A HOLISTIC PLATFORM FOR THE SEISMIC RISK ASSESSMENT OF ANCIENT MONUMENTS

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Abstract: *The protection of cultural heritage against natural hazards and in particular earthquakes is a critical and challenging task because authorities try to tackle the steady onslaught of extreme seismic events and continuous deterioration of the structure. Countries around the Mediterranean Sea have a portfolio of monuments, some of which are in relatively poor condition and in danger of sustaining non-recoverable damage due to earthquake events. Protecting these monuments becomes more daunting within budget limitations. In this framework, a holistic platform for the seismic risk assessment of ancient monuments has been developed within the EU-Greece funded research project ARCHYTAS to serve as a decision-support tool to assist the prioritization and restoration actions before a seismic event happens or in a post-event environment, providing a rapid assessment of the monument structural status for the given event. The overall system is presented indicatively for the Aphaia Temple in Aegina island, Greece.*

1 Introduction

The management and protection of cultural heritage (CH) sites at an urban scale or single monumental structures is a difficult and ever-evolving task as authorities are trying to tackle the increasing deterioration of monuments due to natural hazards. Public awareness has also increased regarding the protection of CH assets, acknowledging their priceless value. At the same time, authorities are trying to find a way of maximizing the efficiency of their protection and prevention actions within budget limitations. All these elements highlight the need for smart digital solutions that allow decision-making for the prioritization of rehabilitations actions, before or after a damaging event takes place. Towards this direction, the ARCHYTAS consortium developed a system comprising software and hardware components that offers the information required for reliable decision-making by relevant stakeholders.

The approach undertaken is based on the performance-based earthquake engineering framework of Cornell and Krawinkler (2000), and it follows on the wake of a number of successful implementations both in USA (e.g., NHERI SimCenter) and Europe (e.g., Horizon 2020 PANOPTIS and HYPERION projects). Furthermore, it employs concepts from urban risk analysis, using spatially correlated fields of ground motion generated by event-based probabilistic seismic hazard analysis (Monelli et al., 2012; Pagani et al., 2014) to enable portfolio-level assessments and allow the simultaneous consideration of multiple assets at nearby locations. Finally, a sensor component has been incorporated, enabling data fusion from multiple on-site instrumentation to deliver fast short-term (what-is) assessments.

2 Platform architecture

The ARCHYTAS platform has been designed and developed to support the Greek authorities and in particular the Ministry of Culture in order to take decisions for preservation and restoration actions, as well as manage and prioritize the resources in the aftermath of an earthquake. The platform is a comprehensive decision-support tool, whose architecture is shown in Figure 1 and consists of four main conceptual parts:

1. Sensors: The structures incorporated in the platform are monitored. Sensor data is sent to the Middleware to perform the risk calculations.
2. Computational models: Hazard and structural vulnerability calculations are performed offline and results are stored in the Middleware.
3. Middleware: The Middleware is the core of the platform and is hosted in the web-cloud. Data from sensors and the computational model results are stored and used by the Risk Assessment Engine to calculate the risk estimates and issue warnings.
4. End-User: The end-user of the platform is the Ministry of Culture, where certified personnel have access, handle the data, and evaluate the results and the warnings issued by the system.

The conceptual structure of the platform is shown in Figure 1, where the modules are shown in green, the sensors in orange, and the database in yellow color. The platform architecture has been developed to:

- Allow the seamless flow of data from sensors and computational models to end-users.
- Offer a user-friendly environment to the end-user.
- Minimize the computational time by employing the concept of pre-computed structural analysis results.
- Be easily customized, allowing the addition of monuments, as well as other natural hazards, such as flood.

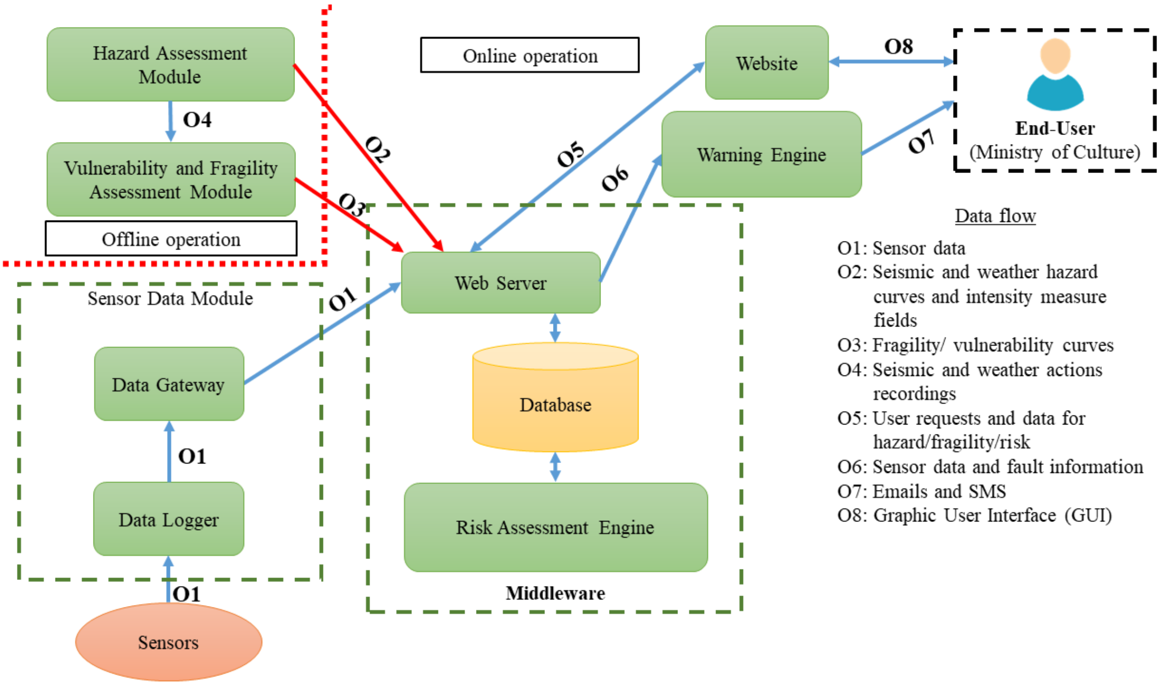

Figure 1. ARCHYTAS platform architecture.

The platform consists of the following modules (Figure 1):

1. Sensor Data Module (SDM): SDM is a physical entity and includes the Logger and the Gateway. It is part of the monument monitoring system along with the sensors. The number of SDMs in the overall ARCHYTAS system equals the number of the monuments being monitored. The module collects the data from the sensors and sends it to the Middleware via wired or wireless connection to the internet, depending on the recourses available at the archaeological site. In more detail, the Data Logger collects data from the sensors, saves it and forwards it to the Data Gateway, while the Data Gateway receives the sensor data and transmits it to the Web Server in the Middleware Module. It is noted that one or

more Loggers may be installed at a monument, depending on the configurations of the sensors. Moreover, the Data Gateway can be part of the Data Logger or a separate physical (hardware) entity.

2. Hazard Assessment Module (HAM): HAM operates offline. The seismic hazard assessment for each site is computed and results are stored in the Database of the Middleware in the form of seismic hazard curves and intensity measure fields.
3. Vulnerability and Fragility Assessment Module (VFAM): The monument's fragility is computed within the VFAM by employing a detailed or a simplified numerical model of the structure. The fragility expresses the probability of exceeding a predetermined level of damage for a given value of the intensity measure and is an integral part of the seismic risk calculations. The VFAM supplies the Middleware with the structure's fragility curves that are stored in the Database for use by the Risk Assessment Engine.
4. Middleware: The web-cloud Middleware is the core of the platform and consists of the Web Server, the Database, and the Risk Assessment Engine. In more detail:

- Web Server: It provides the required functionality in terms of RESTful web services to the Data Sensor Module, the system's Website, and the Warning Engine. It receives data to be stored by the HAM and VFAM.
- Database: The Database is the main storing site for the system's data, namely sensor data, seismic hazard results, fragility curves, and the results from the Risk Assessment Engine.
- Risk Assessment Engine: The Engine calculates risk estimates from the data stored in the Database. The computed risk in terms of the mean annual frequency of exceeding a predefined limit state is sent back to the Database to be broadcasted to the End-Users via the Web Server in the Website of the Warning Engine. The mean annual frequency of exceedance of a limit state indicates the risk level of the monument and is offered in colored ranges to assist the decision making by the end-user.

5. User Interaction Module: The User Interaction Modules (UIM) consist of the Website and the Warning Engine. The Website is the main end-user interface of the ARCHYTAS platform. The end-user's requests to the system are received via GUI in the Website and transmitted to the Web Server. Then, the end-user receives the results (risk estimates, recorded earthquakes from the on-site instrumentation, fragility curves, seismic hazard results, etc.) for the monuments. Then, depending on the thresholds set by the end-user, the Warning Engine sends event alerts to the End-User via email and/or short message system (SMS) after receiving sensor data from the Web Server in case of an earthquake event.

3 Case study

The main advantage of the ARCHYTAS system is that it can incorporate numerous monuments, as well as urban cultural heritage sites. In this study, the capabilities of the system are presented for illustration purposes for a single case-study monument, namely the Temple of Aphaia in Aegina island, Greece.

3.1 Temple of Aphaia

The Temple of Aphaia (Figure 2) in Aegina island, Greece was built around 500BC and was dedicated to the mother-goddess Aphaia. The Temple is considered one of the most important and well-preserved monuments of archaic architecture. The Temple is founded on a three-layer crepidoma (30.55m x 15.50m) and consists of the Opisthodomos (posterior), the Cella (central, 22.50m long and 8.00m wide), the Pronaos (anterior), and the external colonnade. It is a peripteral Doric order temple made of porous limestone with 12 columns on the long side and 6 columns on the short side (with corner columns double-counted). The overall condition of the monument nowadays can be classified in a moderate level of preservation status because its remnants have suffered non-negligible damage due to natural hazards and man-made actions.

Figure 2. The Temple of Aphaia in Aegina island, Greece [courtesy of the authors].

The remains of the Temple nowadays include free-standing monolithic columns [Figure 3(a)], free-standing multi-drum columns [Figure 3(b)], a colonnade of four columns with architraves [Figure 3(c)], colonnades of two columns with architrave [Figure 3(d)], a multi-drum column connected to a part of the Cella wall with an architrave [Figure 3(e)], corner colonnade with architraves [Figure 3(f)], and two-level colonnades with architraves in the Cella [Figure 3(g)]. These sub-assemblages are structurally independent.

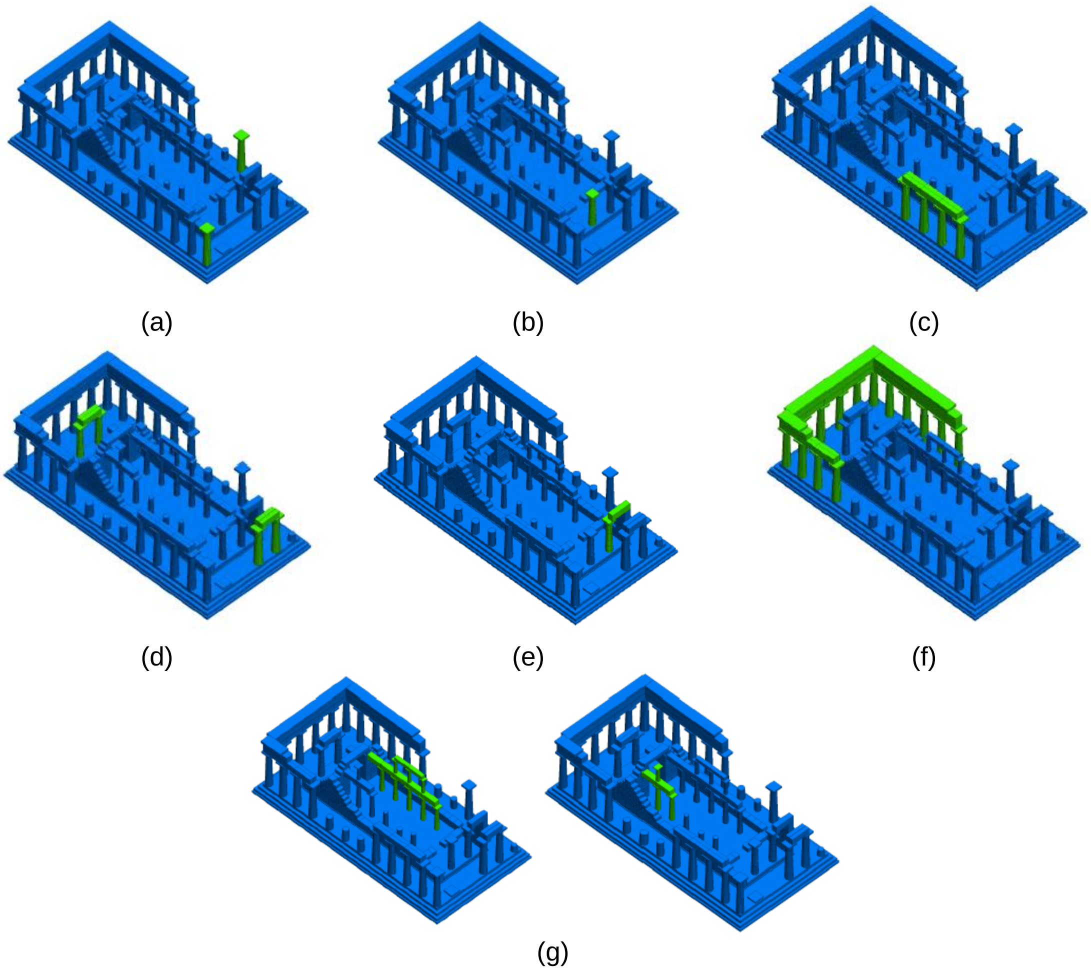

Figure 3. Sub-assemblages of the Temple of Aphaia: (a) free-standing monolithic columns, (b) free-standing multi-drum column, (c) a colonnade of four columns with architraves, (d) colonnades of two columns with architrave, (e) a multi-drum column connected to the Cella wall with an architrave, (f) corner colonnade with architraves, (g) two-level colonnades with architraves in the Cella [adopted from Dasiou et al. (2023)].

3.2 Seismic hazard

The calculation of the seismic hazard within the Seismic Hazard Assessment Module is carried out for the site of the Temple with coordinates N 37 45.274 and E 23 32.018 by employing the open-source OpenQuake engine (Pagani et al., 2014) of the Global Earthquake Model Foundation. The probabilistic seismic hazard analysis (Cornell, 1968) calculations are performed using the 2013 European Seismic Hazard Model [ESHM13 (Woessner et al., 2015)] by employing for simplicity only the area source model and the ground motion prediction equation of Boore and Atkinson (2008).

The intensity measure (IM) allows the information to flow from the seismological analysis to the structural analysis. Two IMs are selected and used in the system, namely the asset-agnostic Peak Ground Acceleration (PGA), being the geometric mean of the PGA values in the two horizontal components, and the moderately asset-aware Average Spectral Acceleration ($AvgS_a$), being the geometric mean of the spectral accelerations evaluated for both principal horizontal direction within a range of periods spanning from 0.1s to 1.5s in increments of 0.1s. Finally, a set of 11 natural ground motion records per 4 discrete hazard levels (return periods equal to 225, 475, 2475, and 4975 years) is selected from the PEER-NGA (Ancheta et al., 2013) database. More details on the record selection are provided by Dasiou et al. (2023). As a final remark, it is noted that the Temple is founded on rock and consequently the monument's response in not affected by soil-structure interaction.

3.3 Numerical model

The Temple of Aphaia is a typical ancient Greek temple that consists of independent structural members, i.e., stone blocks placed on top of each other without any connecting material. The seismic response of this modular structure is characterized by rocking and/or sliding of the stones independently or in groups (Dasiou et al., 2009b; Lachanas and Vamvatsikos, 2022; Vayas et al., 2007; Yim et al., 1980) thus not possessing eigenmodes in the typical sense. The Discrete Element Method (DEM) is employed for the analysis of the structure using the commercial 3DEC code by Itasca Consulting Group, Inc. (Itasca Consulting Group Inc., 1998). The developed model of the Temple (Figure 4) is built using the results of a photogrammetric survey that was performed using an Unmanned Aerial Vehicle. The current status of the structure is modelled, namely any missing parts of the stone blocks are cut off and any dislocation of drums, columns or architraves is considered. The properties of the material are: modulus of elasticity 70GPa, Poisson's ratio 0.30, and density 2750kg/m^3. The stiffness of the contacts between the rigid blocks are $k_n = 5 \times 10^9 \mathrm{Pa/m}$ in the direction perpendicular to the joint and $k_s = 1 \times 10^9 \mathrm{Pa/m}$ parallel to the joint (Dasiou et al., 2009; Dasiou et al., 2009b).

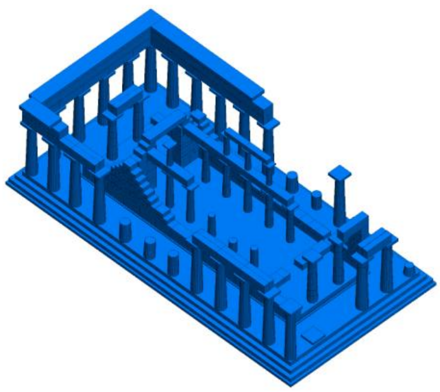

Figure 4. 3D isometric view of the numerical model of the Temple of Aphaia [adopted from Dasiou et al. (2023)].

The structural response of the Temple is evaluated using appropriate Engineering Demand Parameters (EDPs) in terms of displacement for both columns and architraves, namely the maximum value of displacement (δ_{max}) obtained during the excitation and the residual value of displacement (δ_{res}) at the end of the excitation. The displacement values are normalized with respect to the column base diameter and the half-width of the architrave's abaqus for columns and architraves, respectively. Then, the EDP thresholds are defined based on engineering judgment, assessment of analysis results, and previous published results (Dasiou et al., 2009; Dasiou et al., 2009a; Mouzakis et al., 2002; Psycharis et al., 2013). The performance criteria and associated limit states for columns and architraves are listed in Table 1. The interested reader may find more information about the numerical model in Dasiou et al. (2023). The corresponding damage states (DS) are presented in Table 2 and are colored after ATC-20 (Applied Technology Council, 1989).

Table 1. Performance criteria and associated limit states for columns and architraves; exceedance of either EDP threshold signifies violation of the respected limit state (LS).

LS	Monolithic columns		Multidrum columns		Architraves		Performance level
	δ_{max}	δ_{res}	δ_{max}	δ_{res}	δ_{max}	δ_{res}	
LS1	0.25	0.15	0.25	0.15	0.25	0.15	Minor damage
LS2	0.50	0.30	0.50	0.30	0.50	0.35	Significant damage
LS3	1.00	1.00	1.00	1.00	1.00	1.00	Near collapse

Table 2. Damage state classification.

Damage State	Description	Color tagging
DS0	No damage	
DS1	Minor damage	
DS2	Significant damage	
DS3	Near collapse	

3.4 Seismic fragility and risk assessment

Fragility curves are used to assess the susceptibility of a structure to earthquake-induced damage (Bakalis and Vamvatsikos, 2018; Silva et al., 2019). A fragility curve is essentially a function of the IM and provides the probability of exceeding a specific LS. The formal definition of fragility employed in the system is:

$$F_{LS}(IM) = P\left[\delta_{max} > \delta_{max,LS} \text{ OR } \delta_{res} > \delta_{res,LS} \mid IM\right] \tag{1}$$

A single fragility curve is computed per structural member (columns and architraves) of the Temple with VFAM and stored in the Database.

The seismic risk assessment calculations are based on the concept of Performance-Based Earthquake Engineering [PBEE (Cornell and Krawinkler, 2000)]. Focusing on the long-term risk, the mean annual frequency (MAF) of exceeding the *i*-th discrete LS, λ_{LSi}, and the corresponding return period of exceedance $T_{r,i}$ were calculated by integrating the seismic fragility with the seismic hazard:

$$\lambda_{LSi} = \int_{IM} F_{LSi}(IM) \cdot |\mathrm{d}\lambda(IM)| \text{ with } i = 1,2,3 \tag{2}$$

$$T_{r,i} = \frac{1}{\lambda_{LSi}} \text{ with } i = 1,2,3 \tag{3}$$

It is noted that for the aforementioned integration, lognormally fitted fragilities (Baker, 2015) are employed.

4 On-site instrumentation

The installation of measuring devices (on-site instrumentation system) on an ancient monument is a complex procedure that requires a lot of time, specialized studies by archaeologists, architects, civil and electrical engineers, and permissions by the authorities. In order to provide a proof-of-concept for the ARCHYTAS system, it was decided to install an accelerometer close to the Temple on a rigid reinforced concrete block to measure the ground acceleration. This rigid block is located about 70m away from the Temple and is the foundation of the ticket booth for the archaeological site. The on-site instrumentation system was developed by the Institute of Steel Structures at the National Technical University of Athens and is characterized by low cost and high accuracy (El Dahr et al., 2022, 2023). An overview of the accelerometer (fixed on the rigid base) and the logger (inside the ticket booth) is shown in Figure 5. The 3-axis accelerometer was fixed on the rigid base and was filled with mortar for protection. The accelerometer is part of the Sensors module (physical entity) of the system (Figure 1). The Sensor Data Module (Figure 1) of the system, being a physical entity is shown in Figure 5(b). The Logger and the Gateway are integrated in the box shown in the right-hand side of Figure 5(b), while the box on the left hand-side is an Uninterrupted Power Supply (UPS) that provides electrical power to the logger. The logger contains a computing unit (Raspberry Pi) operating in Linux environment, which is serially connected to a 32bit – 600MHz microcontroller, communicating via SPI protocol with an analog to digital converter (ADC) with 24bit signal resolution that receives the analog signal of the accelerometer. The system is designed to record data with a recording frequency of 250Hz. The recording system has the ability to record and send data 5sec before the seismic excitation and for 30sec after its initiation. In case the internet connection is lost, the data is stored in the computing unit of the system and is sent to the Web Server after the internet connection is restored. Each data file contains the acceleration measurements in three axes, a series of time records at the ms (millisecond) level and a timestamp.

(a) (b)

Figure 5. On-site instrumentation system: (a) 3-axis accelerometer and (b) logger.

5 Platform operation

The operation of the ARCHYTAS platform is presented for the case-study monument of the Aphaia Temple (Papanikolopoulos et al., 2023). The system operates in two modes (Vamvatsikos et al., 2021), namely (a) scenario mode and (b) emergency mode, which are presented in detail subsequently.

5.1 Scenario mode

The system provides the seismic risk estimates for the monument for earthquake scenarios that are selected by the user. The system screen for selecting an earthquake scenario is presented in Figure 6. The user is setting the parameters for the selection of the earthquake scenario (where the numbers in parentheses correspond to numbers in Figure 6):

- Set the minimum magnitude (1) and maximum magnitude (2).
- Set the area for searching epicenters (8) on Google Maps in the Attica Region.
- Set the intensity measure (5) [see Section 3.2].
- Perform filtering (3) of the available earthquake scenarios based on the parameters defined earlier (earthquake scenarios are obtained from the seismic hazard analysis and are stored in the Database of the Middleware).
- After filtering, the available earthquake scenarios are shown in the map with red dots. The intensity measure field (9) is also presented on the map along with the colorbar (10).
- The user can hide the circle of searching scenarios (7) for viewing purposes and can adjust the transparency of the intensity measure filed (6).

After selecting an earthquake scenario on the map (Figure 7), the user executes the Risk Assessment Engine via button (4).

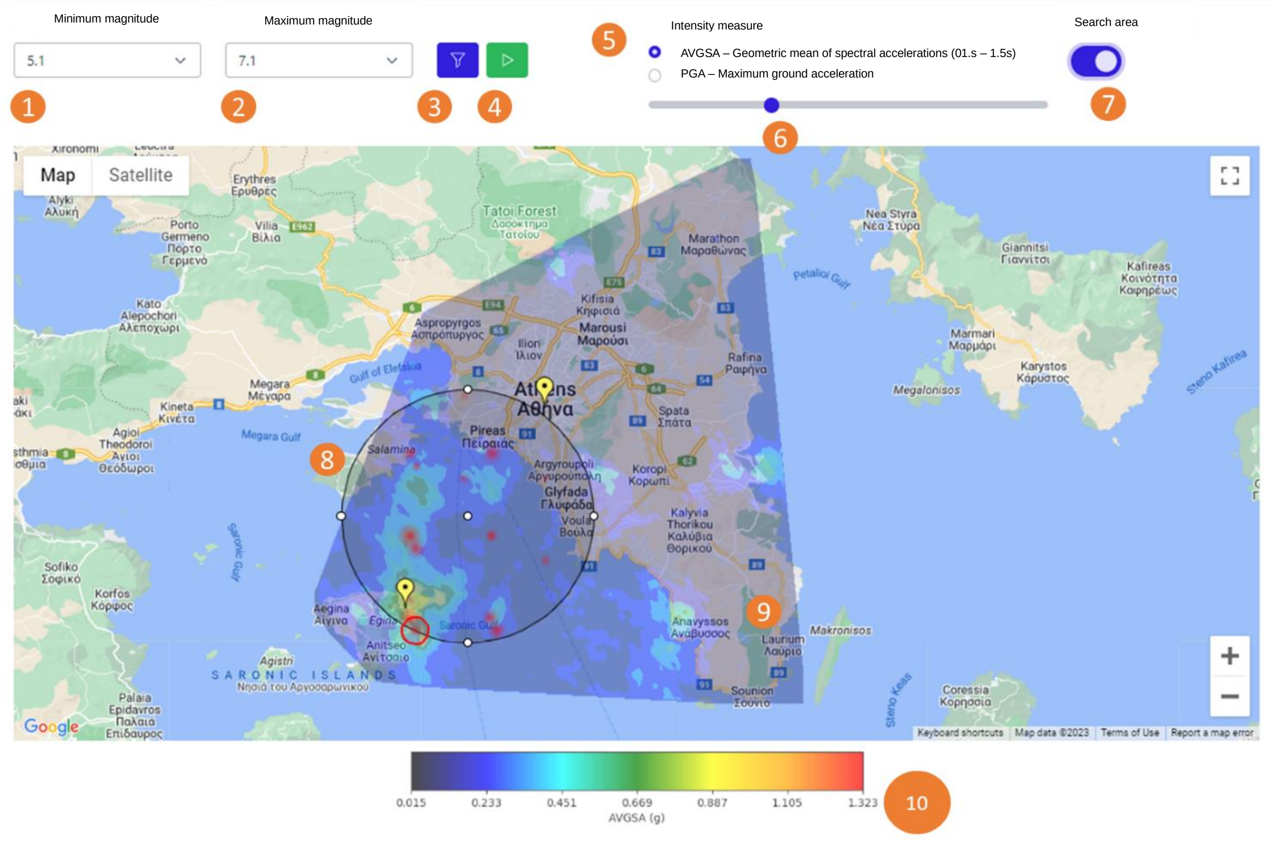

Figure 6. Scenario mode: System screen for selecting earthquake scenario.

Figure 7. Selection of an earthquake scenario.

The risk estimates for the selected earthquake scenario are presented for each structural member of the Temple in terms of the most probable DS using the color tagging of Table 2. An indicative example is shown in Figure 8 where the plan of the Temple is shown and the structural member are colored. The user can also view separately the four elevations (North, South, East, West) of the structure. Moreover, the user can select any member to view the probabilities of exceedance for all DSs, as depicted indicatively in Figure 9 for the column K1.

Figure 8. Coloring of structural members based on the most probable DS for the selected earthquake scenario.

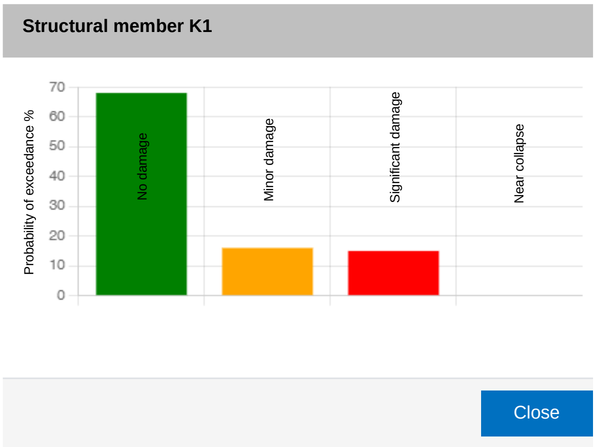

Figure 9. Coloring of structural member column K1) based on the most probable DS for the selected earthquake scenario.

5.2 Emergency mode

The system's Emergency mode offers risks estimates provided that an earthquake event has occurred. The accelerograms in 3 axes are recorded by the accelerometer installed (see Section 4) and sent to the Database via the Web Server. The end-user is able to retrieve, view, and download these ground motion records. In case of an earthquake, the Risk Assessment Engine is triggered and risk estimates are offered in the same format as in the Scenario mode (see Figure 8 and Figure 9).

5.3 Long-term estimates

The seismic hazard results (see Section 3.2) and the long-term seismic risk estimates (see Section 3.4) are pre-computed and stored in the Database to be available at any time to the end-user. In more detail, the seismic hazard curves for the Temple's site are offered for both IMs considered (Figure 10); the end-user can select a structural member from the plan or the elevations of the Temple and obtain the corresponding fragility curves (Figure 11).

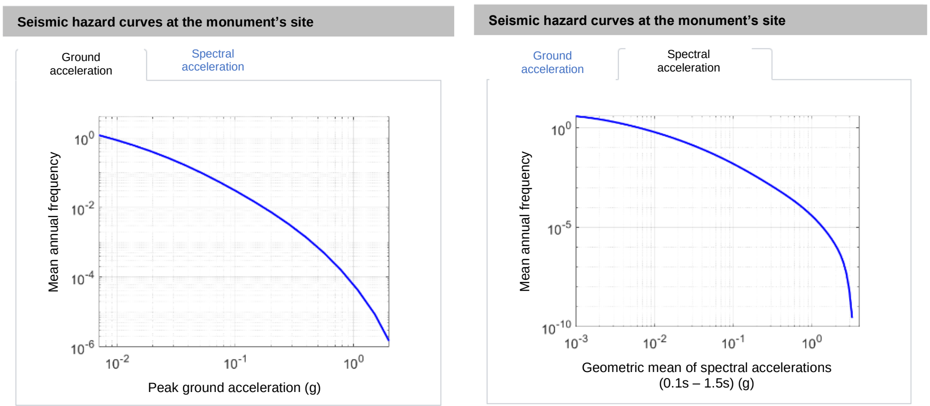

Figure 10. Seismic hazard curves for the site of the Temple of Aphaia for both IMs considered.

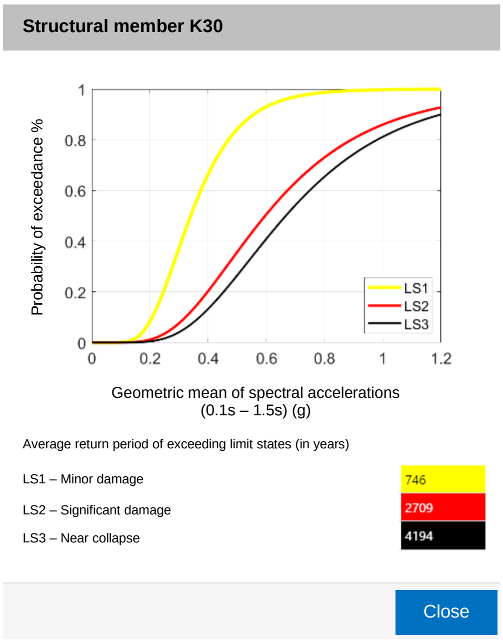

Figure 11. Indicative fragility curves for a structural member (column K30).

6 Conclusions

The ARCHYTAS system is a holistic platform for the seismic risk assessment of cultural heritage monuments. It offers a decision-support to assist authorities in managing portfolios of monuments and even entire urban cultural heritage sites. The system operates in both pre-event and post-event phases providing seismic risk estimates that drive the prioritization of preservation and restoration actions. ARCHYTAS takes advantage of on-site monitoring systems and allows the integration of structural models of different levels of complexity and fidelity, as well as state-of-the-art seismic hazard calculations. The ARCHYTAS platform has been demonstrated within this study using the Temple of Aphaia as a case study.

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