

Quantification of potential natural hazards affecting cultural heritage sites and structural response evaluation. Application at the Acropolis of Athens

Quantification des potentiels hazards naturels affectant les sites du patrimoine culturel et évaluation de la réaction structurelle. Application à l'Acropole d'Athènes

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ABSTRACT: The current research examines the use of smart instrumental monitoring and computational simulations as tools for the quantification of natural phenomena, leading to natural hazards and for the evaluation of the structural response of structures and/or monuments of archaeological sites. More specifically, smart instrumental monitoring at problematic locations of the archaeological sites is proposed, in order to acquire remote and real-time information of both hazards and corresponding vulnerability in terms of structural response and distress. Furthermore, preliminary computational simulations are suggested in order to predict the expected response and distress of the structure(s) under examination when subjected to anticipated and actual natural hazards, being thus essential for the structural vulnerability assessment. The research includes an application at the archaeological site of the Acropolis of Athens.

RÉSUMÉ: La présente recherche étudie l'utilisation de la surveillance instrumentale intelligente et des simulations informatiques comme outils de quantification des phénomènes naturels menant à des hazards naturels et d'évaluation de la réaction structurelle des structures et / ou des monuments de sites archéologiques. Plus spécifiquement, il est proposé la surveillance intelligente des sites archéologiques qui sont potentiellement critiques, afin d'obtenir des informations à distance et en temps réel sur les dangers et la vulnérabilité correspondante en termes de réaction structurelle et de détresse. En outre, de simulations informatiques préliminaires sont suggérées afin de prévoir la réaction et la détresse attendues des structures examinées, lorsqu'elles sont soumises à de risques naturels prévisibles et réels. La recherche inclut une application sur le site archéologique de l'Acropole d'Athènes.

Keywords: Natural Hazards; Smart Monitoring; Computational Modelling; Cultural Heritage; Acropolis of Athens.

1 INTRODUCTION

Natural hazards are naturally occurring physical phenomena caused either by rapid or slow onset events which can be geophysical/ hydrological (i.e. earthquakes, landslides, tsunamis, avalanches and floods), climatological / meteorological (i.e. extreme temperatures, drought, wildfires, storms) or biological (disease epidemics and insect/animal plagues). The natural hazards may have a negative effect on humans or the environment and can sometimes escalate into natural disasters. The current research focuses on the first two general categories of the aforementioned natural hazards (i.e. geophysical / hydrological; climatological / meteorological), which will hereafter be noted as "geological hazards" and "meteorological hazards" respectively. The structural integrity of any engineering structure may be threatened by one or more natural hazards during its lifetime and this can be expressed in terms of structural risk. The structural risk of the engineering structures is directly related, not only to the natural hazards, but also to the vulnerability of the structures, which depends on the design, construction and operational conditions. The overall risk of the engineering structures is a “function” of the structural risk and the anticipated corresponding loss, in terms of human lives and / or socio-economic cost (Fig.1).



Figure 1. The relationship between structural risk, hazard, vulnerability, and loss

Worldwide, the archaeological sites usually include various sensitive engineering structures and monuments (e.g., temples, buildings, masonry retaining walls, etc) that are potentially threatened by a range of natural hazards, leading to structural failures (Figure 2). Furthermore, the archaeological sites are fundamental elements of the national and international cultural heritage, and their overall risk due to natural hazards is extremely high for two reasons: (a) a serious damage and especially a total failure of a structure and/or monument of an archaeological site is practically irreversible, and thus unacceptable, and (b) a failure of an archaeological site may lead to injuries of visitors and/or employees, or even human losses.



(a)



(b)

Figure 2. Examples of damages and failures at archaeological sites in Greece, in the past: (a) a masonry retaining wall at Delphi, (b) central area of the Acropolis Wall with significant part detachments

For the evaluation of the structural risk of an archaeological site, quantitative hazard assessment and realistic evaluation of the structural vulnerability are required. Furthermore, the archaeological sites include various old pre-existing structures and monuments with actually limitless lifetime and quite limited intervention options. Therefore, the cost-efficient assessment and management of the structural risk of an archaeological site is a more demanding task than the corresponding structural risk assessment and management of modern structures.

2 METHODS

2.1 *Smart Instrumental Monitoring*

Regarding the monitoring of structures, remote instrumental sensing is a rapidly growing scientific area, traditionally applied to critical structures and infrastructures of national and economic importance and/or of high risk of failure (e.g. important buildings, large bridges, long lifelines), aiming to their transformation into “smart” (Chatzi, 2017; Soga et al., 2015). Apart from remote hazard assessment (i.e. assessment of the loading conditions), the instruments can provide useful real-time information on specific location(s), necessary for the early detection of probable damage or failure during the lifetime, contributing thus to the optimal risk management and the overall safety. On the other hand, in-situ damage detection is not always feasible and can be particularly expensive.

Designing smart structures utilizes innovative technologies which can be implemented across the whole range of a project (i.e., construction phase and operational phase) in order to collect information at an early stage of a potential damage or failure. Moreover, an early-warning system can be developed to be activated in the case of exceeding predefined limits, leading thus to self-control of an area under examination. In addition, there has been a gradual replacement

of the conventional methods of structural instrumentation and monitoring via the application of optical fibre sensors (e.g. Fiber Bragg Grating-FBG sensors). The optical fibre sensors combine precision (microstrains) with resistance to mechanical stress and multiplexing of signals with a relatively low cost, which is constantly decreasing (Kapogianni et al., 2017). An important advantage is that they are portable systems that can be placed in various positions, on almost any structure, monitoring the hazard(s) (i.e., the loading conditions) along with the structural response / distress on critical locations.

Furthermore, in an environment where various networks of sensors have been deployed, the need for intelligent management and processing of the recorded and transmitted data has emerged. Integral part of the data processing is the combination (i.e., data fusion between heterogeneous networks) and the support of additional meta-data in order to efficiently handle the available measurements. Regarding the intelligent management, several different architectures have been proposed (Vilbrandt et al., 2004).

2.2 *Computational Modelling*

Regarding the computational simulations, various numerical methods (such as the finite-element method) can be applied providing useful information about the structural response and distress of any structure or monument. Usually, a computational simulation requires the geometrical and mechanical properties of the structure under examination and the anticipated static and/or dynamic loading (either external or internal). In the past, various researches have been involved with the numerical modelling of monuments under static and/or dynamic loading conditions. Nevertheless, in order to achieve a more realistic simulation of the response / distress of a structure / monument, the local site conditions (i.e., soil, geomorphology,

topography) and the corresponding potential soil-structure interaction should be taken into consideration. Furthermore, the various uncertainties of the loading conditions may be limited by a reassessment based on real-time monitoring.

The loading conditions may be either static (e.g., gravity, differential settlements, hydrostatic pressures) or dynamic (e.g., earthquake loading, various anthropogenic vibrations). It should be emphasized that the dynamic response of any structure /monument is directly related to local site conditions since the seismic motion at the ground surface may be altered by the soil stratigraphy conditions and the topographic irregularities. The seismic effects of irregular topography have been repeatedly shown to be detrimental to structures. Instrumental evidence of topographic amplification is also abundant in weak seismic motions and rather limited from strong and destructive seismic shaking (Aki, 1988).

3 THE ACROPOLIS OF ATHENS

The Acropolis of Athens (Figure 3) is the most outstanding ancient Greek monumental complex still existing in our time and symbolizes the values and achievements of the classical civilization. It was included in the World Heritage Sites List of Unesco in 1986 and forms the greatest architectural and artistic complex bequeathed by Greek Antiquity to the world. It is situated on a hill of average height of 150 meters above sea level and 70 meters from the level of the city centre and is part of the hill-line of Athens (Acropolis-Philopappou-Strefi-Lycabettus-Tourkovounia) by a geological and tectonic aspect. The hill is rocky and steep on all sides, except for the western side, and has an extensive, nearly flat top.

Among the standing monuments on the hill (Parthenon, Erechtheion, Propylaia, Athena Nike, Arrephorion), the Circuit (i.e. Perimeter) Wall serves also a geotechnical purpose, since it functions as a typical gravity wall, retaining the

backfill that forms the plateau of the Acropolis (Eleftheriou, 2015; Manidaki, 2006). It has a total length of about 800 m and a height varying between 5 and 20 m. The importance of the Circuit Wall is significant since it serves as the foundation of other monuments on the Hill and the passing of time has seen it undergo numerous damages due to extreme weather conditions, various types of loading (e.g. earth pressures due to the backfill and seismic loading according to Ambraseys, 2010; Zambas, 2011), as well as the human interference, leading to structural damages, such as cracks, block falls and displacements, increasing the risk of local and/or extensive structural failures (Trikkalinos, 1977).

The Acropolis Hill is geologically composed mainly by limestone which is overlying a schist system of marls and sandstones (Higgins & Higgins, 1996; Koukis, 2015). The Athenian schist is visible on the main entrance of the archaeological site and less in other positions, while the limestone is visible on the Hill when it is not covered by artificial embankments, built in order to create the surface level of the Hill.

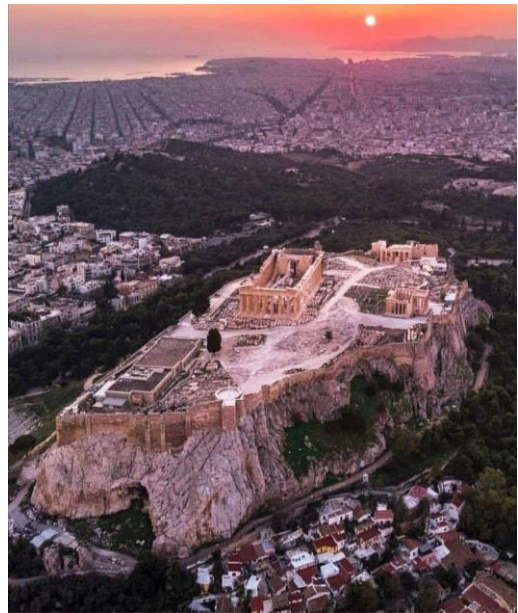


Figure 3. The Hill of the Acropolis of Athens

4 APPLICATION

4.1 Monitoring Array

The historical significance of the Acropolis of Athens, the complexity of the geomorphological conditions in the region, the vulnerability to natural and man-made hazards, as well as the need to resolve practical problems encountered during the restoration works have led to the application of various contemporary technologies on the Acropolis Hill and its monuments over the last years (Egglezos, 2010; Kalogeras & Egglezos, 2013; Astreinidis & Egglezos, 2010). Such an example is the multidisciplinary monitoring via optical fibre sensors which have been included to serve the extensive restoration works, aiming at real-time data gathering for immediate intervention when required.

More specifically, between 2015 and 2016 a new Fiber Bragg Grating (FBG) (i.e. optical fibre-sensor) array was installed on the Circuit Wall of the Acropolis, consisting of eight (8) active strain sensors, two (2) temperature sensors and one (1) acceleration sensor, continuously transmitting real-time data since June 2016 to date (Kapogianni, 2016).

Figure 4 shows the South-East view of the Acropolis, parts of the monitoring array and the data transmission scheme. Furthermore, Figures 5, 6 and 7 show (a) indicative wavelength recordings via the FBG acceleration sensor, (b) indicative wavelength recordings via one of the FBG temperature sensors, and (c) indicative wavelength recordings via one of the FBG strain sensors, respectively. After processing, the recordings can lead to real-time acceleration, temperature and strain measurements, respectively.

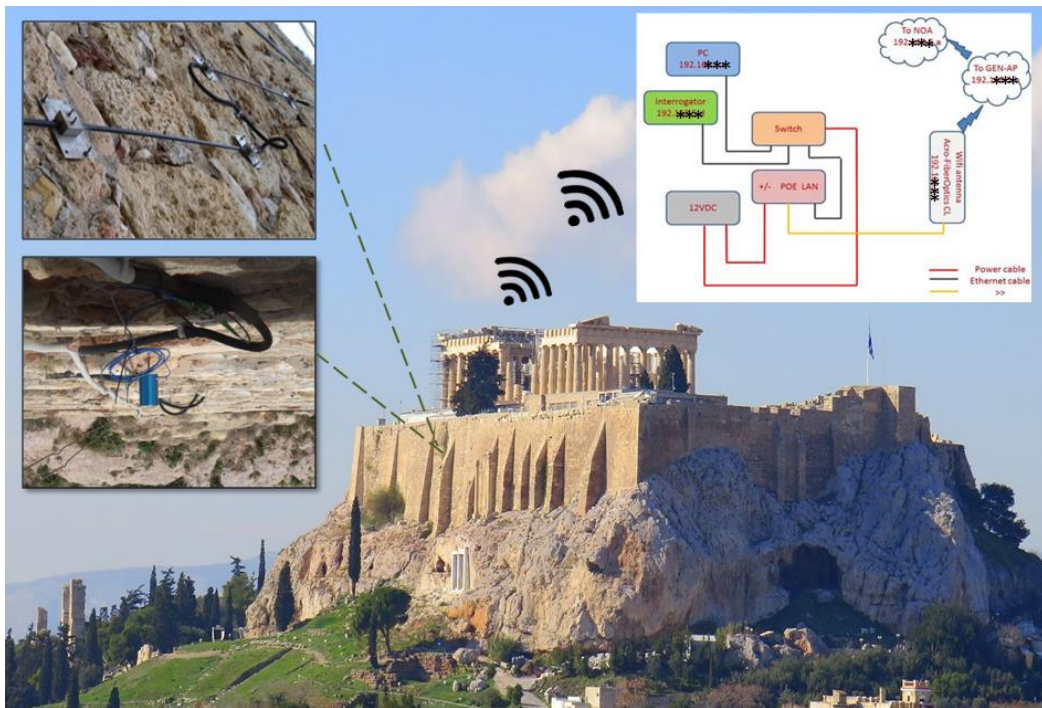


Figure 4. The South-East view of the Acropolis, parts of the monitoring array, and data transmission scheme

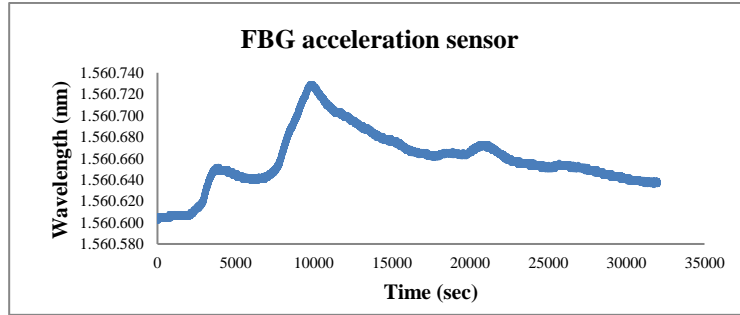


Figure 5. Indicative wavelength recordings via FBG acceleration sensor

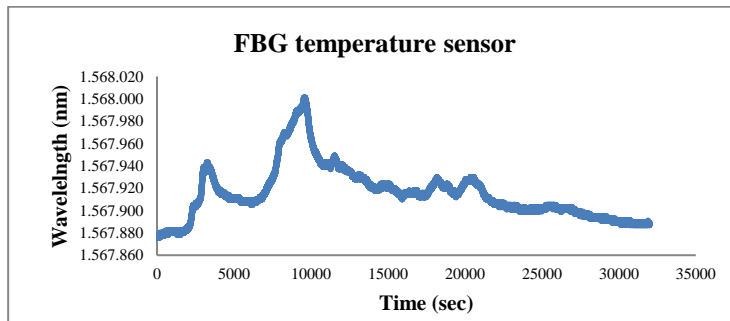


Figure 6. Indicative wavelength recordings via FBG temperature sensor

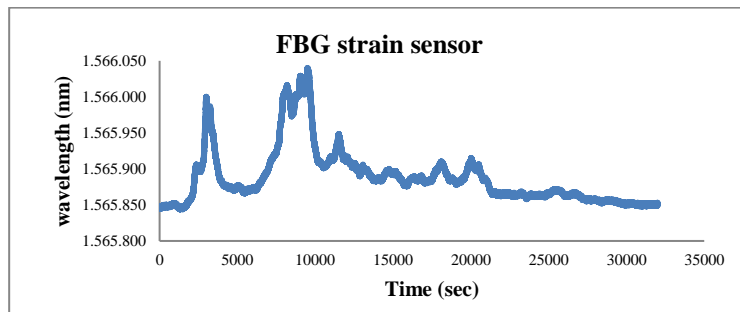


Figure 7. Indicative wavelength recordings via FBG strain sensor

4.2 Computational Modelling

Apart from monitoring, preliminary finite-element modelling of the Acropolis Circuit Wall has provided useful information concerning its structural response due to various types of loading and details can be found in Psarropoulos et al. (2017). Furthermore, ground response analyses with pulses and real accelerograms

have been performed in order to investigate the impact of local site conditions (i.e., topography) on the seismic motion at the ground surface of the Acropolis Hill, as well as to verify the available records and comprehend the amplification pattern.

Figure 8 shows (a) a detail of the discretization of the numerical model with the location of four of the accelerographs at the

Acropolis Hill (ACRB, ACRF, ACRG, ACRJ) (Kalogeras et al., 2010) and (b) some indicative results (i.e. transfer functions) in the case of a Ricker pulse excitation of 2Hz. Despite the discrepancies, the results are regarded as

satisfactory, given the uncertainties regarding the mechanical and geometrical properties of the Hill and the simplifications of the modelling.

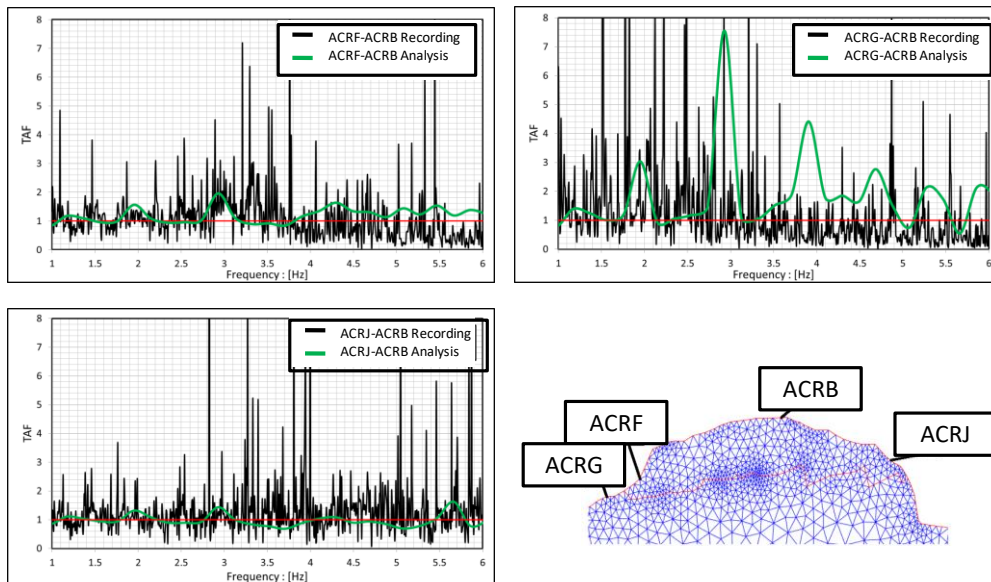


Figure 8. Transfer functions in the case of a Ricker pulse excitation (2Hz)

5 CONCLUSIONS

In the current study the use of smart instrumental monitoring and computational simulations as tools for the quantification of natural phenomena (leading to natural hazards) and in order to evaluate the structural response of structures and/or monuments of archaeological sites has been examined. More specifically, smart instrumental monitoring at specific problematic locations at the Acropolis of Athens has been presented, aiming to the remote and real-time information gathering of both the actual hazards and the corresponding vulnerability in terms of structural response and distress. More specifically, wavelength measurements via FBG sensors were made possible, which can be transformed into acceleration, temperature and strain measurements. In addition, preliminary

computational modelling utilizing the finite element method has been performed in order to predict the expected response of the Circuit Wall and the Hill of the Acropolis, aiming to their structural vulnerability assessment. It is noted that a further calibration of the numerical models with more recordings could improve the numerical results. The study showed that the applied methods (i.e. smart instrumental monitoring and computational analyses) could assist towards the preservation of the structural integrity of the cultural heritage sites.

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