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Multi-Scenario Physics-Based Seismic Hazard Assessment of Cultural Heritage Sites

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Abstract For relevant engineering purposes a viable alternative to standard estimates of seismic hazard is represented by the use of physics-based ground shaking scenarios. The scenarios are characterized in terms of magnitude, distance and faulting style, taking into account the complexity of the kinematic source rupturing process. In fact, ground-shaking scenarios modelled before the occurrence of an earthquake can be of extreme value in any seismic risk study, in particular in sites with priceless cultural heritage. In those places the effect of low occurrence rate - high consequences events can lead to invaluable losses, therefore an accurate evaluation of the expected ground motions is desirable. To this purpose, a web application, with a friendly graphic user interface, has been developed for multi-scenario physics-based seismic zoning and microzoning (considering site effects). Computational examples at different space and detail scales are presented, focussing on historical sites, such as the Dahshur pyramids, the Madrasa of the Princess Tatar al-Higaziya, Saint Catherine's Monastery in Egypt. For all the cases, the acceleration time histories, generated with the knowledge of the physical properties of the earthquake source and of the medium travelled by the seismic waves, can be used by engineers as seismic input for the vulnerability assessment.

Keywords ground shaking scenarios, synthetic seismograms, physics-based hazard assessment, Cultural Heritage Sites

Introduction

For historical sites and monuments, the economic quantification of damages due to earthquakes can be incalculable. In fact, given their uniqueness it is impossible to establish a level of seismic action for which their loss is acceptable, and an accurate estimate of seismic hazard is needed also for very strong rare earthquakes.

In such conditions standard methods based on the use of Ground Motion Prediction Equations (GMPEs) can be difficult to apply, as there may not be enough observations to constrain their definition. For some countries, there may be no observations at all or available GMPEs.

An alternative to standard methods of seismic hazard evaluation is represented by the use of physics-based scenario earthquakes, characterized at least in terms of magnitude, distance and faulting style, also taking into account the complexity of the source rupturing process. Physics-based ground motion simulations are purely based on the geophysical and seismotectonic features of a region and can supply realistic time series of ground motion readily applicable by engineers in dynamic time-history analyses of structures. Physics-based scenarios can provide information on the expected accelerations also at very short distances, or due to large magnitude, which are usually the conditions in which the observed data are lacking. Therefore, they are useful to plan the preservation of historical monuments and relevant man-made structures, in particular when a Multi-Scenario assessment is applied accounting for all known sources that could affect a site of interest.

This paper shows the application of physics-based ground shaking scenarios to estimate the seismic hazard at cultural heritage sites. As illustrative examples, the methodology is applied to different Egyptian historical sites. The ground shaking scenarios for all the case studies were modelled using a web app (Vaccari 2016, Vaccari and Magrin 2019) that implements the proposed methodology. This methodology has been successfully applied to many urban areas worldwide for the purpose of seismic microzoning, to strategic buildings (Panza et al. 2016), lifelines and cultural heritage sites such as the city of Venice or Rome (e.g. Romanelli and Vaccari 2016) and it has proved reliable even in comparison to real events (Fasan et al. 2016).

Method

In this work, to assess the seismic hazard, a "physics-based" methodology was used, in which the ground shaking is represented by broadband accelerograms in the three spatial components, calculated through the tensor product between the tensors of the earthquake source and the Green's function of the medium (including the soil layers) crossed by the seismic waves (Panza et al. 2001, 2012; Fasan 2017). The hazard evaluation is based on the modelling of the propagation of seismic waves starting from the knowledge of the seismic sources and of the structural properties of the earth's lithosphere, allowing to take into account the kinematic complexity of the rupture process of the seismic source as well as site and path effects and, thus, considering the intra and inter-event spatial variability of the ground motion.

In order to assess the ground shaking associated with the hypothesized seismic scenario, the calculation of synthetic accelerograms occurs in two phases:

- 1: simulation of the fault rupture process on the fault plane;
- 2: simulation of wave propagation and calculation of synthetic accelerograms for the sites of interest.

It is therefore necessary to model the properties of the seismic source and of the bedrock-soil structure interposed between the fault and the sites of interest.

The source can be modelled as extended source (ES) or Size and Time Scaled Point Source (STSPS) (Gusev 2011); this modelling allows us to catch the effects related to the kinematic rupture process (i.e. directivity) and, in the near field, to the dislocation (i.e. static displacement - fling step).

When the extended model is used, the source of the earthquake is considered a relative sliding field distributed on the fault surface, on which the rupture process is presumed to occur. This surface is then modelled as a grid of point sub-sources, whose seismic moment is calculated by considering each of them as a component of a realization of a non-stationary random process. Assuming a realistic kinematic description of the rupture process, the extended seismic source model allows us to generate a spectrum (in amplitude and phase) of the temporal function of the source that takes into account both the rupture process and the effects of directivity. The simulation of the space and time evolution of the rupture is performed by the algorithm PULSYN06 (Gusev 2011). For the chosen scenario, different possible realizations of the rupture process can be considered: in this way the stochastic nature of the fault rupture is accounted for. Each realization is characterized by a different slip distribution on the fault plane, nucleation point and time evolution.

When the STSPS approximation is used, the source time functions generated by the distributed (point) subsources are summed up in order to obtain the equivalent single source, representative of the entire space and time structure of the extended source, and the related Green's Function.

The calculation is usually conducted in laterally homogeneous media, i.e. the bedrock-soil structural model is represented by a semi-infinite space in plane and parallel inelastic layers, up to a frequency of 10 Hz and using two different techniques: the MS - modal summation technique (Panza et al. 2001, 2012) and the DWN - discrete wavenumber (Pavlov 2009).

It is also possible to estimate the ground motion in laterally heterogeneous media in order to account for site and topographic effects. In the latter case, the wave-field generated by the MS technique is introduced in the mesh that defines the local heterogeneous area, where it is propagated according to the finite-differences scheme (Fäh and Panza 1994).

Web app and case studies

The calculation of synthetic accelerograms following this method can be very tedious in the initial phase of input definition. Moreover, the user should handle thousands of information in the postprocess phase. To help users in this process, a web app has been developed in order to make the method available with a user friendly interface, and all the generated data can be easily downloaded. This application is organized in different tabs, each one dedicated to a specific functionality as summarized in Tab. 1.

Table 1 Description of the main functionalities available in the web app.

Tab name	Functionality
Structure	Definition of the properties of the soil layers (thickness, density, V_p and V_s velocities and their attenuations Q_p and Q_s). Generation of Love and Rayleigh modes to be used in the modal summation technique (Fig. 1).
Eigen	Computation of eigenfunctions.
Source	Modelling of the source rupturing process. In this panel several realizations of the rupturing process can be generated, each one with different slip distribution, rupture velocity and nucleation point (Fig. 6).
Parametric	Explore the dependency of the ground shaking scenarios on specific parameters of the model.
Scenario	Quick generation of a ground shaking scenario around the epicentre of an earthquake. The user can select regional structure, the source rupturing model, the fault mechanism, the minimum and maximum epicentral distances, and the step to be used in the calculation of synthetic seismograms.
Fault Scenario	Prediction of the ground motion expected at a specific site using an extended source model (ES). The user can select the structure, the source parameters, the number of realizations to be performed and the site of interest. Synthetic accelerograms and their response spectra are computed at the site for each realization. As output there are statistical analyses, period by period, of the generated response spectra (median values and their variability), the plot of each realization of the fault rupture and the possibility to extract the accelerograms at a given structural period and percentile of interest (Fig. 2, Fig. 3).
2D Scenario	Calculation of seismograms in cases where the effects of lateral heterogeneities cannot be neglected, as implemented by Fäh and Panza (1994)
Sites	This tab allows to run, for a given site along the considered 2D profiles, different realizations of

	the rupture process. The user can select magnitude, type of rupture, directivity and number of realizations to be performed. As output there are statistical analyses, period by period, of the generated response spectra (median values and their variability) and the possibility to extract the accelerograms.
MCSI	Combination, for a given site, of results coming from different scenarios (from 2D and Fault scenarios) (Fig. 7). This tab allows the computation of a Multi-Scenario seismic input, extracting, at each vibrational period, the scenario with the highest median value and its variability. Selection of accelerograms for engineering purposes is performed similarly, selecting the vibrational period, the percentile and the desired number of signals.

In order to show the power of the method and the capability implemented in the web app, the different functions are presented through several case studies having different levels of detail and modelling strategies. Applications aim at showing how physics-based ground motion simulations cab be a helpful tool for the seismic hazard evaluation of cultural heritage sites, where losses due to rare strong earthquakes are invaluable.

The case studies deal with three Egyptian cultural heritage sites. Egypt is characterized by the occurrence of small to moderate intra-plate events, while the large events generally take place farther east, along the northern Red Sea or Gulf of Aqaba, and offshore to the north, the Mediterranean Sea and toward Crete and Cyprus. Egypt is located at the north eastern part of the African continent and is bounded by three main tectonic elements; the African-Eurasian plate margin, the Red Sea plate margin and the Levant transform fault. The present-day tectonic deformation within Egypt is related to interaction and relative motions along these boundaries and their remote effects inside the Egyptian land. The predominant factor in terms of seismic hazard is generally related to the occurrence of moderate size earthquakes near to the population crowded areas (i.e. the Cairo 1992 earthquake, with mb = 5.8 in the ISC catalogue), rather than large earthquakes that occur at large distances along the northern Red Sea and the two Gulfs of Suez and Aqaba (i.e. the Shedwan 1969 earthquake, with mb = 6.1 by USGS, the 1995 Gulf of Aqaba earthquake, with mb = 6.2 in ISC), as well as the Mediterranean offshore earthquakes (i.e. the 1955 Alexandria earthquake, with mb = 6.1 in the USGS catalogue, the Cyprus 1996 earthquake, with mb = 6.3 in the ISC catalogue, the Ras El-Hekma 1998 earthquake, with mb = 5.8 in the ISC catalogue).

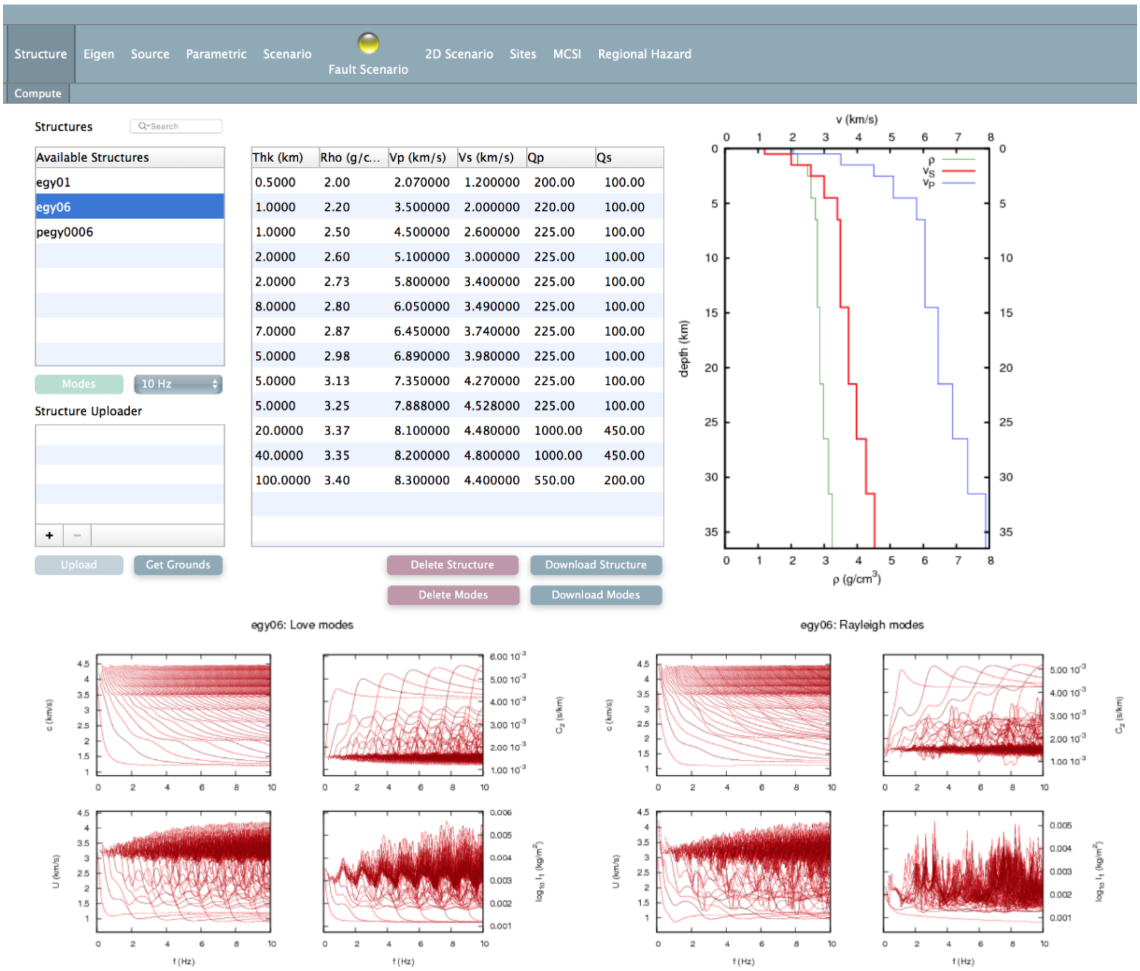


Figure 1 Panel used for the definition of the layer properties and the computation of the Love and Rayleigh modes. The structure properties are those used for the computations at the sites of Dahshur Pyramids and Madrasa of the Princess Tatar al-Higaziya.

Egypt has a very long historical record of earthquakes going back about four millennia. Nevertheless, detailed and reliable information is available only for a few destructive earthquakes, and their parameters have a limited accuracy. Lack of reliable data makes it difficult to apply methods based on the use of GMPEs that cannot be adequately calibrated. This lack can be overcome thanks to the use of physics-based ground motion simulations as proposed in the method section.

Saint Catherine's Monastery

The first case study deals with the Saint Catherine's Monastery. The monastery lies on the southern part of Sinai Peninsula, at the foot of the highest mountain in Egypt and Sinai, near the town of Saint Catherine. The monastery is named after Catherine of Alexandria, is controlled by the autonomous Church of Sinai, part of the wider Greek Orthodox Church, and is a UNESCO World Heritage Site. Built between 548 - 565 AC, the monastery is one of the oldest working Christian monasteries in the world. The site contains the world's oldest continually operating library. For this site an example of extended fault scenario modelling was performed and the appropriate panel of the web application is shown in Fig. 2. The adopted structural model is shown in Fig.1 with the associated Love and Rayleigh modes, and is taken from El-Khrepy (2008). The selected scenario is the 22 November, 1995 Gulf of Aqaba event which, with an estimated magnitude Mw = 7.3, is the largest instrumentally observed in Gulf the of Aqaba and Egypt as well. The fault and site positions are shown in the map along with other relevant information about the modelled scenario. Given the scenario, synthetic accelerograms and their response spectra are computed at the site for many realizations of the source rupturing process (up to 100 in this case) in order to account for its stochastic nature. The response spectrum plot shown is then obtained by using a statistical analysis, period by period, of the generated response spectra and represents the variability expected in the spectral acceleration for the selected scenario. The grey area in the plot spans from the median to the 95th percentile. The user can select which realization to be shown in the bottom part of the panel. In the right part of the panel the user can extract and download the generated accelerograms selecting the vibrational period of interest (e.g. the first vibrational period of the building to be analysed), the percentile of interest and the number of desired accelerograms. Both the response spectrum and/or the selected accelerograms can be used by engineers to run a Scenario-Based seismic hazard assessment. All accelerograms are three-components, including the vertical one that can have significant influence on the expected performance of masonry structurers (see Rinaldin et al. 2019).

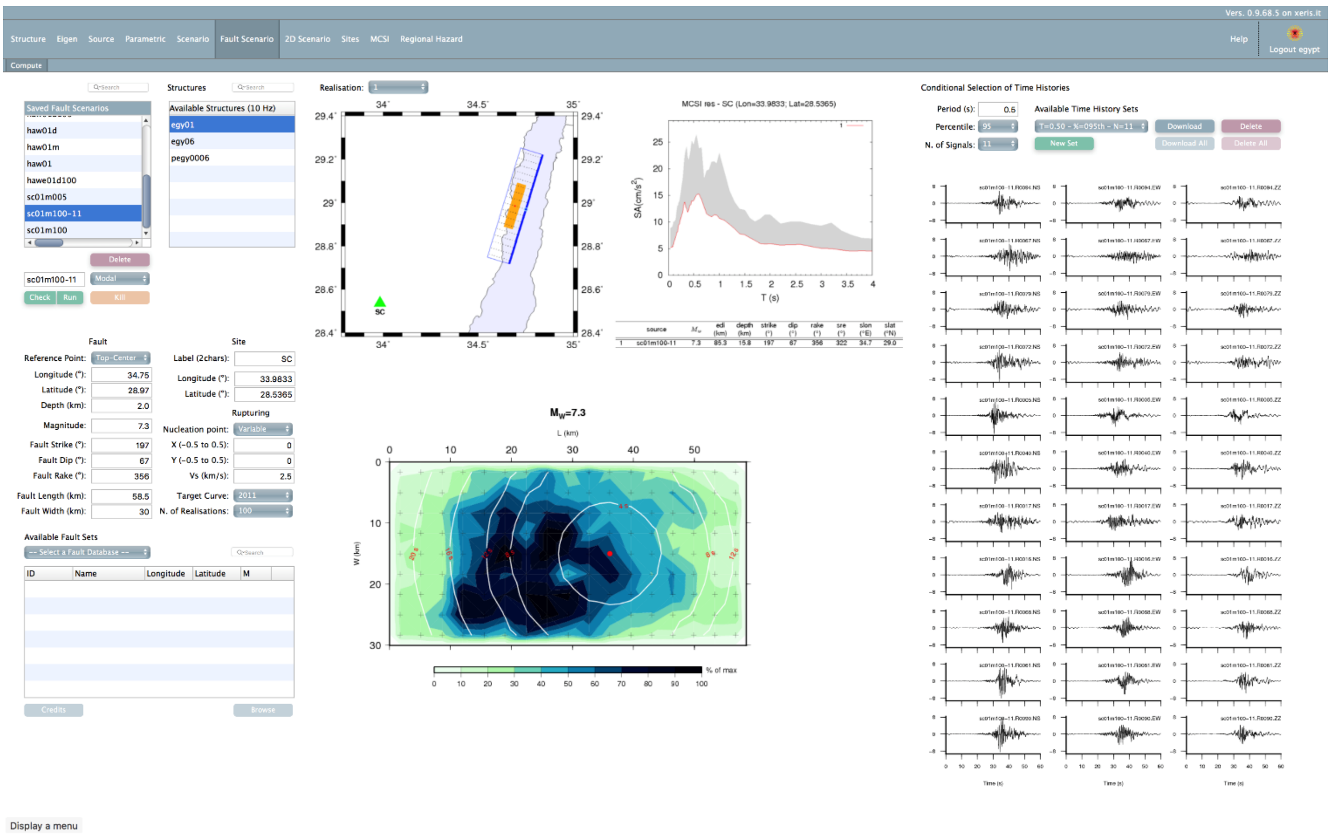


Figure 2 Computation of multiple ground shaking scenarios at a single site for many realizations of the rupturing process of an extended fault: an example for the case of the Saint Catherine's Monastery.

Dahshur Pyramids

The site of the Dahshur pyramids is located at an ancient royal necropolis, located approximately 40 kilometres south of Cairo. The pyramids were built from 2613 – 2589 BC and are among the oldest pyramids in the country. For such historical monuments it is essential to evaluate accurately the expected accelerations due to different scenarios. In this case an extended source model was again considered (see Fig. 3), but showing the possibility to combine multiple scenarios in a final unique seismic input definition. Two scenarios were selected: a magnitude Mw = 5.9 at about 8 km, corresponding to the 12 October 1992 Cairo earthquake (see Fig. 4) and a magnitude Mw = 6.7 at about 65 km corresponding to the 22 July 950 lower Egypt earthquake (see Fig. 5), as reported in Ambraseys et al. (1994).

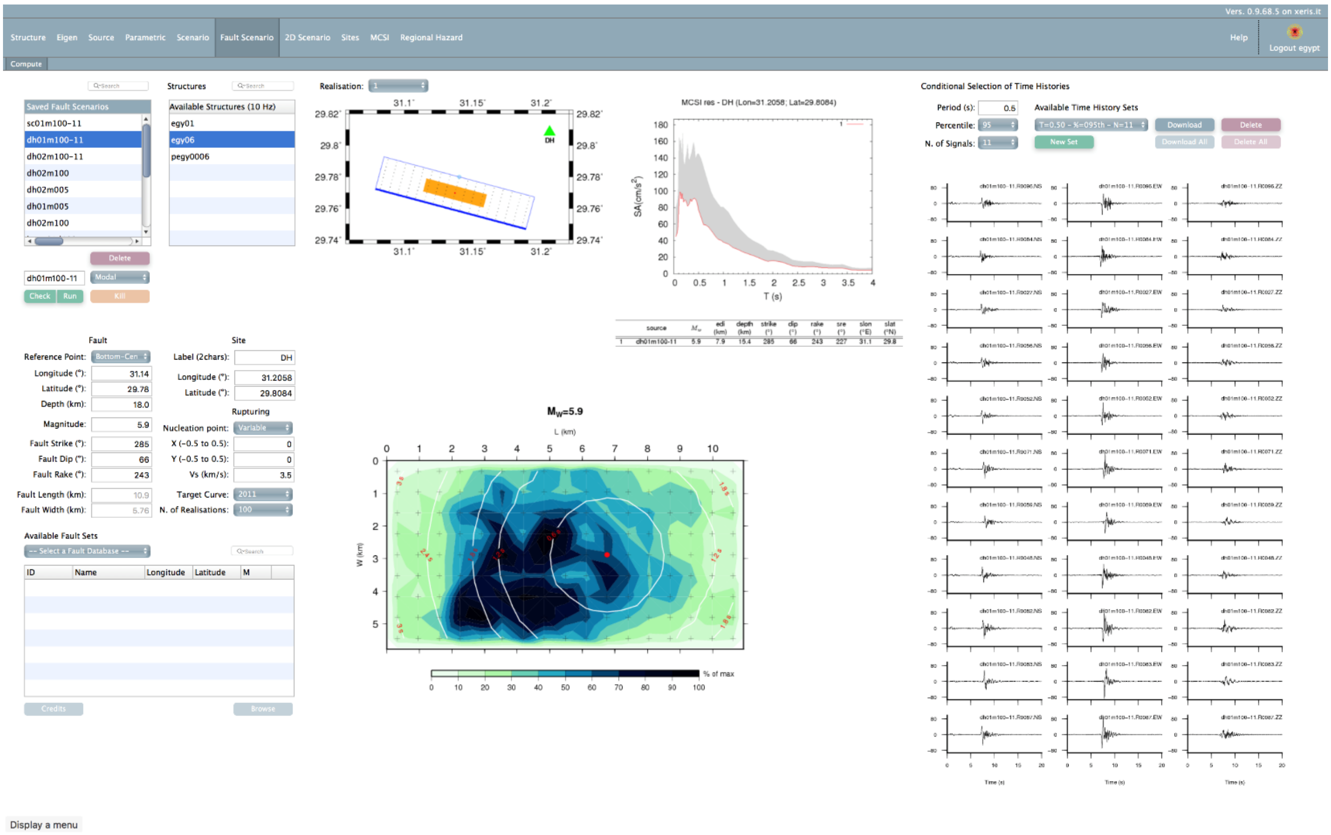


Figure 3 Fault Scenario example for the site of the Dahshur Pyramids.

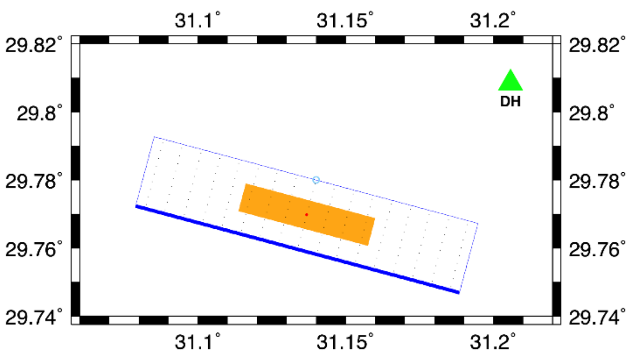


Figure 4 Dahshur Pyramids case study: fault and site positions for the Mw = 5.9 scenario (12 October 1992 Cairo earthquake).

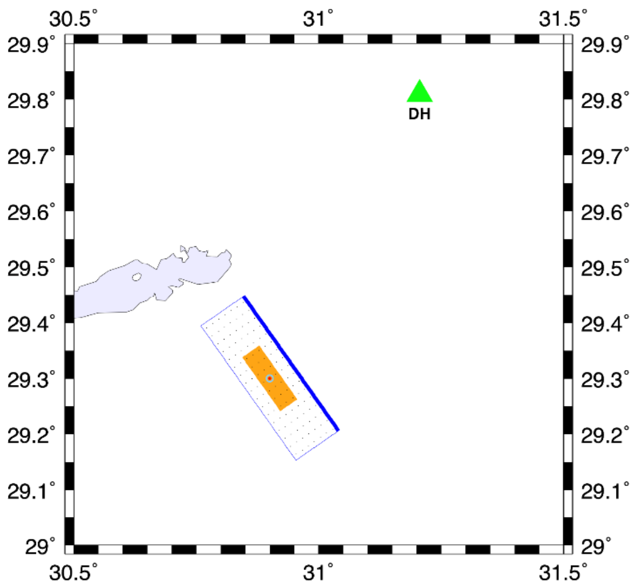


Figure 5 Dahshur Pyramids case study: fault and site positions for the Mw = 6.7 scenario (22 July 950 lower Egypt earthquake).

For each of the selected scenarios, 100 realizations of the possible rupture process of the fault were computed. This is performed in order to catch the variability in the expected ground motions due to source effects. Fig. 6 shows two of these realizations, one for the Mw = 5.9 scenario and the other for the Mw = 6.7 scenario. A description of the picture is given in the caption.

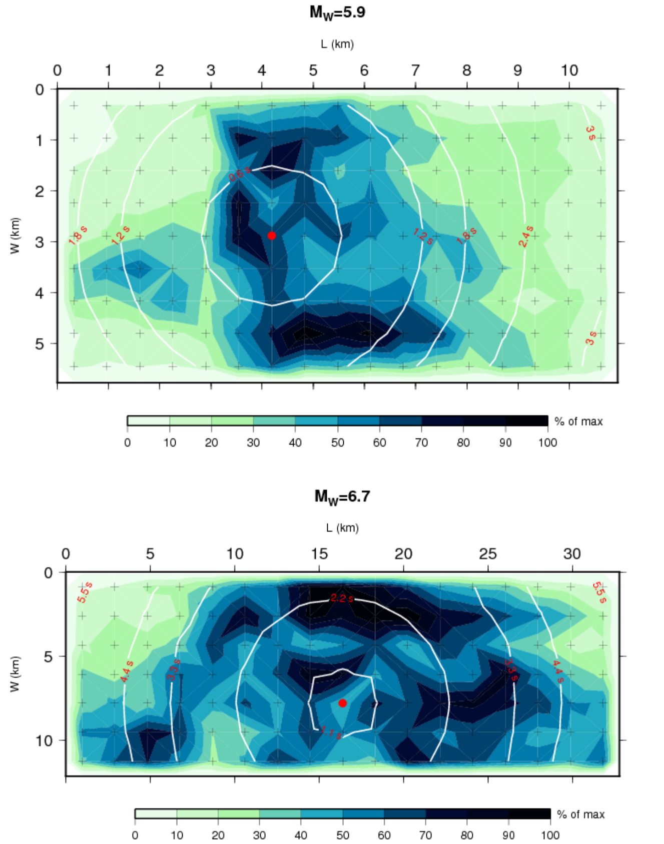
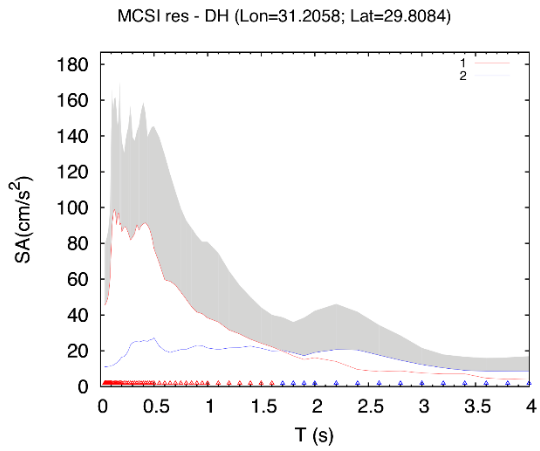


Figure 6 Two rupture processes for (up) the Mw = 5.9 scenario (12 October 1992 Cairo earthquake) and (bottom) the Mw = 6.7 scenario (22 July 950 lower Egypt earthquake). The dark areas correspond to a large slip on the fault, and the red dot shows the nucleation point of the rupture. The white isochrones describe the time evloution of the rupturing process.

Results from both scenarios are then combined into a single multi-scenario response spectrum (see Fig. 7) using the MCSI tab available in the web app. For the construction of this response spectrum, at each period the values of the scenario with the highest median value (or a selected percentile) are retained only (see Fasan 2017). The reported variability is the one associated with the winning scenario at each period and is represented by the grey area (values from the median to the 95th percentile). In this case study, only two scenarios are combined together. However, the procedure can be adopted with all known possible scenarios coming from faults, seismogenic zones, historical catalogues etc. If all known sources are taken into account, the procedure can be used to estimate the Maximum Credible Seismic Input (MCSI), which represents a reasonable upper bound for the ground motion level at a site of interest (Fasan 2017).

Otherwise, if only a selected number of sources is taken into account, it is proper to call it a Multi-Scenario Seismic Input (MSSI).



	source	M_w	edi (km)	depth (km)	strike (°)	dip (°)	rake (°)	sre (°)	slon (°E)	slat (°N)
1	dh01m100-11	5.9	7.9	15.4	285	66	243	227	31.1	29.8
2	dh02m100-11	6.7	63.7	10.0	145	32	332	117	30.9	29.3

Figure 7 Combination of Dahshur scenarios into one single response spectrum. The picture shows the median values for each scenario (red for scenario 1 and blue for scenario 2). The grey area represents the variability of spectral accelerations from the median to the 95th percentile of the winning scenarios. The table reports the main characteristics of the winning scenarios.

Madrasa of the Princess Tatar al-Higaziya

The third case study is the Madrasa (meaning school in Arabic) of princess Tatar al-Higaziya in Old Cairo. This building was constructed in 1348 AC as an extension to princess Tatar's house; then, after thirteen years, the palace and the mausoleum was converted into the Madrasa. The Madrasa complex consists of a mausoleum, minaret, and an ablutions court, and it is one of the few schools endowed by a woman in Cairo. The school was built and endowed for educating orphan children and for uplifting the daily prayers, as well as serving as a public library.

Simulations presented in previous subsections were developed assuming a laterally homogeneous layered structure of the crustal and site soil model. When the site of interest lies on a complicated subsurface geology, the effects of lateral heterogeneities cannot be neglected. They can generate, combined with the characteristics of the incoming wave field originated at the source, significant amplifications, and often at very specific frequencies.

For this case study a laterally heterogeneous profile is used (Fig. 8). The profile was developed for the Old Cairo area by Hassan (2018) and a detailed description is reported in Hassan et. al (2020) For this type of modelling, the web application makes use of the computer codes that implement the hybrid approach developed originally by Fäh and Panza (1994). A laterally homogeneous inelastic layered model is defined to represent the average lithospheric properties along the path from the source to the vicinity of the site. In this part of the model wave propagation is modelled by the MS technique. The generated wavefield is then introduced in a mesh that describes the local heterogeneous area characterizing the site of interest (Fig. 8), where it is propagated according to the finite difference scheme. With this hybrid approach, the source, path, and site effects are all taken into account, and the detailed ground shaking scenarios can be efficiently evaluated along a 2D profile even at large distances from the epicentre. In particular, this kind of modelling allows to evaluate amplifications with respect to homogeneous soil conditions and bedrock (Fig. 9) and to account for reflections and refractions due to the interfaces between different layers. These effects are accounted for in the simulated accelerograms. The web application allows to select and download these site-specific accelerograms as shown in Fig. 10. Structural engineers can use these accelerograms in dynamic time history structural analyses to perform site-specific hazard and vulnerability assessments.

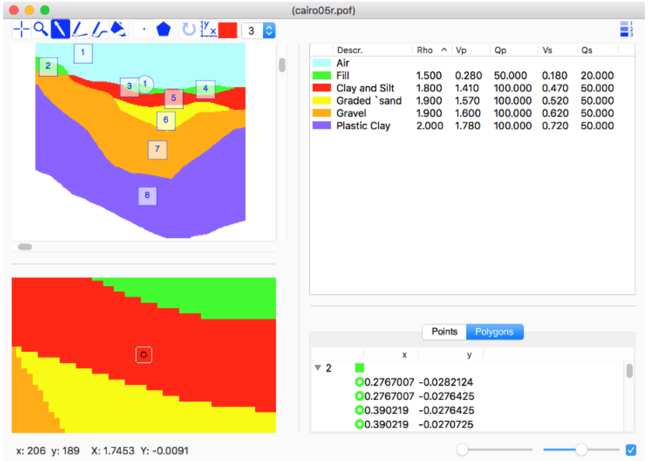


Figure 8 2D profile developed for the “Madrasa” case study.

Figure 9 Amplifications (dark red areas) are shown with respect to a laterally homogeneous bedrock model for the “Madrasa” profile. From top to bottom, the amplifications are shown along the profile for the vertical, radial, and transverse components. The abscissa shows the position along the profile, represented at the bottom, while the ordinates in the upper images refer to the frequencies at which the amplifications eventually occur.

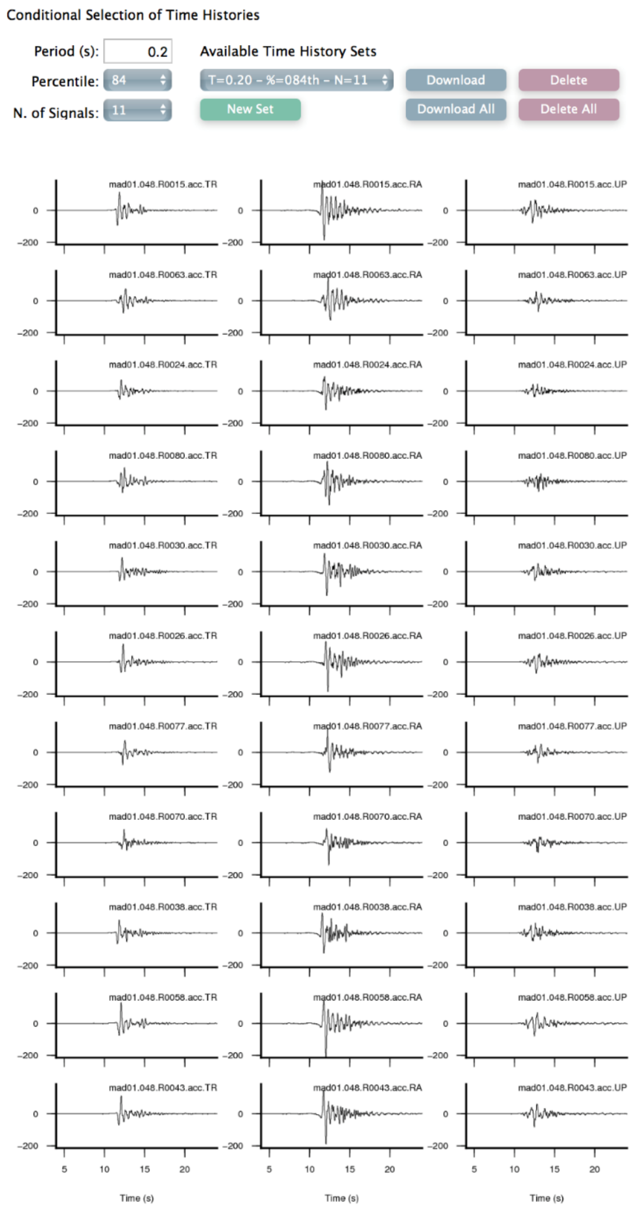


Figure 10 Accelerograms selection for the site of the Madrasa. 11 three-component accelerograms were selected around the 84th percentile at a vibrational period of 0.2s.

Conclusions

Physics-based ground motion simulations allow making accurate estimations of expected accelerations even in areas where little or no recorded data are available. Synthetic accelerograms can be generated and used to perform non-linear time history analysis of structures.

Being based on geophysical and seismotectonic features of a region, physics-based scenarios can be a helpful tool to evaluate the seismic hazard for ancient cultural heritage sites and monuments. In fact, the uniqueness and invaluable loss of this kind of assets makes it necessary to evaluate the hazard even for very strong rare earthquakes.

In this paper, a method for multi-scenario physics-based hazard evaluations is proposed and applied to some Egyptian sites. The generated synthetic seismograms include source, path and site effects. The modelling of ground-shaking scenarios for the considered case studies was done using a web app that implements the proposed method at different scale and level of detail.

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