The ARCHYTAS Intelligent Decision-Support System for the Protection of Monumental Structures

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Abstract The ARCHYTAS platform is based on using (i) reliable mechanical models and damage thresholds for assessing structural performance (ii) a network of sensors for updating the model parameters, (iii) detailed estimates of earthquake and flood hazard at the sites of interest and (iv) a state-of-art approach for multi-hazard risk assessment that can deliver accurate pre/trans/post-event evaluation of the risk at multiple geographically distributed cultural heritage sites. The core of the proposed system comprises a cloud-deployed computational platform, where data obtained from on-site measuring systems is processed, critical environmental actions are identified and flags are raised to provide alerts on the predicted monument structural condition. The decision-support system is fully uncertainty-aware, employing the concept of the mean annual frequency of limit-state exceedance under specified confidence levels to offer monument-specific courses of action based on the convolution of the current state of the monument (as determined by its best-estimate fragility, and updated by current or past measurements) and the predicted, recorded or evolving hazard. All-in-all, the platform can assist the relevant authorities to prioritize inspection, maintenance and rehabilitation actions before or after events subject to limited available resources.

Keywords: cultural heritage, seismic hazard, flood hazard, sensor network, uncertainty, risk assessment

1 Introduction

The protection of cultural heritage is a difficult and ever-evolving task as authorities attempt to tackle the steady onslaught of extreme natural hazards and continuous weathering deterioration. At present, most Mediterranean countries have their share of monumental structures whose structural condition is relatively poor and are in danger of sustaining non-recoverable damage or even losing their structural integrity. Protecting endangered monuments from environmental actions, such as the dominant seismic and pluvial flooding hazards that are prevalent around the Mediterranean Basin is a challenge that only becomes more daunting when tackled within severe budgetary constraints. Finding ways to maximize the impact of every euro spent is of paramount importance, especially within a crisis environment. Such structures are priceless and, consequently, the application of novel engineering solutions needs to be handled with care, involving archeologists, restoration specialists, architects and structural engineers to ensure optimal outcomes. All the above elements highlight the need for an intelligent decision-support platform for the prioritization of rehabilitation actions, before or after a damaging event takes place. The ARCHYTAS project aims to develop such a software & hardware system that will offer the data required for reliable decision-making by relevant stakeholders. Its theoretical foundations and conceptual architecture are presented as applied to monuments of classical antiquity in Greece.

2 Platform architecture

The ARCHYTAS platform is the core of the intelligent decision-support system for the protection of monumental structures and consists of four conceptual entities:

- End-user: The end-user of the platform is the Ministry of Culture and Sports, where certified personnel can access the platform, handle the data, and assess the potential risks to the monuments.
- Sensors: The sensors are installed in the monuments and provide the data to the web-cloud to perform the risk calculations.
- Computational models: Hazard and vulnerability computational models run offline and generate data that is stored in the web-cloud to be used for risk assessment.
- Web-Cloud Middleware: The core of the platform is hosted in the web-cloud, where sensor data are stored, risk assessment calculations are performed, the platform's website and warning engine are provided with data.

The conceptual architecture of the platform is illustrated in Fig. 1, where the modules are presented with green color, the sensors with orange, and the database with yellow. The platform architecture supports the seamless flow of data from sensors and computational models to the end-user, as well as the interaction with the end-user.

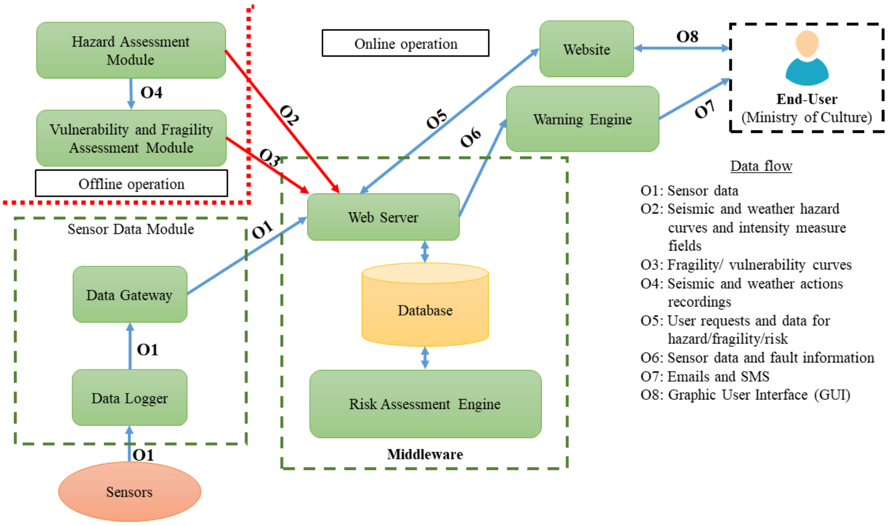

Fig. 1 Signs of visible damage in the columns of the Temple of Aphaia (top) and temporary local support measures for a cracked lintel (bottom)

2.1 Sensor Data Module

The Sensor Data Module is a physical entity and includes the Logger and the Gateway. The module collects the data from the sensors and sends it to the webserver located in the web-cloud that is part of the Middleware. The Data Logger collects data from the sensors, saves it and forwards it to the Data Gateway. Usually, one recorder per monument is used and more than one sensor is connected to it. The Data Gateway receives the sensor data and transmits it to the Web Server located in the web-cloud. The Data Gateway can be part of the Data Logger or a separate physical entity (hardware). The data is transmitted asynchronously either wirelessly, or via a landline.

2.2 Hazard, Fragility and Vulnerability Assessment Modules

The hazard assessment for each site is carried out in the Hazard Assessment Module (operating offline), which supplies the Middleware with the (seismic and weather) hazard curves and the intensity measure fields, which are stored in the Database for use by the Risk Assessment Engine. Seismic hazard assessment is carried out with the OpenQuake (Pagani et al. 2014) open-source platform and the European seismic model SHARE (Woessner et al. 2015) to produce the seismic hazard curve for the site of the monument, the seismic intensity measure fields. Then, the appropriate accelerograms are selected using state-of-the-art tools and procedures. Accelerograms are transferred to the Vulnerability and Fragility Assessment Module, while the seismic hazard curves and the intensity measures fields are transferred to the Middleware. For weather hazards such as wind, rain, temperature, etc., local measurements from national meteorological stations and stochastic models are used. The weather hazard curves are transferred to the Vulnerability and Fragility Assessment Module, while the weather hazard data is transferred to the Middleware.

The assessment of the monument fragility is critical for calculating the risk. Fragility presents the possibility of exceeding a predetermined level of damage for a given value of the intensity measure. The Vulnerability and Fragility Assessment Module operates offline. The module supplies the Middleware with the structure's fragility curves, which are stored in the Database to be used by the Risk Assessment Engine.

2.3 Web-Cloud Middleware

The Middleware is the core of the platform and is located in the web-cloud. It comprises a Web Server that interacts with the rest of the platform modules and part, the Database and the Risk Assessment Engine. The Webserver provides the required functionality, in the form of RESTful web services, to (i) the Sensor Data Module that records the measurements from the sensors installed in the monuments, (ii) the system's Website where information for the monuments and measurements are presented, and (iii) the Warning Engine. The Web Server also receives data to be stored in the Database by the Hazard Assessment Module and the Vulnerability and Fragility Assessment Module.

The Database is part of the Middleware, where sensor data, the fragility curves of the monuments, the hazard curves and the intensity measure fields are stored, as well as the results obtained from the Risk Assessment Engine.

The Risk Assessment Engine is located in the cloud as being part of the Middleware and interacts with the Database for data exchange:

- Seismic and weather hazard curves produced in the Hazard Assessment Module;
- Intensity measures fields generated in the Hazard Assessment Module;
- Fragility curves produced in the Vulnerability and Fragility Assessment Module;
- Sensor data sent from the Sensor Data Module.

After performing the seismic and/or weather risk calculations, results are sent to the Database in order to be transmitted to the Website or the Warning Engine via the Web Server. The calculation of the risk is carried out by taking into account the effects of the hazard and the fragility. The result is the calculation of the mean annual frequency of exceeding a predefined limit state.

The mean annual frequency of exceedance of a limit state indicates the risk level of the monument. The ranges of this mean annual frequency are illustrated with color indications: green for low damage estimation, orange for medium damage estimation and need for on-site inspection, red for severe damage estimation and need for immediate visit to the monument. This color scale enables the End-User to immediately prioritize its needs and optimize the allocation of available financial and human resources.

2.4 User Interaction Modules

The Website is the central end-user interface to the ARCHYTAS platform. The Website receives End-User requests via GUI and transmits them to the Web Server and receives the hazard, vulnerability and risk data for the monuments from the Web server to be presented to the End-User. The Warning Engine sends event alerts to End-User via email and/or short message system (SMS) after receiving sensor data and fault information from the Web Server.

The End-User of the telemetry control platform is the Directorate for the Restoration of Ancient Monuments of the Ministry of Culture and Sport as the authority responsible for monitoring the status of the monuments. The End-User accesses the platform via the Website and receives notifications of emergency events from the Warning Engine.

3 Case studies

3.1 Horologion of Andronikos Kyrristos

The Horologion, also known as the tower of the Winds, is an octagonal clocktower with 3.2m sides and a conical roof built in the first half of the 1st century B.C. by the astronomer Andronicos, from Kyrrhos, Macedonia. It resides in the Roman Agora of Athens and comprises sundials and a water clock. It is entirely composed of marble blocks, fitted without the use of mortar joints, and it suffers from lateral spreading (rotation) of the top of walls with subsequent lowering of the roof (Fig. 2). Due to the obvious risk of loss of structural integrity, it has been designated as “very vulnerable” by the authorities. The monitoring system comprises extensometers and inclinometers (Fig. 3), which will be complemented by the addition of accelerometers and a local weather station that will transmit data directly to the Web-Cloud Middleware.

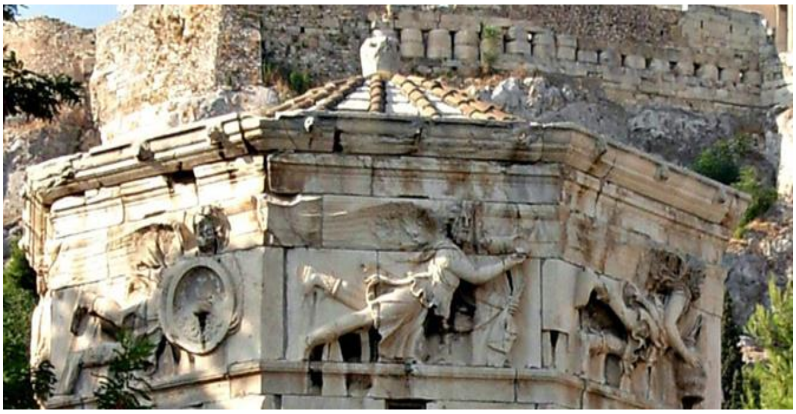

Fig. 2 The laterally spreading roof of the Horologion of Andronikos Kyrristos

Fig. 3 Sensors currently installed at the Horologion: Extensometer (left) and inclinometer (right)

Fig. 4 North view of the Temple of Aphaia, Aegina Island, Greece

3.2 Temple of Aphaia

The Temple of Aphaia stands on a hill at the north-east side of the island of Aigina, within view of Athens. It is a Doric temple constructed from porous stone (tuffa) and erected circa 500BC. It comprises both monolithic and multi-drum columns, some standing alone and others connected by architraves (Fig. 4). Originally, plastering protected the porous stone of the columns, yet this has mostly disappeared over the millennia. Due to its exposure to the elements, it has sustained significant damage, with visible cracks in some architraves and columns, some requiring temporary shoring until a permanent solution is found (Fig. 5). The monitoring system will only comprise accelerometers.

Fig. 5 Signs of visible damage in the columns of the Temple of Aphaia (top) and temporary local support measures for a cracked lintel (bottom)

4 Hazard and Risk Assessment Framework

Probabilistic representations of hazard will be adopted to capture the natural randomness of environmental stressors such as earthquakes, pluvial floods and weathering of the stone. In the case of earthquakes, Probabilistic Seismic Hazard Analysis (PSHA) will be employed (Cornel, 1968, Baker, 2008). Specifically, the event-based approach of PSHA will be adopted to offer scenarios of seismic intensity occurring due to a single seismic event over multiple sites, as shown in Fig. 6. This allows us to capture the spatial variability and correlation of ground motion, as well as the cotemporaneous nature of losses at multiple monuments subject to the same event, as these will most stretch the resources for any post-event restoration.

Risk assessment is based on the concept of Performance-Based Earthquake Engineering, as proposed by Cornell and Krawinkler (2000), and adopted by the Pacific Earthquake Engineering Research (PEER) Center:

$$\lambda(DV) = \int\int\int G(DV|DM)\ |dG(DM|EDP)|\ |dG(EDP|IM)|\ |d\lambda(IM)| \qquad (1)$$

DV is a scalar or vector of Decision Variables, e.g., monetary cost, downtime or human casualties, to be used by decision makers to undertake restoration actions. *DM* is the Damage Measure, representing the level of damage and typically discretized into distinct damage states of structural and non-structural elements. The Engineering Demand Parameter (*EDP*) characterizes the structural response in engineering terms (e.g., strains, stresses, displacements, etc.) while *IM* is the intensity measure whose mean annual frequency is estimated by PSHA. $G(x)$ is the complementary cumulative distribution function of x, and $\lambda(y)$ offers the mean annual frequency of y. In essence, this is the embodiment of the total probability theorem that allows us to combine the results of multiple seismic hazard scenarios (Fig. 6) with the fragility assessment results to determine the risk of one or more monumental structures in terms understandable by non-engineer stakeholders.

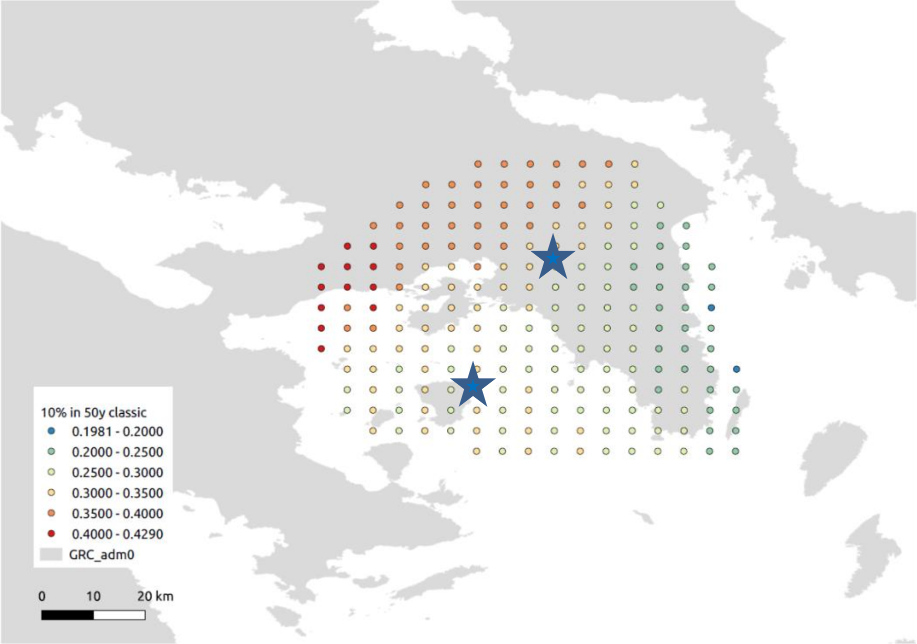

Fig. 6 Peak ground acceleration (PGA) with a return period of 475 years in the region of Attica based on the SHARE model (Woessner et al., 2015). The location of the case studies is indicated by two stars

6 Structural Modeling

Monuments of classical antiquity, like the two case studies presented, are mainly prone to rocking under seismic excitation. Both 2D and 3D models have been proposed to capture such a behavior. The simplest approach for modeling the rocking motion of a rigid body has been proposed by Housner (1963). Since then, many authors have recommended more elaborate models to capture rocking and/or sliding using either equivalent non-rocking oscillators or explicit solutions of the rocking/sliding motion. These range from single-degree-of-freedom systems, comprehensively presented in Fig. 7 by Diamantopoulos and Fragiadakis (2019), up to large-scale multi-degree-of-freedom finite element or discrete element models (Dasiou et al. 2009, Psycharis et al. 2013), as shown in Fig. 8. Each modeling choice represents a different compromise in terms of computational cost, modeling complexity, ease of convergence and accuracy, whose pros and cons need careful consideration for each case study. Selecting the simplest possible model with an acceptable level of fidelity is key for efficiently running the time-history analyses required for accurate fragility assessment.

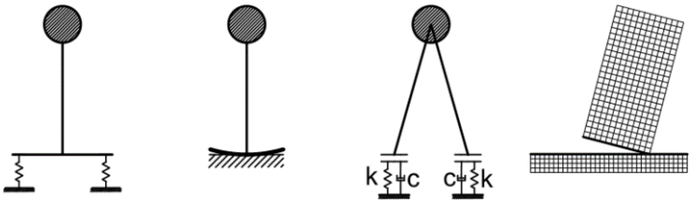

Fig. 7 Alternative models of rigid or flexible rocking bodies (Diamantopoulos and Fragiadakis, 2019)

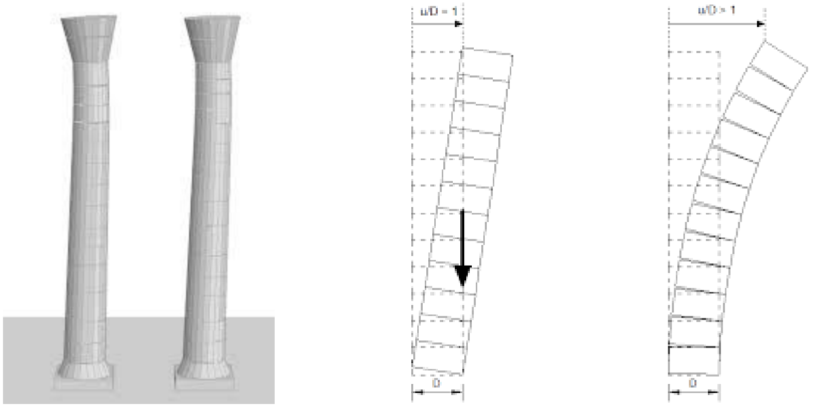

Fig. 8 Discrete element models of multi-drum columns (Psycharis et al., 2013)

7 Conclusions

The ARCHYTAS platform is a viable approach for supporting decision-making for pre-event or post-event rehabilitation actions for cultural-heritage sites. It supports multiple monuments at the same, or at spatially distributed sites. It allows integrating models of different levels of complexity and fidelity within a homogeneous flexible risk assessment framework with true multi-hazard capabilities. In the ever-present fiscal constraints and under a changing climate, it represents a way forward to achieve efficient resource management for protecting our cultural heritage.

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