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Abstract- The Acropolis of Athens is one of the most prestigious ancient monuments in the world, attracting daily many visitors, and therefore its structural integrity is of paramount importance. During the last decade an accelerographic array has been installed at the Archaeological Site, in order to monitor the seismic response of the Acropolis Hill and the dynamic behaviour of the monuments (including the Circuit Wall), while several optical fibre sensors have been attached at a middle-vertical section of the Wall. In this study, indicative real time recordings of strain and acceleration on the Wall and the Hill with the use of optical fibre sensors and accelerographs, respectively, are presented and discussed. The records aim to investigate the static and dynamic behaviour – distress of the Wall and the Acropolis Hill, taking also into account the prevailing geological conditions. The optical fibre technology, the location of the sensors, as well as the installation methodology applied is also presented. Emphasis is given to the application of real time instrumental monitoring which can be used as a valuable tool to predict potential structural risk.

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MONITORING OF THE HILL AND THE CIRCUIT WALL OF THE ATHENIAN ACROPOLIS UTILIZING OPTICAL FIBRE SENSORS AND ACCELEROGRAPHS

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Monitoring of the Hill and the Circuit Wall of the Athenian Acropolis Utilizing Optical Fibre Sensors and Accelerographs

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Abstract- The Acropolis of Athens is one of the most prestigious ancient monuments in the world, attracting daily many visitors, and therefore its structural integrity is of paramount importance. During the last decade an accelerographic array has been installed at the Archaeological Site, in order to monitor the seismic response of the Acropolis Hill and the dynamic behaviour of the monuments (including the Circuit Wall), while several optical fibre sensors have been attached at a middle-vertical section of the Wall. In this study, indicative real time recordings of strain and acceleration on the Wall and the Hill with the use of optical fibre sensors and accelerographs, respectively, are presented and discussed. The records aim to investigate the static and dynamic behaviour – distress of the Wall and the Acropolis Hill, taking also into account the prevailing geological conditions. The optical fibre technology, the location of the sensors, as well as the installation methodology applied is also presented. Emphasis is given to the application of real time instrumental monitoring which can be used as a valuable tool to predict potential structural risk.

List of notation

$\Delta\epsilon$ strain change

$\Delta\lambda$ wavelength change

$K\epsilon$ ratio expressing strain-wavelength relation

K_T ratio expressing strain-temperature relation

ΔT temperature change

1. INTRODUCTION

The Acropolis Hill is the most outstanding ancient Greek monumental complex still existing in our time and was chosen due to its geomorphology since the Neolithic period (4000 / 3500-3000 BC) as a place for local residents. It has a height of about 150 m above sea level and 70 m from the level of the city of

Athens. Among the standing monuments of the Hill, the Circuit (perimeter) Wall serves a pure geotechnical purpose, since it functions as a typical gravity wall, retaining the backfill that forms the plateau of the Acropolis and has total length of about 800 m and variable height areas 5-20 m. In Figure 1, a panoramic view of the Acropolis Hill from the south-east is depicted.

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Figure 1: Panoramic view of the Athenian Acropolis, where the South Wall (right) and the West Wall (left) are shown

The historical significance of the Archaeological Site, 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. In this framework, multi-disciplinarily instrumental monitoring (via accelerographs and optical fibre sensors) has been included, serving also the extensive restoration works and aiming to real time data gathering for immediate intervention when needed (Sakellariou et al, 2016; Kalogeras et al, 2012).

(Koukis et al., 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 is not covered by artificial embankments, which have been built in order to create the surface level of the hill. The embankments are thicker on the south side and held around the Wall and the limestone karstification has led to cavities which facilitate the water flow, further erosion and rock fall phenomena. Figure 2 shows a geological plan view of the Acropolis Hill (Higgins & Higgins, 1996).

II. GEOLOGY OF THE HILL AND THE PERIMETER WALL

The Acropolis Hill is geologically composed mainly by limestone overlying the Athenian Schist

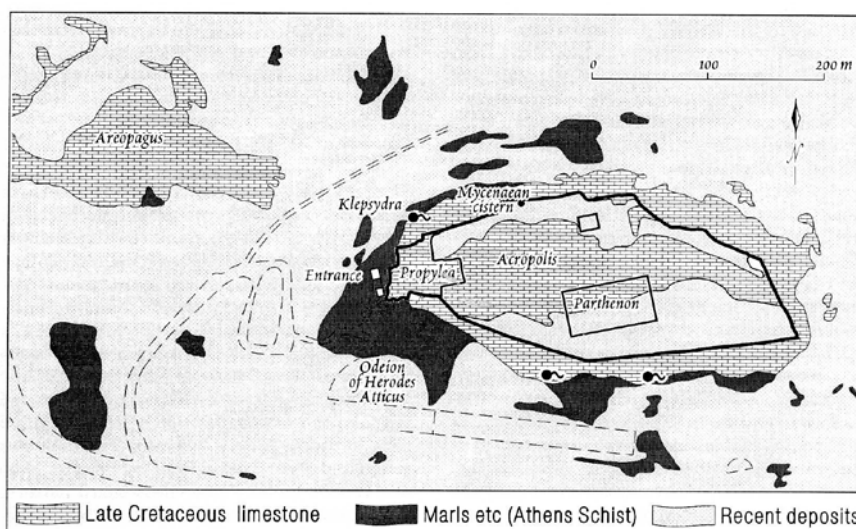


Figure 2: Geological plan view of the Acropolis Hill

The importance of the Perimeter Wall is very high since it provides foundation of other monuments of the hill and the passing of time has seen it undergo numerous damages mainly due to the weather conditions and various types of loading, as well as the human intervention, leading to crack creation and

therefore increasing the risk of local and/or extensive structural failures (Ambraseys, 2010; Trikkalinos, 1977). In Figure 3 the central area of the South Wall is noted, which comprises mainly irregular mixed courses made up of ancient marble blocks in second use (spolia) and small stones, added in later repairs.



Figure 3: Central area of the South Wall on the Acropolis Hill

III. MONITORING INFRASTRUCTURE ON THE ACROPOLIS HILL

Over the last years, 10 high-quality broadband accelerometers (Guralp CMG-5TD) have been installed on specific locations on the hill, recording in continuous mode on 24-bit digitizers and transmitting data in real-time to the Institute of Geodynamics (NOA) facilities in Thissio and the Acropolis Restoration Service (YSMA)

facilities in Plaka, using governmental telecommunication infrastructures (Kalogeras & Egglezos, 2013). The accelerographs were installed, considering the various geotechnical conditions on the hill as well as the specific interest of YSMA for individual sites (Parthenon, South Wall, etc.). In Figure 4 the location of the accelerographs are presented.

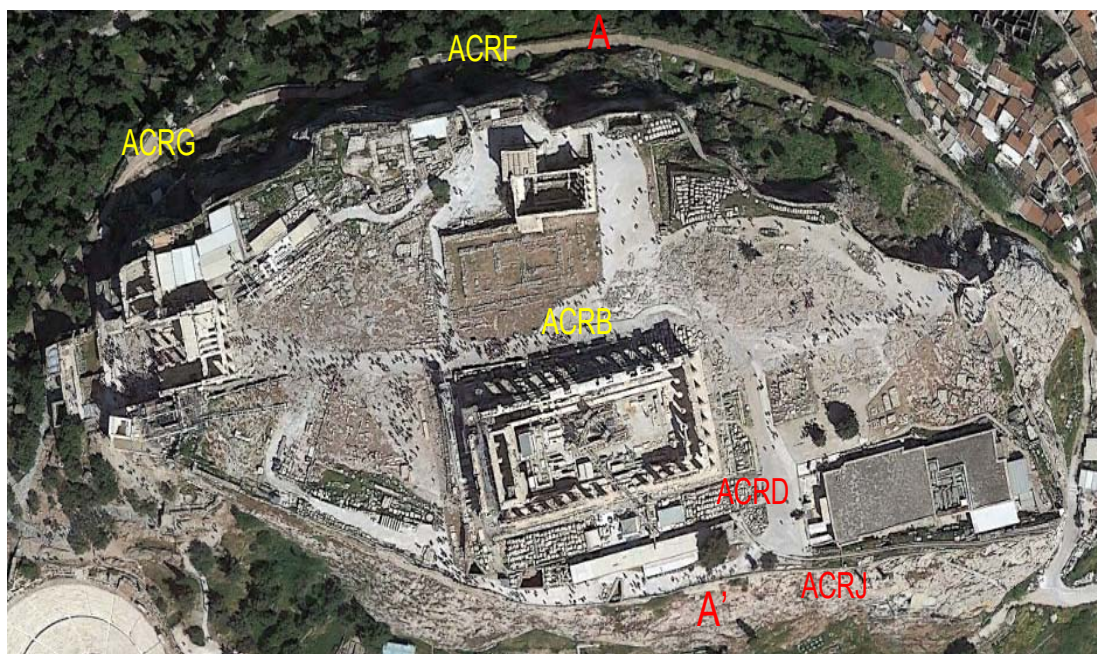


Figure 4: Plan view of the Acropolis Hill showing the location of the ten accelerographs. The red stars correspond to the two accelerographs (ACRD and ACRJ) located on the South Wall (adjacent to the optical fibre sensors array)

In addition, during 2015-2016 a new optical fibre network was developed on the South Wall consisting of eight active strain sensors (Smart Rods) and one acceleration sensor (attached directly on the South Wall), continuously transmitting real time data since June 2016 to date (Kapogianni et al, 2016a; Kapogianni et al, 2016b). The sensors were fixed at predefined positions on the South Wall with the use of stainless steel plates, anchored to the substrate. The critical positions of the optical fibre arrays were defined

by analyzing computational models, utilizing the finite element method (Kapogianni et al., 2017) and the area selected for the final installation was near the pre-existing accelerometers ACRD and ACRJ (see Figure 4). Connection in series was achieved via in situ splicing, while strain measurements were made possible with the use of the Optical Sensing Interrogator SM 130. In Figure 5 the location of the new measuring equipment is presented.

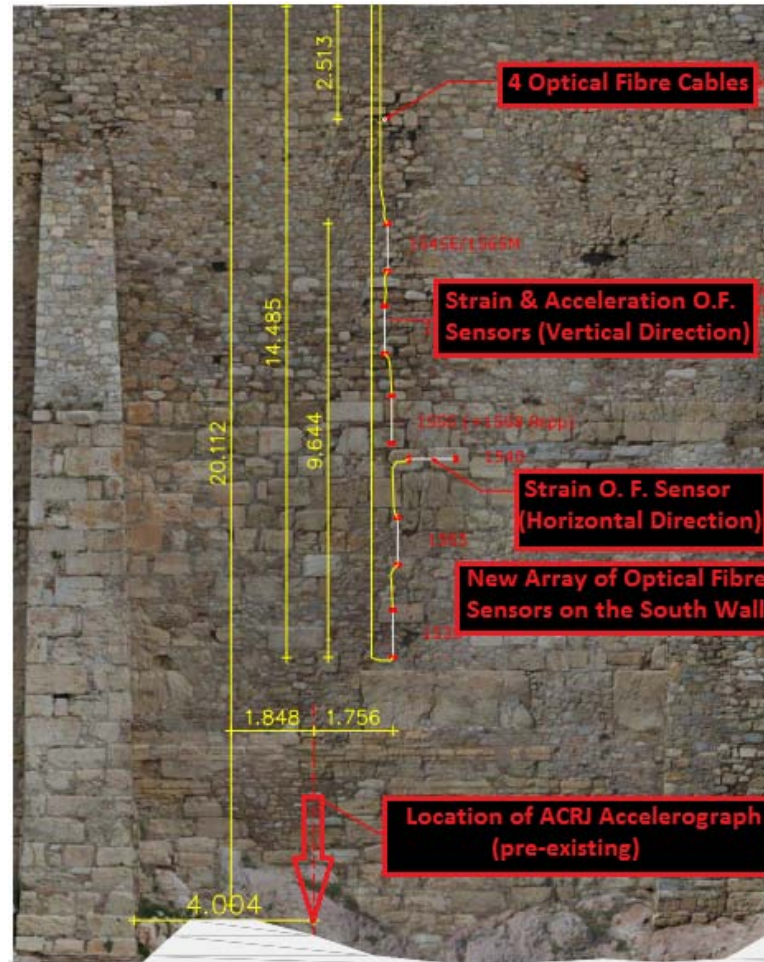


Figure 5: New array of strain and acceleration optical fibre sensors on the South Wall

IV. OPTICAL FIBRE SENSORS AND ACCELERATION RECORDINGS

Time stamped non-continuous and real-time continuous strain and temperature optical fibre measurements were recorded at various positions on the South Wall. Since various physical phenomena affect the Acropolis Hill and the Perimeter Wall, such as very high and low temperatures, excessive rainfalls, earthquakes, etc., the optical fibre monitoring infrastructure aims to quantify their influence on the monument. Equation 1 is used in order to derive strain measurements from the correspondent wavelength recordings.

$$\Delta \varepsilon = (\Delta \lambda - K_T \cdot \Delta T) / K_\varepsilon \quad (1)$$

where

$\Delta \varepsilon$ [%] is the strain change;

$\Delta \lambda$ the wavelength change;

K_ε is a ratio expressing the strain-wavelength relation and is equal to 1.2 picometer (pm)/ μ strain for the sensors type that was used for the current study;

$K_T \cdot \Delta T$ incorporated the wavelength changes due to the temperature variations, where K_T is equal to 11.2 pm/C° for the sensors used and ΔT is the temperature variation, measured during the tests (starting value and actual-final value).

In Figures 6 and 7 characteristic recordings for time-stamped, non-continuous and real-time continuous strain recordings (including temperature) are presented. The results so far indicate that temperature plays an important role on the strain levels on the Wall. Due to lack of a strong seismic event, no notable acceleration recording has been obtained via the optical fibre sensor. In addition, it is noted that information gained from the

non-continuous recordings is of different magnitude and pattern compared to the corresponding ones from the real-time records. In order to derive comprehensive conclusions related to the behavior of the Wall, real-time recordings should be gathered and analyzed for a long period of time and at various positions, including various loading events (e.g. seismic).

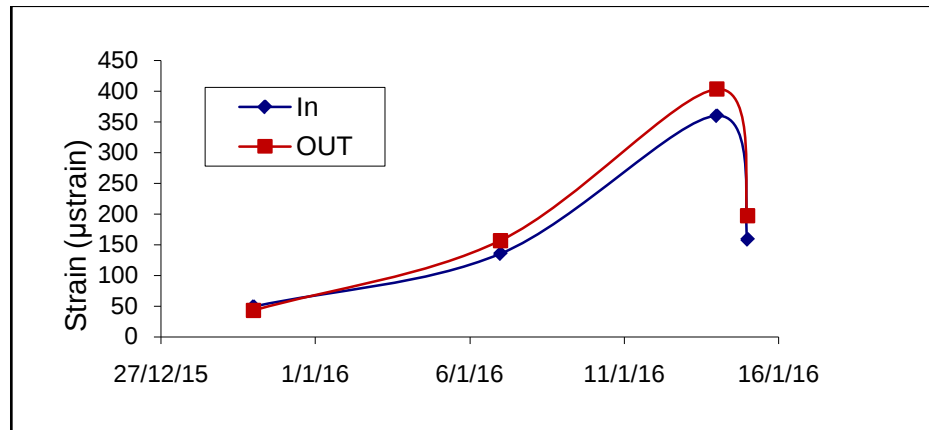


Figure 6: Time-stamped, non-continuous strain recordings on the South Wall

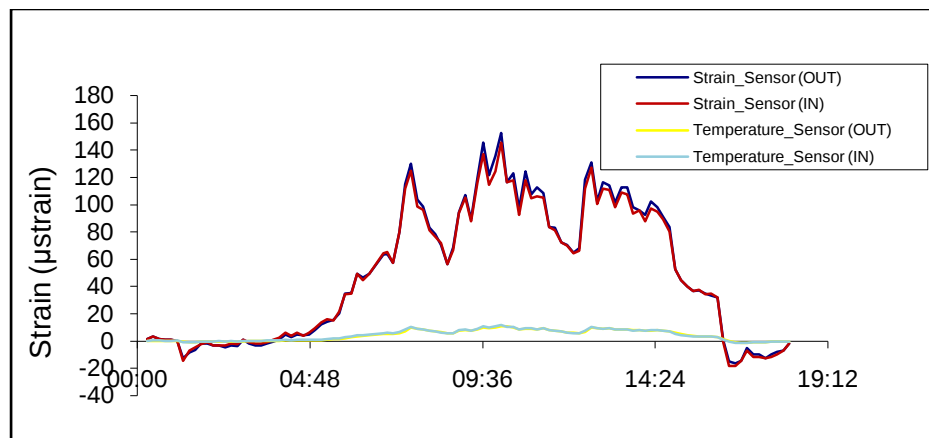


Figure 7: Real-time strain and temperature recordings on the South Wall

Furthermore, real-time continuous strain and temperature recordings are presented in Figures 8a to 8d, for sensors attached on four different locations on the South Wall of the Acropolis Hill. In particular, results via sensors on the top, middle and bottom of the Wall are presented, for an approximately 20-hour period of time. It can be noted that strain increases during the morning and noon and decreases during the night, due to the temperature increase and decrease, respectively. In addition, recordings near the vertical middle section of the Wall are higher, compared to the correspondent values near the top and bottom of the Wall. It should be emphasized that remotely real-time monitoring on various locations on the Wall can provide long-term useful conclusions related to its structural behaviour, especially during various loading events such as

seismic, restoration works on the Acropolis site and/or extreme weather conditions.

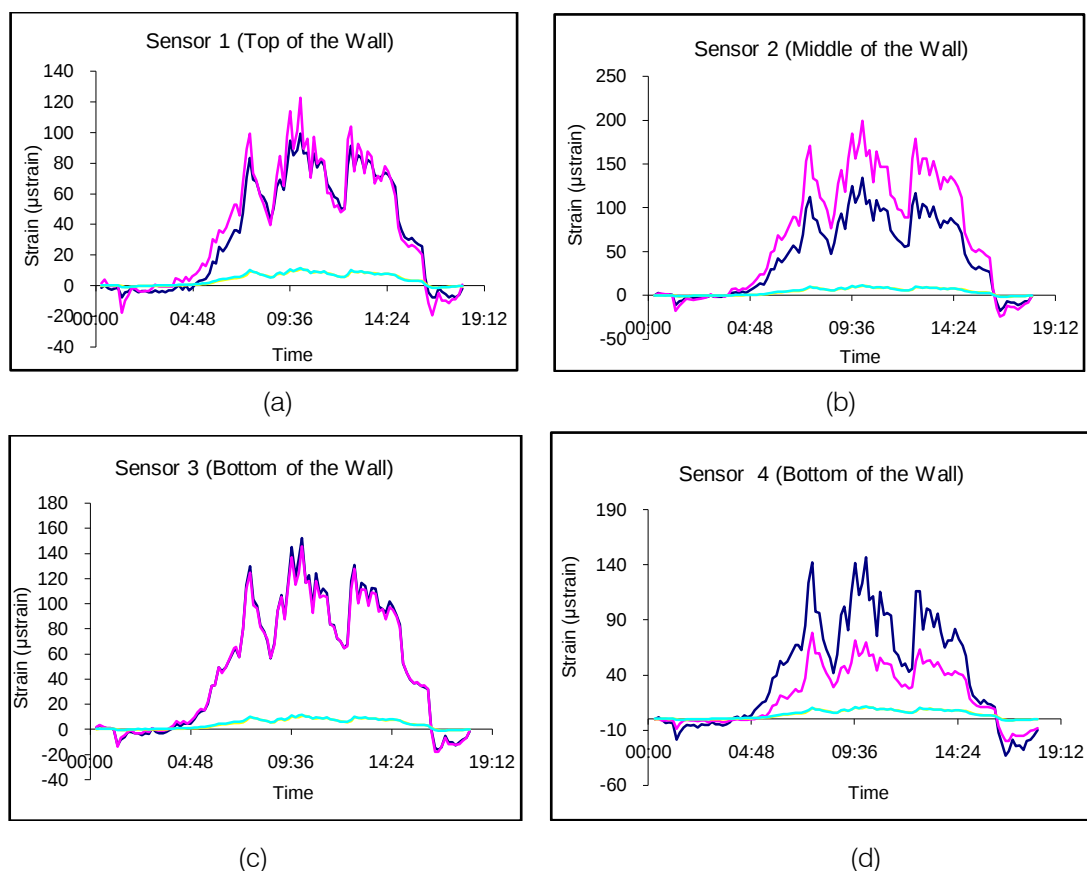
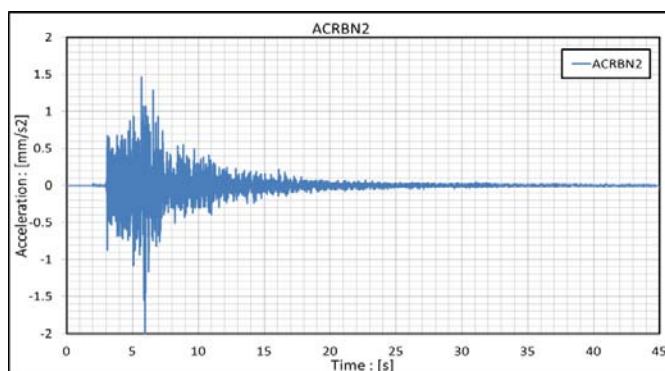


Figure 8: Real-time-stamped strain and temperature recordings at four different locations on the South Wall.

Moreover, since the installation of the first accelerograph in 2006 and of the deployment of the array in two periods (2008 and 2013), many near-field and far-field seismic events have been recorded. In the current study two earthquakes have been considered. The first seismic event (on 05/12/2014) was a small earthquake close to Athens with local magnitude $M_L = 2.4$ and focal depth of 18.4 km from a distance of 17 km, while the second seismic event (on 24/05/2014) was a strong earthquake almost 300 km away from Athens,

close to the island of Samothraki, Northern Aegean, with local magnitude $M_L = 6.3$ and focal depth 28.3 km. Figure 8 shows the acceleration time-histories of the instrument ARCB (N-S component) recorded during the two aforementioned seismic events.



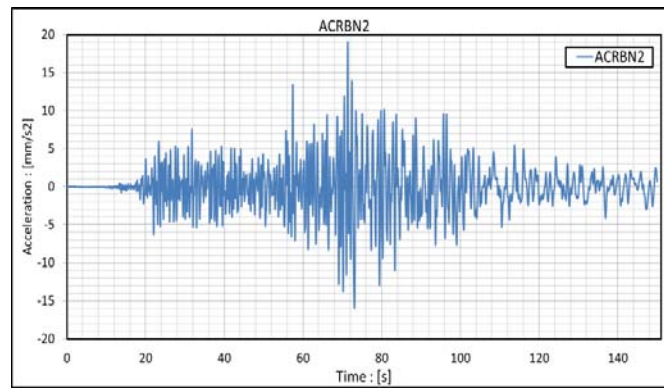


Figure 8: The acceleration time histories recorded by ACRB instrument during the small near-field seismic event (upper) and the strong far-field seismic event (lower)

It is evident that the recorded ground motion of the small near-field seismic event is characterized by very low peak ground acceleration (PGA) levels, short duration and high frequency content, while on the contrary, the recorded ground motion of the strong far-field seismic event is characterized by higher PGA levels, longer duration and lower frequency content.

Figure 9 shows the elastic response spectra of four recorded ground motions (ACRB, ACRF, ACRG and ACRJ) during the two examined seismic events. Judging

from the shape of the spectra, it becomes evident that, apart from the obvious great differences between the two seismic events, the discrepancies between the four records during the far-field earthquake are relatively small, while on the contrary, during the near-field event there is a substantial variability referencing to the installation site characteristics: the instruments located at the north side of the hill (i.e. ACRF and ACRG) exhibit higher PGA levels and higher spectral accelerations.

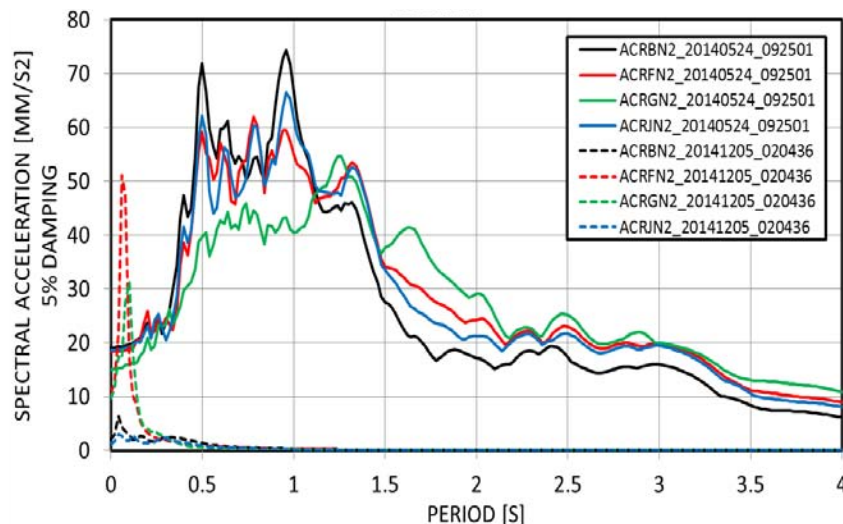


Figure 9: The elastic response spectra of four recorded ground motions during the two examined seismic events. Continuous lines correspond to the far-field event, while dashed lines correspond to the near-field event

V. CONCLUSIONS

Structural health monitoring is a rapidly growing scientific area, applied initially to structures of economic importance, historical significance and high risk of failure. The use of measuring systems aims to the creation of intelligent structures such as bridges, buildings, geotechnical constructions, etc., that are instrumented with sensors and other devices, providing important real time information on various locations, necessary for early detection of failures. Through sensors and devices installation, useful real time

information is gathered, necessary for early detection of structural problems, during construction and life cycle, contributing to safety and their optimal management.

The current paper is involved with the structural health monitoring of the Acropolis Archaeological Site, via optical fibre sensors installed on the South Wall and accelerographs located on the Hill, continuously transmitting data from various locations. The results so far indicate that temperature plays an important role on the strain levels on the Wall however, due to lack of a strong seismic event, no notable acceleration recording has been obtained. It can be noted that strain increases

during the morning and noon and decreases during the night, due to the temperature increase and decrease respectively. In addition, recordings near the vertical middle section of the Wall are higher, compared to the correspondent ones near the top and bottom of the Wall. Concerning the recorded ground motion via the accelerographs, it is noted that the small near-field seismic event is characterized by very low peak ground acceleration (PGA) levels, short duration and high frequency content, while on the contrary, the recorded ground motion of the strong far-field seismic event is characterized by higher PGA levels, longer duration and lower frequency content.

Concluding, it should be highlighted that remotely real-time monitoring on various locations on the Acropolis Hill can provide long-term useful conclusions related to its structural behaviour, especially during various loading events such as seismic, restoration works on the Acropolis site or/and extreme weather conditions.

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