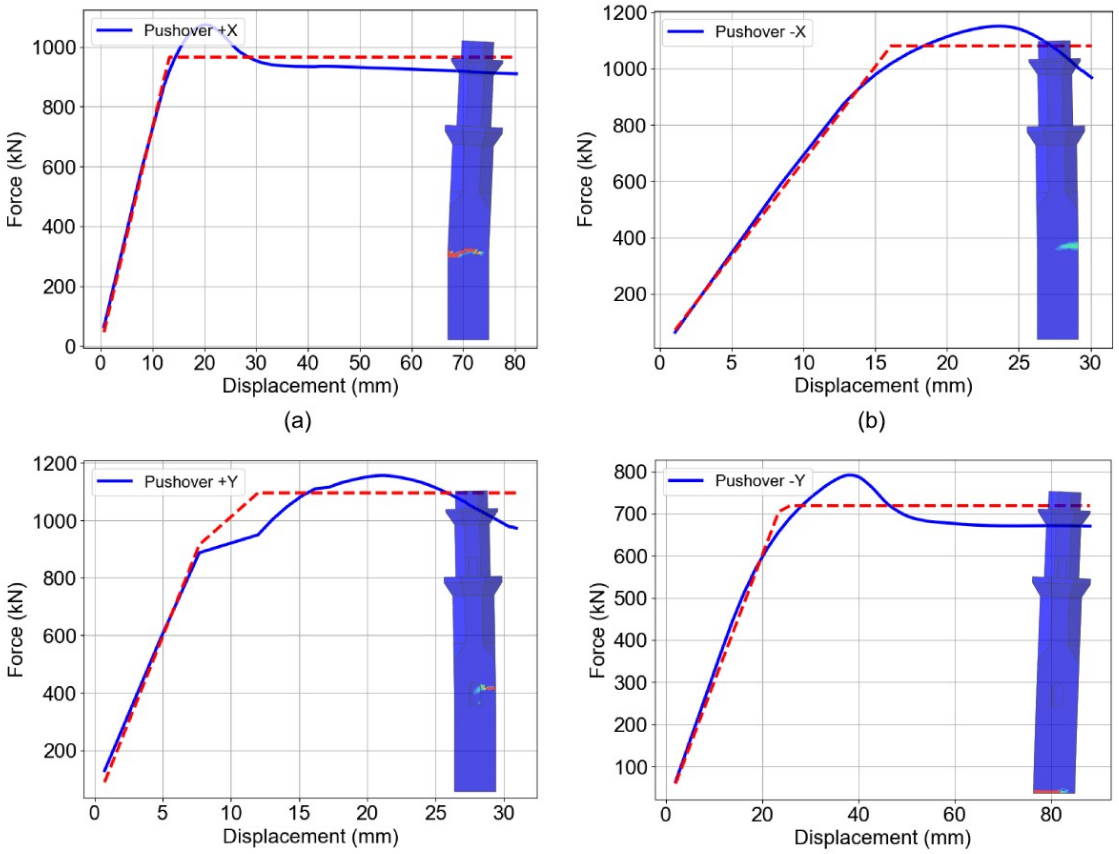

Figure 5: Pushover curves and their bi-linearisation.

To calculate the structure's demand, the normalised response spectrum of the four different scenarios from Table 1 (Sce01-04) was utilised, with analyses performed for the 95th, 84th, 50th, 16th, and 5th percentile values. When the structural assessment for the higher percentile was not satisfied, the lower percentile value was also assessed. In contrast, if the structural assessment for a higher percentile value was satisfied, the response spectrum at lower percentiles was not investigated and not reported in Table 4.

For Sce01, demand-to-capacity ratios remain below unity in all directions, indicating satisfactory performance across the board. However, in Sce02, the structure does not satisfy the performance criteria in the –X direction even at the 5th percentile, whereas the other directions meet the target at or above the 50th percentile. Both Sce03 and Sce04 reveal critical limitations under –X loading: demand-to-capacity ratios reach 1.87 and 2.86, respectively, already at the 5th percentile, indicating a high likelihood of failure under modest seismic demand. Conversely, the +X, +Y, and –Y directions consistently exhibit ratios below unity across most scenarios, reflecting favourable directional performance likely due to boundary conditions and interaction with adjacent structural components.

Event id	+X		-X		+Y		-Y	
	q^*	d^*_D/d^*_C	q^*	d^*_D/d^*_C	q^*	d^*_D/d^*_C	q^*	d^*_D/d^*_C
Sce01	1.45(5th)	0.41(95th)	1.28(50th)	0.97(50th)	1.36(95th)	0.72(95th)	1.62(5th)	0.66(95th)
Sce02	1.73(16th)	0.59(16th)	1.19(5th)	0.79(5th)	1.50(16th)	0.82(16th)	1.88(50th)	0.87(50th)
Sce03	2.45(16th)	0.77(16th)	2.06(5th)	1.87(5th)	1.86(5th)	1.09(5th)	2.21(5th)	0.87(5th)
Sce04	2.42(5th)	0.92(5th)	2.49(5th)	2.86(5th)	2.30(5th)	1.79(5th)	2.63(5th)	1.29(5th)

Table 4: Summary of results.

5 CONCLUSIONS

The built cultural heritage conservation and preservation, as known, is a critical challenge for many sites, particularly for those regions characterised by medium-high seismicity, especially when historic earthquake records are not available. In this paper, a preliminary study was proposed for a case-study minaret located in Old Cairo, in the Madrasa of Princess Tatar al Higaziya. The methodology that is presently under elaboration by the running Italy-Egypt "CoReng" research project takes advantage of physics-based models to define synthetic accelerograms, and combine them with refined structural models. As shown, the integrated use of geosciences and structural engineering skills can support a more in-depth seismic risk and vulnerability assessment for historic monuments. The case-study minaret withstood the 1992 Cairo earthquake. However, the numerical results show that new seismic events could cause major damage or even collapse. Future CoReng applications will be extended to the monumental buildings of the Religions Complex in Old Cairo.

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